Turbulent Mixing and Beyond

Sixth International Conference

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PROCEEDINGS

ABSTRACTS

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Preface

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

Program 'Turbulent Mixing and Beyond' has been founded in 2007 with the support of international scientific community and of international funding agencies and institutions. This is the program established for scientists by scientists. It is merit-based, and is shaped by requirements of novelty, academic credentials, and information quality. To date, TMB community unites thousands researchers worldwide, including scientists from academia, national laboratories, corporations and industry, at experienced and at advanced stages of their careers.

TMB International Conferences have been organized in 2007, 2009, 2011, 2013, and 2014. They found that TMB-related problems have in common a set of outstanding research issues; these challenging TMB problems can indeed be solved, via discovery of their fundamentals; the TMB participants conduct highly innovative research and their interactions strengthen the community might.

TMB-2017 is the 6th International Conference 10th Anniversary Program. It considers the broad variety of TMB themes, and is focused on fundamentals of non-equilibrium transport. Its objectives are to advance knowledge of non-equilibrium dynamics, and to have a positive impact on our understanding of a variety of natural phenomena, from atomistic to astrophysical scales, on principles of theoretical modeling of non-equilibrium dynamics at continuous and at kinetic scales, on methods of experimental diagnostics and numerical modeling techniques, and on technology development in, for instance, fusion, nano-electronics, telecommunications, aeronautics, gas and oil industry.

Non-equilibrium processes control a broad variety of phenomena in fluids, plasmas and materials, over celestial to atomistic scales. Examples include inertial confinement and magnetic fusion, supernovae and accretion disks, planetary convection and geophysics, reactive flows and super-critical fluids, formation of phase boundaries and material transformation under impact, non-canonical turbulence and turbulent mixing, nano-technology and communications. Addressing contemporary scientific and societal challenges posed by alternative energy sources, developing cutting-edge technologies for laser micromachining and for industrial applications in the areas of aeronautics and aerodynamics, efficient using of non-renewable resources, - requires us to in-depth understand the fundamentals of non-equilibrium dynamics, to be able gather high quality experimental and cyber data and derive knowledge from these data, and, ultimately, to achieve a better control of these complex processes.

Non-equilibrium processes present everywhere. They often involve sharp changes of vector and scalar flow fields, and may also include strong accelerations and shocks, radiation transport and chemical reactions, diffusion of species and electric charges, among other effects. At macroscopic scales, their spectral and invariant properties differ substantially from those of canonical turbulence. At atomic and meso-scales, they depart from the standard scenario given by Gibbs ensemble averages and the quasi-static Boltzmann equation. At the same time, in the vastly different physical regimes the non-equilibrium dynamics may exhibit certain features of universality and similarity, and may lead to self-organization and order, thus offering new opportunities for their diagnostics and control. Capturing properties of non-equilibrium transport can aid better comprehension of fundamentals of Eulerian and Lagrangian dynamics as well as coupling of kinetic to meso- and macroscopic scales, and can further advance the methods of studies of a broad variety of phenomena in nature and technology.

Significant success has been recently achieved in our understanding of non-equilibrium transport on the sides of theoretical analysis, large-scale numerical simulations, laboratory experiments, and technology development. This success opens new opportunities for studies of fundamentals of non-equilibrium dynamics across the scales, and for developing a unified description of particles and fields on the basis of synergy of experiment, theory and numerics. This fundamentals knowledge can be further applied to address the challenges of modern science, technology and society, via the interplay of ideas and approaches from the interdisciplinary areas of research.

TMB program provides the opportunity to bring together researchers from the areas, which include and 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 dynamics.

TMB-2017 is structured to encourage the participants' communications with experts from different fields, to promote the exchange of ideas and suggestion of open problems, and to motivate the discussions of rigorous mathematical problems, theoretical approaches and state-of-the-art numerical simulations along with advanced experimental techniques and technological applications.

The Organizing Committee hopes that program 'Turbulent Mixing and Beyond' will serve to advance knowledge of fundamental aspects of non-equilibrium processes, their predictive modeling capabilities and physical description, and, ultimately, control of these complex processes.

The Book of Abstracts includes 195 accepted contributions of 375 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 the members of the Scientific Advisory Committee.

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, H. Azechi, B. Galperin, S. Gauthier,
W. Gekelman, K. Nishihara, P.K. Yeung

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TURBULENCE and MIXING

Internal intermittency and finite Reynolds number effect for turbulent mixing of passive and active scalars

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Solving the 'theory of turbulence' would be to derive a tractable quantitative theory, based soundly on the underlying physics, as described by the first principles. Despite classical asymptotic theories (Kolmogorov, Obukhov, Corrsin, or KOC), both velocity and scalar fields are significantly affected by the flow-dependent large scales, either because of the large scale anisotropy which propagates down to the smallest scales, or, simply because the Reynolds number is finite (this is usually referred to as the Finite Reynolds Number, or FRN, effect). Scale-by-scale transport equations for high-order moments of the scalar increment are: (i) formulated with an explicit account of the finite Reynolds number effect, and (ii) assessed using direct numerical simulations of several flows at different Reynolds numbers. Special emphasis is laid on the scaling of the 'source' term that directly connects the instantaneous dissipation rate to the local variance of the scalar. Thus, the effect of internal intermittency is entangled by a complex mechanism involving both small and large scales. The equations are further analyzed to show that the similarity scales (i.e. variables which allow for perfect collapse of the normalized terms in the equations, or an affine transformation of these terms) are, for the second-order moments, fully consistent with KOC theory. However, for high-order moments, adequate similarity scales are built from high-order moments of the dissipation rate of the scalar variance. This is pointing to the invalidity of the KOC theory for high-order statistics. Closures of the transport equations are proposed and validated, for the particular case of decaying homogeneous isotropic turbulence, for the second and fourth order moments of scalar increments. These are based on the notion of characteristic time at any scale. The discussion is extended to active scalars, such as variable-viscosity components.

Geometrical shock dynamics in turbulent mixing

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This paper concerns advanced numerical simulations and analysis of geometrical shock dynamics in turbulent mixing. Using high-order implicit large eddy simulations (iLES), we have investigated the shock physics, transition and turbulent mixing of a range of Richtmyer-Meshkov problems, including double-planar, inverse chevron, and half-height multi-component flow configurations. Our aim is to shed light on the shock structures and shock dynamics and their effects on turbulent mixing, as well as to investigate the numerical uncertainties associated with high-order iLES methods with accuracy ranging from 5th to 11th order. Particular attention is paid into the shock reflections and shock-shock interactions effects on demixing. Furthermore, the formation and evolution of various 'organized' turbulent structures that develop during Richtmyer-Meshkov mixing of miscible fluids is

discussed. The iLES approach is based on high-order weighted essential non-oscillatory schemes (WENO) in conjunction with low-Mach corrections for improved resolution of low-Mach turbulent eddies.

The non-stationary turbulent energy cascade in the framework of scaling symmetry approach

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The idea of scaling symmetry (i.e. going through the hierarchy of spatial scales, a disordered complex system exhibits the auto-similarity) has been successfully exploited in different areas of physics. In our work, this idea is used in formulation of non-stationary cascade of turbulent energy in 3D incompressible flows. To this end, the energy transfer downward from large-to-smaller scales is considered in the framework of fragmentation under scaling symmetry, and the kinetic evolution equation for the energy per unit length-scale is introduced. This equation is renormalized (the continuity-type equation is derived), and along with the integral of motion, the self-similar solutions (or intermediate asymptotic) were found. In the case of decaying turbulence, these solutions were expressed by elementary functions. The non-stationary distributions of the energy density and of its flux show the following scenario across turbulent length-scales. On negative times, the small scales are dominant in the onset of turbulent cascade. At zero time, similar to a statistical system near critical point, the energy flux at zero length-scale 'jumps' discontinuously from minus infinity to the finite value, while energy density is manifested by by 'minus one power law. Further, on positive times, the energy density evolves to its long-time limit distribution, and taking the special limit, this distribution comes to the classical Kolmogorov 'minus one-third law in the statistically stationary turbulence. Thereby the constant in this law, known usually from measurements, was predicted analytically. The non-stationary solutions are compared with DNS in the statistically isotropic decaying box turbulence. On the basis of this theory, the stochastic model of the non-stationary cascade was developed and illustrated in examples.

Intermittency effects on passive scalar spectrum at very high Schmidt number

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Spectrum of passive scalar at very high Schmidt number (Sc) is studied theoretically and numerically. Batchelor’s theory and the Lagrangian spectral theory predict the Gaussian decay of the spectrum in the far diffusive range. On the other hand, the Kraichnan model which assumes the multivariate Gaussian velocity field with delta correlation in time yields the exponential decay. Direct numerical simulations (DNSs) and experiments have found that it decreases exponentially in spite of the fact that the velocity field is non-Gaussian and has finite correlation in time. This disharmony means that our knowledge lacks some essential physics in the scalar mixing. For more consistent explanation we examined the intermittency effects of the incompressible fluid turbulence on the scalar spectrum. First we have studied

the scalar spectrum up to Sc=1000 by using a newly developed DNS which uses the spectral method for the velocity and the combined compact finite difference method for the scalar. The k^(−1) spectrum in the viscous-convective range is confirmed and the Batchelor constant is found to be CB = 5.57, and the scalar spectrum is found to exponentially decrease in the far diffusive range. Theoretically, the intermittency of the straining motion of fluid is taken into account as follows. (1) The scalar spectrum in Batchelor's or the spectral theory is regarded as the one conditioned on the negative eigenvalue of the rate of strain tensor for the former or the energy dissipation rate for the latter, respectively, then (2) to take the average over the distribution of those fluctuations. With analytical model of PDFs of gamma or epsilon based on the DNS data, we calculated the asymptotic form of the scalar spectrum in the far diffusive range and found that they are consistent with the DNS results.

The work is supported by JSPS No.15H02218, NIFS-PS (NIFS16KNSS076).

Simulation of a Richtmyer-Meshkov turbulent mixing zone using a probability density function model

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Turbulent mixing zones (TMZ) driven by the Richtmyer-Meshkov instability (RMI) play a significant role in a wide range of contexts. Direct and Large-Eddy simulations of RMI turbulent flows remain expensive and statistical models, such as Reynolds-Stress and k-epsilon models, are preferred for engineering applications. One weakness of these models lies in the way they deal with the turbulent transport of kinetic energy. This limitation can be avoided by using instead a different class of models, based on Probability Density Functions (PDF) and for which turbulent advection is treated exactly. However, these models have never been applied to RMI driven flows. Thus, the purpose of this work is to apply a PDF model to a RMI driven TMZ and assess its performances. To this end, we consider the simplified Langevin PDF model (SLM) and solve it on a RMI configuration with a Monte Carlo code. The results highlight the role played by the closure coefficient C1 of the SLM. When varied on its admissible range, C1 leads to a transition in the shape of the PDF: from a diffusive-like shape obtained from an asymptotic expansion when C1 is high to a shape dominated by higher order Hermite coefficients when C1 is close to 1. The role played by pressure transport is also evaluated by introducing an additional closure accounting for this effect. The Monte Carlo simulations are then compared against Large-Eddy simulations (LES). The role played by the large scale initial conditions of the LES is discussed. In particular, we show that some coefficients of the SLM are required to depend on the initial infra-red exponent of the LES in order to reproduce the correct self-similar evolution of the TMZ statistics.

Passive scalar transport by a non-Gaussian turbulent flow (Batchelor regime)

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The problem of passive scalar advection by a turbulent flow has been widely discussed for several decades. Most of analytic results have been obtained in the frame of Kraichnan model: velocity statistics assumed to be Gaussian and delta-correlated. The model appeared to be very productive and revealed many interesting properties. However, in real turbulent flows velocity statistics differs significantly from that in Kraichnan model. To study the intermittent (non-Gaussian) case, one uses the Batchelor limit: velocity field is assumed to be smooth. This regime corresponds to the scales below the viscous length, and implies that the diffusivity of the advected quantity is small as compared to the fluid viscosity. Important qualitative results in this field were obtained by Balkovsky and Fouxon. In the presented work we calculate exact expressions for statistical moments of a passive scalar in the Batchelor regime, for arbitrary velocity statistics. The important new step as compared with previous results on the subject is that we derive all the statistical properties from velocity statistics, using the results of our previous papers [1]. In particular, it appears that the increment of the second eigenvalue of the inertia tensor is determined entirely by the non-Gaussian part of the probability density, and one cannot take it nonzero while assuming the Gaussian approximation. Generally, the non-Gaussianity cannot be neglected in calculation any of the exponents of passive scalar moments, though qualitative behavior of the exponents remains the same as that for the Gaussian distribution. For example, saturation takes place for orders more than some critical value. Moreover, this critical value appears to be universal. But for exponents of lower-order moments the function may differ significantly from the parabola corresponding to the Gaussian.

[1] A.S. Il'yn, V.A. Sirota, K.P. Zybin J. Stat. Phys. 163(4), 765 (2016); J. Stat.Phys 166, 24 (2017)

Scaling of velocity structure function within boundary layers in turbulent convection

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We present the scaling of the second order longitudinal structure function in Rayleigh-Benard convection inside the boundary layers, calculated from the velocity fields obtained using stereoscopic particle image velocimetry, for Rayleigh number, Ra=3.97x10^7 and Prandtl number, Pr=5.27. Second order centered longitudinal structure function S2(r) are estimated from spatial and ensemble averaged velocity fields over 10^3 realizations. The S2(r) is found to scale as r^(6/5), starting from a separation distance of 6mm, which is supposed to be the Bolgiano Length (LB), above which the buoyancy effect is significant. Such a BO59 scaling is predicted by [1] and [2] by balancing of thermal forcing and nonlinear velocity advection in Boussinesq equation. Few experimental BO59 evidences reported so far are from point measurements in the bulk, while we present field measurements in the boundary layers. A downward bending of structure function curve at larger separations is found and expected to be due to the effect of intermittency. An extended self-similarity (ESS) analysis [3] give S5~S3^1.4 showing the presence of an extended scaling window. The property of ESS allows one to find well defined scaling exponents for intermittency.

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341, 1994; [4] K.R. Sreenivasan and R.A Antonia 1997 The phenomenology of small scale turbulence. Annu. Rev. Fluid Mech. 29:435-72; [5] Detlef Lohse and Ke- Qing Xia. 2010. Small scale properties of turbulent Rayleigh Benard convection. Annual Rev. Fluid Mech. 42:335-64

Non-Richardson scaling laws in turbulent particle pair diffusion

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Richardson's theory of turbulent particle pair diffusion in 1926 [1] is based upon the idea of locality and predicts that the turbulent pair diffusivity K scales like, s**(4/3), where, s(t) is the rms ensemble average of l(t) which is the distance between particles in a pair at time t. An ensemble of particle pairs is released at time t=0. But this locality scaling has never been proven, " … there has not been an experiment that has unequivocally confirmed R-O scaling over a broad-enough range of time and with sufficient accuracy", [2]. Furthermore, a reappraisal of the 1926 dataset reveals that unequivocal non-local scaling, with K(s) scaling with the power law s**(1.564). Recently, a new non-local theory based upon the principle that both local and non-local diffusional processes govern pair diffusion in homogeneous turbulence has been developed [3]. Using a novel mathematical approach based upon the Fourier decomposition of the pair relative velocity, the theory is developed in the context of generalized power law energy spectra over extended inertial subrange, E(k) = k**(-p) for p in the range (1,3). The theory predicts that the power law scaling for K is s**g, with g=g(p) intermediate between the purely local, g=(1+p)/2, and the purely non-local g=2, scaling. Numerical simulations using Kinematic Simulations [4,5] produce the power law scaling, K(s) = s**(1.545) to s**(1.57), in the range of intermittent turbulence spectra, E(k) = k**(-1.72) to k**(-1.74) in the inertial subrange. The result for k**(-1.74) is in remarkably close agreement with the Richardson’s 1926 dataset. The non-local theory provides a new picture for the turbulent particle pair diffusion process. The consequences of non-locality for the general theory of turbulence are the subject of active investigation by the author.

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Reynolds stress closure for the RANS-equation

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The assumption that the Reynolds stress is an objective operator similar to the Cauchy stress is not supported by direct numerical simulations of the Navier-Stokes equation. Continuum scale hydrodynamic fluctuations, unlike molecular scale fluctuations, are not objective vector fields. Consequently, in a rotating frame-of-reference, the Coriolis acceleration has a profound impact on the redistribution of turbulent kinetic energy among the three components of the fluctuating velocity. The normalized Reynolds (NR-) stress is a non-negative and non-objective operator with non-negative eigenvalues that depend on the Reynolds number as well as the Rossby number. Although Reynolds stress modeling has been a core issue of turbulence research for more than a century, realizability and frame dependence of the NR-stress has not been ubiquitously adopted by CFD analyst. Why? Previous (and ongoing) Reynolds stress modeling studies assume (either explicitly or implicitly) that at some space/time scale turbulent velocity fluctuations can be approximated as objective vector fields. Although this is an excellent approximation for molecular scale velocity fluctuations, it is a poor approximation for continuum scale hydrodynamic fluctuations. The recently developed algebraic URAPS mapping of the NR-stress into itself, which will be discussed in this presentation, depends explicitly on the local mean velocity gradient and the Coriolis operator. The URAPS closure is a significant paradigm shift from the classical "eddy" viscosity closure introduced by Boussinesq (and others) more than 100 years ago.

Specific interface area in a thin layer system of two immiscible liquids with vapour generation at the contact interface

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For multiphase well-stirred liquid systems, the mean contact interface area per unit volume, or the 'specific interface area', is an important characteristic of the state. It is especially significant for the systems where this interface is active chemically or in some other way. We provide the assessments for the process of gas generation at the direct contact interface [1,2]. The generated vapour volume in the system is assumed to be proportional to the heat influx to the interface. Therefore, our results are relevant both for the case of endothermic chemical reaction between two liquids with the gaseous form of one of the reaction products and for the case of interfacial boiling. At the direct contact interface, a vapour layer grows and produces bubbles which breakaway of the interface and rise. The presence of vapour bubbles changes the fluid buoyancy and performs a 'stirring' of the system. Additional kinetic energy is brought into the system by bubble popping at the liquid–atmosphere interface. Based on the energy flux balance in the system and transport laws for turbulent boundary layers, the specific interface area was evaluated as a function of parameters, which can control the system state: average overheat above the interfacial boiling point and heat inflow into the system. The results are restricted to the case of thin layers, where the potential gravitational energy of bubbles leaving the contact interface is small compared to their surface tension energy. The description of the transport processes in the system heavily relies on the theory of the turbulent boundary layer for the momentum and heat transfer.

[1] Goldobin DS, Pimenova AV 2107 Eur. Phys. J. ST 226, 1155-1168; [2] Pimenova AV, Gazdaliev IM, Goldobin DS 2017 IOP Conf. Series: Materials Science and Engineering 208, 012033. The work was supported by the Grant of the President of the Russian Federation (MK-1447.2017.5).

Dynamics of the vortex line density in anisotropic superfluid turbulence

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Describing superfluid turbulence at smaller scales (of the order of the inter-vortex distance) requires an acceptable equation of motion for the density of quantized vortex lines CL. The closure of such an equation for superfluid anisotropic flows requires additional inputs besides CL and the super and normal velocity fields. In this lecture I will describe a minimal closure using one additional anisotropy parameter I_l0. Using the example of counterflow superfluid turbulence we derive two coupled closure equations for the vortex line density and the anisotropy parameter I_l0 with an input of the normal and super velocity fields. The various closure assumptions and the predictions of the resulting theory will be compared with numerical simulations.

Transition from direct to inverse energy cascade in three-dimensional turbulence

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Three dimensional turbulent flows are different from two dimensional flows in a very fundamental manner; while energy transfers from large scales to small scales in 3D it switches the direction in 2D. However many flows in nature, like atmospheric and oceanic flows, could not be strictly categorized to either 3D or 2D. In this work [1] we show that the nonlinear dynamics of the Navier-Stokes equations could be controlled to observe a discontinuous transition in energy transfer in three-dimensional turbulence. Using a control parameter that could enhance or suppress some of the basic interactions among scales in turbulent flows, as it naturally occurs in flows under different boundary conditions or sustaining mechanism, we show that at critical point energy transfer changes the direction even though the dimensionality and symmetries of the system were not touched. Such a discontinuous transition in direction of energy transfer suggests turbulent flows as out-of-equilibrium systems very close to criticality.

[1] Discontinuous Transition from Direct to Inverse Cascade in Three-Dimensional Turbulence, G Sahoo, A Alexakis, and L Biferale, Physical Review Letters 118, 164501 (2017). We acknowledge support from AtMath collaboration at University of Helsinki and ERC grant No. 339032.

Influence of zero-modes on the inertial range anisotropy of Rayleigh-Taylor turbulence

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Most theoretical studies dedicated to the small scales of Rayleigh-Taylor (RT) turbulence have focused on determining the isotropic properties of the velocity and concentration spectra in the inertial range [1-3], leaving aside the question of anisotropy. Yet, as observed in numerical simulations [4], anisotropy has a strong imprint on inertial scales and requires a description of its own. Following [5], two main contributions to inertial range anisotropy can be identified. The first one arises from the balance between mean forces and non-linear transfer terms. It has already been studied in [6] for RT turbulence. The second one comes from the so-called zero-modes [5], which properties have yet to be specified in the RT context. Therefore, the purpose of this work is to study the properties of zero-modes in RT turbulence. To this end, we use the eddy-damped quasi-normal markovianized (EDQNM) model proposed in [7]. Then, using the procedure devised in [8], we perform a zero-mode analysis of this model. This analysis yields approximate -7/3 scalings for the velocity and concentration spectra. It also provides proportionality relationships between them. At small scales, zero-modes become predominant against the spectra derived in [6], except for the concentration flux spectrum. To verify these predictions, we perform EDQNM simulations at very high Reynolds numbers and carry out large-eddy simulations of RT flows.

[1] Chertkov. Phys. Rev. Lett., 91, 2003, [2] Abarzhi. Eur. Phys. Lett., 91, 2010, [3] Soulard. Phys. Rev. Lett., 109, 2012, [4] Cabot and Cook. Nat. Phys., 2, 2006, [5] Biferale and Procaccia. Phys. Rep., 414, 2005, [6] Soulard and Griffond. Phys. Fluids, 24, 2012,[7] Burlot, Grea, Godeferd, Cambon, and Griffond. J. Fluid Mech., 765, 2015, [8] L'vov, Procaccia, and Tiberkevich. Phys. Rev. E, 67, 2003.

Editors' comment: Ref. [2] does not presume an isotropy of RT mixing and finds that properties of anisotopric inhomogeneous statistically unsteady interfacial RT mixing departs subtstantially from those of canonical isotropic homogeneous statistically steady turbulence.

Ten years of the TMB program

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Turbulent mixing as a topic of intellectual and practical importance has been studied by many communities such as those devoted to laboratory-scale fluid flows, plasmas, combustion, material science, geophysics, astrophysics, etc., in all of which mixing plays a central role. These communities have traditionally worked somewhat disjointly for understandable reasons. Turbulent mixing takes many forms: it is both steady and unsteady; it is single phase and multiphase; it is subsonic, supersonic and hypersonic; it is a phenomenon at nanoscales to cosmic scales, etc. The program on Turbulent Mixing and Beyond (TMB) was conceived to bring together diverse communities devoted to turbulent mixing, for purposes of tackling not only the fundamental aspects of the problem but also to assist in application in technological contexts. TMB was started ten years ago at ICTP primarily under the leadership of Professor Snezhana Abarzhi, whose energy has sustained the effort over the years.This talk is devoted to an assessment of the program's performance in the last decade: its successes and accomplishments, its frustrations and shortcomings, etc. It will also aim to look ahead to future directions that the program might take, both scientifically and organizationally.

Turbulence and mixing in thermal convection

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Gravity is ubiquitous in the Universe, hence buoyancy plays a major role in turbulence processes including mixing in the interiors and atmospheres of planets and stars. In this paper we present the current status of the turbulence phenomenology of turbulent thermal convection. Using pseudospectral simulations of turbulent thermal convection at very high resolution (4096^3) and high Rayleigh number (1.1 × 10^11) with unit Prandtl number, we conclude that convective turbulence exhibits behaviour similar to hydrodynamic turbulence, that is, Kolmogorov's k^(−5/3) energy spectrum with nearly constant energy flux. The shell-to-shell energy transfer is forward and local, along with a nearly isotropic energy distribution in Fourier space. This result rules out Bolgiano-Obukhov spectrum for thermal convection [1]. We also compute the rms values of various terms of the momentum equation of turbulent convection. We show that the acceleration of a fluid parcel is provided primarily by the pressure gradient; the buoyancy and viscous term are quite close to each other. Thus, in convective turbulence, the effect of buoyancy is annulled by viscous force, leading to behaviour similar to hydrodynamic turbulence (Kolmogorov's theory). The aforementioned quantification of turbulence will help model the turbulence mixing in nature more accurately.

[1] M. K. Verma, A. Kumar, and A. Pandey, New J. Phys. 19, 025012 (2017). His work was supported by the research grants SERB/F/3279 from Science and Engineering Research Board, India. Simulations were performed on Cray XC40 Shaheen II at KAUST supercomputing laboratory through project k1052.

DNS of lid rotating Rayleigh Benard convection

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In the present numerical study, we perform DNS of 3D Navier Stokes equations for a fluid inside a cylinder with top cold rotating lid and hot stationary bottom wall. We investigate the physical mechanism of vortex breakdown bubble formation. This convective system with a vortex breakdown bubble is a canonical problem to investigate vortex breakdown under unstable thermal gradient as in swirl combustion systems, where the vortex breakdown bubble is used for the flame stabilization. They also play a role in maintaining a stable and compact flame for the combustion systems. The base flow is established by rotating the top wall and fluid moves along the axis, forming an axial core, from the bottom to top end wall. This axial core, under certain rotational Reynolds number (Re), breaks down to a bubble. This breakdown bubble is modified by thermal convection. We study the effect of heating, at Rayleigh number, Ra = 2e5 and Re= 2200 in which buoyant force and inertial force due to lid rotation competes with viscous forces. The equations are formulated in such a way that pure rotation and pure Raleigh-Benard convection are extreme cases of the same physical and numerical set-up. The present numerical results are validated with the available results for pure rotation case and rotating thermal convection case. We observe for the Ra and Re mentioned above, the size of bubble increases and axisymmetry is lost compared to pure lid rotation case. The bubble is also found to be rotating inside the domain. We also investigate the importance of Stewartson layers in the flow field. We observe that heat transfer, quantified by Nusselt number, scales with a power of 1/5 of Ra for Re = 2200 for 2e4 < Ra < 2e5. Other parameter range is currently being pursued and will be presented.

Modeling of turbulent flow through the ejector of a two-stage ejector refrigeration system

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An important advantage of ejector refrigeration cycles is the capability of utilizing comparatively low-temperature thermal resources, like solar energy, waste heat or any low-cost/subsidized energy source. They have lower initial costs and easier maintenance and installation compared to vacuum pumps, since they work without any moving part. They also operate without noise and have higher safeness coefficient. In this research, in addition to thermodynamic cycle analysis, we numerically studied the performance of a two-stage ejector refrigeration system and the effects of operation factors on the entrainment ratio of first and second stages of ejector, as well as the coefficient of performance (COP), are made. For this purpose, a two-dimensional model is selected for the ejector and the governing conservation equations together with the equation of state are solved numerically. We employed a realizable k-epsilon turbulence model with special considerations to non-equilibrium transport of turbulent quantities in transport equations, as well as the near-wall treatments. The results are verified with available experimental data for an ejector with R245fa working fluid and a good agreement was obtained. It was found that a cycle with working fluid of water has the COP of 1.808 at generator and evaporator temperatures of 120oC and 12oC, respectively. Increasing the generator temperature at fixed evaporator and condenser temperatures leads to increase in entrainment ratio of first and second stages. When the ejector operates in critical mode, change in pressure and temperature of the condenser has no influence on the entrainment ratio. Moreover, raising the evaporator temperature at constant generator and condenser temperatures causes the entrainment ratio to decrease. Higher evaporator temperature also reduces the heat of generator and work of the pump and consequently, enhances the COP as well.

WALL-BOUNDED and SHEAR FLOWS

Compressibility effects on initial evolution of mixing layers

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The shear layer growth rate in compressible mixing layers has been studied extensively for the last few decades. Reduced growth rates at higher values of convective Mach number were observed in experimental as well as numerical studies. Detailed investigations revealed that the reduction in growth rate is due to reduced levels of turbulent kinetic energy production, rather than due to increased dissipation arising from dilatation at higher Mach numbers. Most

of these studies have been done for the self-similar stages of mixing layer evolution. The transient evolution before attainment of self-similarity is affected by compressibility and is evident from the shear layer growth during this period. Early stages of evolution are dominated by unstable modes, characteristic of specific flow conditions. We perform numerical simulations of temporally evolving mixing layers, for values of convective Mach number ranging from nearly incompressible to compressible regime. The aim is to study the effects of compressibility on the evolution of shear layer during the initial phases. Three-dimensional computations of counterflowing equal density streams are performed in a cuboid domain with periodic boundary conditions in streamwise and spanwise directions, using a BGK-Boltzmann based gas-kinetic scheme, which is capable of simulating unsteady compressible flows. We study the flow structures and statistics to investigate how compressibility plays a role in the evolution during this period. The objective is to find if the evolution is similar to modal evolutions during the very early stages or to the self-similar evolution.

Transition to turbulence in reciprocating channel flow

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Direct numerical simulation of a reciprocating channel flow is used to study transition to turbulence in periodic flows. The simulations are performed at two Stokes Reynolds numbers: Re_s = 648 and 1019, representing self-sustaining transition and intermittently turbulent flow regimes, respectively. For Re_s=1019, the balance of the leading order terms in the phase-averaged mean momentum equation shows that fully-developed turbulence first emerges at the early phases in the decelerating portion of the cycle. By investigating the mean flow properties prior to and during the onset of turbulence, it is found that the underlying mechanism of transition to turbulence is the emergence of an internal layer that first develops during the phases just prior to the onset of turbulence. In the absence of this internal layer (i.e., at Re_s=648), the flow remains transitional over the entire cycle. An analysis of instantaneous spanwise vorticity contours suggests that the internal layer is likely formed from the concatenation of strong opposite sign (relative to the mean) vorticity concentrated in the near-wall region. This concentrated region of near-wall opposite sign vorticity leads to the rapid production of Reynolds stress and Reynolds stress divergence that underlie transition to turbulence. The flow moves towards relaminarization during the late phases in the decelerating portion of the cycle when the concentrated region of opposite sign vorticity moves toward the center of the channel and the near-wall production of Reynolds stress is diminished.

Turbulent flow in the bulk of thermal convection: comparison of smooth and different roughness boundaries

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The flow structure and time-evolution of the large scale circulation (LSC) is investigated numerically for a fluid of Prandtl number Pr=0.7 confined within a cubic cavity. We use highly resolved large eddy simulations (LES), which allow for relatively long time records, for Rayleigh numbers 10e7 - 10e9. Consistent with experimental observations in water due to Bai et. al. [1] we observe nonperiodic reorientations of the LSC between the two diagonal vertical planes, through a transient process that involves a horizontal rotation of the flow rather than a cessation and re-initiation. The average switching rate for the LSC is in excellent agreement with the experimental results of BJB16. Finally, we present preliminary results corresponding to the addition of 2D and 3D-roughness elements.

[1] Bai et al. 2016 Phys. Rev. E 93, 023117

Large-eddy simulations of turbulent flow past the Aerospatiale A-airfoil at high Reynolds number

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The flow around the Aerospatiale A-Airfoil at maximum lift (angle of attack = 13.3 degree) and Re = 2.1 million is investigated by wall-modeled large-eddy simulations (WMLES). The subgride-scale (SGS) stress tensor is modeled by the stretched-spiral vortex model originally developed by Misra & Pullin (1997) [1]. The virtual wall model, originally developed by Chung & Pullin (2009) [2] in the Cartesian coordinates, was extended to the curvilinear coordinates and implemented in the body-fitted structured mesh environment. The wall model dynamically couples the resolved LES region with the near-wall region, without assuming the local state of the boundary layer or requiring any tunable model coefficients [3]. The fractional step method [4] is used to solve the filtered Navier-Stokes equations, and all the spatial derivatives are approximated with the energy conservative fourth-order finite difference scheme. The present wall model is validated with the experiment data [5], and good comparisons (pressure coefficient, skin friction coefficient, mean velocity profile and Reynolds stress) have been found in both the attached and separation zones. The results indicate that the suction side boundary layer is characterized by a laminar separation bubble near the leading edge, following with turbulent separation and reattachment at the trailing edge.

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Mean equation based scaling analysis of fully-developed turbulent channel flow with uniform heat generation

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Multi-scale analysis of the mean equation for passive scalar transport is used to investigate the asymptotic scaling structure of fully developed turbulent channel flow subjected to uniform heat generation. Unlike previous studies of channel flow heat transport with fixed surface temperature or constant inward surface flux, the present flow has a constant outward wall flux that accommodates for the volumetrically uniform heat generation. This configuration has distinct analytical advantages relative to precisely elucidating the underlying self-similar structure admitted by the mean transport equation. The present analyses are advanced using direct numerical simulations [1] that cover friction Reynolds numbers up to 4100 and Prandtl numbers ranging from 0.2 to 1.0. The leading balances of terms in the mean equation are determined empirically and then analytically described. Consistent with its asymptotic universality, the logarithmic mean temperature profile is shown analytically to arise as a similarity solution to the mean scalar equation, with this solution emerging on an interior domain where molecular diffusion effects are negligible as the Reynolds number becomes large. In addition to clarifying the Reynolds and Prandtl number influences on the von Karman constant for temperature, the present theory also provides a couple of self-consistent ways to estimate this fundamental quantity. As with previous empirical observations, the present analytical predictions for the thermal Karman constant indicate values that are larger than found for the mean velocity Karman constant. The potential origin of this observation is briefly discussed.

[1] Pirozzoli S, Bernardini M, Orlandi P 2016 J. Fluid Mech. 788, 614.

Lagrangian coherent structures resulting from three-dimensional axial vortex breakdown

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Axial vortices are ubiquitous in engineering and nature. Flow past delta wings, flow inside a rotating pipe, flow inside a swirl combustion chamber, bio-reactors and geophysical flows like tornadoes are some examples. Axial vortices are known to undergo 'vortex breakdown', where an instability triggered by the appearance of a stagnation point in the core leads to a complicated topology of the flow. Axial vortices are canonically simulated using a closed cylinder with one (top) rotating lid. When the top end is rotated, the fluid is driven radially outward under the action of the centrifugal force, and then descends down from the side wall. Upon reaching the cylinder bottom, the fluid is turned up at the non-rotating wall and circulatory flow is set up with a dominating axial core. The flow regime is determined by two non-dimensional parameters: (i) aspect ratio, H/R, where H & R are the height and radius of the cylinder and (ii) Reynolds number, Re based on lid rotation speed and R. This configuration is known to exhibit bubble type breakdown at the axis when Re is increased beyond a specific critical value. Here, we adopt the framework of Lagrangian Coherent Structures (LCS) to visualize and understand the advective material transport during and after axial vortex breakdown. Hyperbolic and Elliptic LCSs, which objectively identify regions of intense material stretching/folding and Lagrangian vortices, will be extracted using recently developed variational methods. A specific focus of our study would be to understand mass transport in and around the vortex-breakdown bubble in the steady, time-periodic and aperiodic regimes of the flow. Spatially and temporally well-resolved velocity fields during the different flow regimes will be generated using direct numerical simulations at values of Re in the range [0, 5000].

Turbulent flows in ducts of arbitrary shape

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In wall turbulent flows it is not fully understood whether the outer and the near-wall region are coupled. This is important in applications related to heat and mass transfer. In real life the walls are corrugated. Have been, therefore, analyzed the changes of the outer flow in ducts with different shape of the surfaces. The Navier-Stokes equations in cylindrical coordinates discretized by a second-order finite difference scheme, together with the immersed boundary technique allow one to simulate the flows. The basic geometry is a circular pipe of radius R, with perturbations eta sin (k theta). Simulations by varying k at fixed eta were performed to investigate the effect of the wave-number, by fixing k and varying eta allow to investigate the influence of the amplitude of the wall corrugation. The modifications of the near-wall structures are well depicted through contour plots of the radial component of the vorticity. The geometrical disturbances enforce the structure variations at the locations with curvature changes their shape is strongly linked to the amplitude of the disturbance. Our interest is also to understand the influence of the shape of the surface on wall friction. We were expecting changes in the profile of the total stress with respect to that of the circular pipe, which instead were not found. This is a first indication that changes in the near-wall region do not affect the outer region, and that Townsend's similarity hypothesis holds. The perimeter of the surface changes, the cross-sectional area together with the flow rate are constant, therefore the two latter parameters fix the resistance of a duct. A quantity, in wall-bounded flows accounting for the formation of the structure is the shear parameter S*. Also for S* the greater changes occur by varying eta, the wavenumber of the corrugations does not affect S*.

On coherent structures in a turbulent mixing layer created downstream of a “Lambda” notch

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Measurements were carried out in a three-dimensional turbulent mixing layer created downstream of a “Lambda” shaped splitter plate representing a single element of a chevron nozzle. This type of a trailing edge creates a pair of counter-rotating streamwise vortices that force the center of the mixing layer to penetrate into the high-speed stream by inducing velocities in the cross flow plane that bend the mixing layer. Oscillating small fliperons located along the trailing edges of the Lambda enables one to study the behavior and the interaction among the phase locked coherent structures. An oblique wave generated by forcing from a single leg of the Lambda, is initially parallel to the oscillatory trailing edge that creates it, but as it propagates to the other side of the notch it turns and becomes normal to the free-stream. Vorticity contours indicated that these coherent structures amplify in the direction of streaming near the plane of symmetry. Forcing from both trailing edges of the splitter plate at the same amplitude and phase enhanced the amplification rate of these structures near the plane of symmetry while forcing 180 degrees out of phase inhibited the growth of these structures in that region. Considerable interaction exists near the plane of symmetry between the coherent structures emanating from the two legs of the Lambda, which are recognized by the large distortions of the phase-locked velocity profiles that are also responsible for the generation of small scale turbulence. It is interesting to note that the amplification of the large coherent structures enhances the streamwise rate of growth of the mixing layer but the latter never saturates as it does in two-dimensions because of the three-dimensional incoherent fluctuating velocities that are much stronger in this flow.

Entrainment and scalar mixing process near turbulent/non-turbulent interface in compressible boundary layers

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Direct numerical simulations (DNSs) of temporally developing compressible boundary layer with a passive scalar transport are performed in order to investigate the turbulent mixing near turbulent/non-turbulent interface (TNTI) in the compressible boundary layers. The DNSs are initialized with the flow induced by a wall-mounted trip-wire, in which a fluid is set at rest and the wall moves at a constant speed. The source of the passive scalar is placed on the wall. These DNSs codes are validated by comparing with experimental data and previous DNS data. Based on the present DNSs data, the outer edge of the TNTI layer, called irrotational boundary, is detected as an isosurface of small vorticity magnitude. The TNTI layer is found to have a thickness of about 20 times Kolmogorov scale. The movement of fluid elements relative to the irrotational boundary movement is analyzed for investigating the entrainment. Both entrainment and de-entrainment are observed in the compressible turbulent boundary layers. The scalar transport in relation to the TNTI movement is also analyzed for elucidating the scalar mixing process near the TNTI.

NON-EQUILIBRIUM PROCESSES

Hydrodynamic instabilities

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Hydrodynamic instabilities developing at a material interface and the interfacial mixing they induce govern variety of phenomena in fluids, plasmas and materials. Realistic environments are often characterized by dramatic changes of material properties at the interface and by extensive interfacial transports, whereas existing studies focus primarily on nearly uniform conditions and on smooth diffusive mechanisms. In this work, while looking from a far field at a discontinuous front separating fluids with highly contrasting densities, we find the critical effect on the front stability of energy fluctuations that are produced by the perturbed front. The front is stable or unstable depending upon whether the flux of the energy fluctuations is small or large compared to the flux of kinetic energy across the planar front. Landau's solution for the Landau–Darrieus instability is consistent with one of the cases. In the other case, in the presence of gravity a new kind of hydrodynamic instability develops and leads to coherent vortex-less nonlinear dynamics at late times. Molecular clouds in the Universe, ablation front in inertial confinement fusion, and super-critical fluids in laboratory environment are exemplary cases of this unstable interfacial transport.

Highly symmetric interfacial coherent structures in Rayleigh Taylor instability with time-dependent acceleration

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Rayleigh Taylor (RT) instability in a power-law time dependent acceleration field is investigated theoretically for a flow with the symmetry group p6mm (hexagon) in the plane normal to acceleration. In the nonlinear regime, regular asymptotic solutions form a one-parameter family [1-4]. The physically significant solution is identified with the one having the fastest growth and being stable (bubble tip velocity). Two distinct regimes are identified depending on the acceleration exponent. Particularly, the Richtmyer–Meshkov (RM)-type regime, where the dynamics is identical to conventional RM instability and is dominated by initial conditions, and the RT-type regime where the dynamics is dominated by the acceleration term. For the latter, the time dependence has profound effects on the dynamics. In the RT non-linear regime, the time dependence has no consequence on the morphology of the bubbles; the growth rate (bubble tip velocity) evolves as power law with the exponent set by the acceleration. The solutions form a one-parameter family, and are convergent with exponential decay of Fourier amplitudes. The solutions are stable at maximum tip velocity, whereas flat bubbles are unstable, and the growth/decay of perturbations is no longer purely exponential and depends on the acceleration exponent.

[1] A.K. Bhowmick, S.I. Abarzhi 2016 Richtmyer-Meshkov unstable dynamics influenced by pressure fluctuations. Physics of Plasmas 23, 111610; [2] S.I. Abarzhi 2008 Review of nonlinear coherent

dynamics of the unstable fluid interface: conservation laws and group theory. Physica Scripta T132, 014012; [3] S.I. Abarzhi, K. Nishihara, R. Rosner 2006 A multi-scale character of the large-scale coherent dynamics in the Rayleigh-Taylor instability. Phys. Rev. E 73, 036310; [4] S.I. Abarzhi 1998 Stable steady flows in Rayleigh-Taylor instability. Phys. Rev. Lett. 81, 337-340.

Dimensional crossover in Richtmyer-Meshkov unstable flows in the presence of pressure fluctuations

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We analyze Richtmyer-Meshkov (RM) unstable interfacial dynamics in the presence of pressure fluctuations. The pressure fluctuations are scale invariant and are modeled by an effective time dependent acceleration field with power law exponent -2. The group theory based analysis is applied to 3D rectangular p2mm, 3D square p4mm and 2D pm1 RM flows [1-3]. From the symmetry analysis, we find that 3D square and 2D bubbles form a one parameter family and 3D rectangular bubbles form a two parameter family. The families are parametrized by the principal curvature(s). The bubble velocity and Fourier amplitude profiles exhibit RM type behavior for weak accelerations and RT type behavior for strong accelerations. Under the dimensional crossover, the bubbles elongated in one of the directions reduce to the 2D solutions, whereas the bubbles elongated in the other direction flatten. Stability analysis shows that 3D square bubbles are stable with respect to isotropic as well as anisotropic perturbations. 2D bubbles are unstable to 3D perturbations. No continuous transition is possible between 3D square and 2D bubbles and the dimensional crossover is discontinuous for both strong and weak pressure fluctuations.

[1] A.K. Bhowmick, S.I. Abarzhi 2016 Richtmyer-Meshkov unstable dynamics influenced by pressure fluctuations. Physics of Plasmas 23, 111610; [2] S.I. Abarzhi 2008 Review of nonlinear coherent dynamics of the unstable fluid interface: conservation laws and group theory. Physica Scripta T132, 014012, pp. 1-18; [3] 3S.I. Abarzhi, K. Nishihara, R. Rosner 2006 A multi-scale character of the large-scale coherent dynamics in the Rayleigh-Taylor instability. Phys. Rev. E 73, 036310.

Dimensional crossover in Richtmyer-Meshkov flows

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We analyze nonlinear dynamics of large scale coherent structures in Richtmyer-Meshkov (RM) flows. Group theory based analysis is applied with a detailed consideration of RM dynamics invariant with respect to p2mm (3D rectangular), p4mm (3D square) and pm1 (2D) groups [1-3]. Symmetry dictates that asymptotic solutions form a 2 parameter family for rectangular flows and a 1 parameter family for 3D square and 2D flows. For 3D square and 2D symmetry, asymptotic solutions are obtained for the 1st and 2nd order of approximation and the fastest growth rate occurs at zero bubble curvatures. Fourier amplitudes exponentially decay with increase in order showing that solutions are convergent. Both 2D and 3D square solutions are stable with respect to symmetry conserving perturbations. Isotropic 3D square solutions are universally stable, while 2D solutions are unstable to anisotropic perturbations. Furthermore, the 3D and 2D solutions cannot be continuously transformed from one to another, and the dimensional crossover is discontinuous.

[1] A.K. Bhowmick, S.I. Abarzhi 2016 Richtmyer-Meshkov unstable dynamics influenced by pressure fluctuations. Physics of Plasmas 23, 111610; [2] S.I. Abarzhi 2008 Review of nonlinear coherent dynamics of the unstable fluid interface: conservation laws and group theory. Physica Scripta T132, 014012; [3] S.I. Abarzhi, K. Nishihara, R. Rosner 2006 A multi-scale character of the large-scale coherent dynamics in the Rayleigh-Taylor instability. Phys. Rev. E 73, 036310.

Local and non-local energy spectra of superfluid He3 turbulence

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Below the phase transition temperature Tc=1 mK, He3-B has a mixture of normal and superfluid components. Turbulence in this material is carried predominantly by the superfluid component. We explore the statistical properties of this quantum turbulence, stressing the differences from the better known classical counterpart. To this aim we study the time-honored Hall-Vinen-Bekarevich-Khalatnikov coarse-grained equations of superfluid turbulence. We combine pseudo-spectral direct numerical simulations with analytic considerations based on an integral closure for the energy flux. We avoid the assumption of locality of the energy transfer which was used previously in both analytic and numerical studies of the superfluid He3-B turbulence. For T<0.37 Tc, with relatively weak mutual friction, we confirm the previously found ‘subcritical’ energy spectrum E(k), (given by a superposition of two power laws that can be approximated as E(k) proportional to k^{-x} with an apparent scaling exponent 5/3 <x(k)< 3). For T>0.37 Tc and with strong mutual friction, we observed numerically and confirmed analytically the scale-invariant spectrum E(k) proportional to k^(-x) with a (k-independent) exponent x > 3 that gradually increases with the temperature and reaches a value x=9 for T=0.72 Tc. In the near-critical regimes we discover a strong enhancement of intermittency which exceeds by an order of magnitude the corresponding level in classical hydrodynamic turbulence.

Slow, fast and ultra-fast components of ordered structures in fluid flows

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For structures analysis the fundamental set including the equations of state (thermodynamic potentials, relations between thermodynamic quantities, which are density, pressure, temperature, concentration) and analogues of conservation laws, which are the differential equations for transport of mass (continuity), momentum, energy (temperature) and concentration was used. The compatibility condition, which determines rank of a nonlinear system of equations, order of its linearized form, and degree of the corresponding characteristic (dispersion) equation, is applied. The high rank of the governing equations set describes a large number of coexisting large and small components, which leads to non-stationary effects [1]. Intrinsic temporal and spatial scales of observable structural elements are defined. Descriptions of dissipative media flows are carried out using the singular perturbations theory revealing both the large long-lived and fine dissipative components of structures. On the large scales, typical times are determined by the mechanical and diffusion parameters. On small scales, the exchange rate is governed by fast molecular interactions, transforming the available potential energy, which can be either chemical or surface nature, into thermal and mechanical energy of motion. Evolution of diffusion-induced flows; generation, propagation, reflection and nonlinear interaction of internal wave beams[2]; flows around obstacles in transient vortex regimes; free multicomponent convection over heat sources with various dimensions are studied theoretically, numerically and experimentally. Processes of homogeneous suspension structuring at transient eigen-oscillation modes in a vessel, in compound vortices, around a drop falling into a fluid are investigated [3,4]. In all the cases, compact volumes of soluble admixtures are splitting into fibers.

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Understanding turbulence from a kinetic theory perspective

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Understanding statistically averaged large scale dynamics of turbulence is important from both the fundamental and practical points of view. The direct practical consequence is that such understanding would help formulate closed form models for computation of high Reynolds number flows. For a very long time, the framework has been based on modeling turbulent fluctuations as an effective ‘eddy’-viscous process, borrowing a notion from the molecular dynamics. From the kinetic theory, however, a viscous process is only pertaining to hydrodynamic fluctuations that are very close to equilibrium, which is a consequence of scale separation between the mean and fluctuations. However, dynamic scales in a turbulent flow are anything but possessing such a scale separation. This motivates interest for a more thorough kinetic theoretic based representation including investigation of a deeper non-equilibrium regime. There are various analogies that may be made between this proposed kinetic theory representation of turbulence and the conventional kinetic theory for molecular dynamics. To that end, we use effective kinetic equations describing large-scale properties of turbulent flow by introducing a turbulent relaxation time that defines how the large-scale shear relaxes asymptotically towards the equilibrium of statistically homogeneous and isotropic hydrodynamic fluctuations. In this talk, we discuss how such a kinetic theory - based description for turbulent flows can be constructed.

Similarity of anisotropic, variable viscosity flows

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The focus here is on variable-viscosity flows and mixing in density-matched fluids. The issue is whether or not these flows may be self-similar, or self-preserving. The importance of the question stands on the predictability of these flows; self-similar dynamical systems are much easier tractable from an analytical viewpoint. Self-similarity analysis, as first introduced by Townsend, is applied to the relevant transport equations of the velocity field (mean momentum, one-point energy budget equation as well as scale-by-scale energy transport equations- the latter represent the transport of energy at each scale and each point of the flow). Extensions of these equations for the transport of the scalar field are discussed, with particular focus on their mathematical analogy. It is stressed that neither local isotropy nor high Reynolds numbers are necessary conditions for the similarity to be valid. Scale-by-scale energy budget equations are developed for flows in which the viscosity varies as a result of heterogeneous mixture or temperature variations. Additional terms are highlighted, accounting for the viscosity gradients, or fluctuations. These terms are present at both small and large scales, thus rectifying the common belief that viscosity is a small-scale quantity. It is further shown that the condition of self-preservation is not necessarily satisfied in variable-viscosity jets. As far as round jet is concerned, the jet momentum conservation, as well as the constancy of the Reynolds number along the axis of the jet, cannot be satisfied simultaneously. This is pointing to the necessity of considering less stringent conditions (with respect to classical, single-fluid jets) when analytically tackling these flows and reinforces the idea that viscosity variations must be accounted for when modelling these flows.

Intermittent many-body dynamics at equilibrium

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The equilibrium value of an observable defines a manifold in the phase space of an ergodic and equipartitioned many-body system. A typical trajectory pierces that manifold infinitely often as time goes to infinity. We use these piercings to measure both the relaxation time of the lowest frequency eigenmode of the Fermi-Pasta-Ulam chain (FPU), as well as the fluctuations of the subsequent dynamics in equilibrium. The dynamics in equilibrium is characterized by a power-law distribution of excursion times far off equilibrium, with diverging variance. Long excursions arise from sticky dynamics close to q-breathers localized in normal mode space. Measuring the exponent allows to predict the transition into nonergodic dynamics. We generalize our method to Klein-Gordon lattices (KG) where the sticky dynamics is due to discrete breathers localized in real space.

Particle clustering and turbophoresis in elastic turbulent flow

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Understanding how passively transported particles, like solid impurities, distribute in turbulent flows is a subject of interest both at a fundamental level and for applications as, e.g., environmental or industrial ones. The phenomenon of preferential particle concentration in high-Re number flows of Newtonian [1], as well as non-Newtonian [2], fluids was addressed by previous investigations, which have put in evidence both large and small-scale effects. In this study, we examine inertial particle transport in a turbulent flow of a viscoelastic fluid in the absence of inertia and at high Weissenberg numbers. Flows in such an elastic turbulence regime [3] are promising for enhancing mixing efficiency in microfluidic applications. By means of extensive numerical simulations, we explore the aggregation properties of point-like material particles, heavier than the carrier fluid. We choose the periodic Kolmogorov shear flow of a two-dimensional dilute polymer solution [4] described by Oldroyd-B model, for elasticities well beyond those corresponding to the onset of purely elastic instabilities. We focus on the connection between the underlying flow structure and the inhomogeneity of particle concentration, as a function of the inertia of the latter. The results indicate that the particle distribution is closely related to the mean turbulent-like fluctuations of the flow. We find that particles accumulate in small-scale fractal clusters and at the same time undergo turbophoretic segregation at larger scales [5, 6]. The analysis reveals that small-scale clustering and large-scale concentration modulations are controlled by a common time scale, related to the typical mixing time of the flow. The similarities and differences with respect to the phenomenology observed in an analog Newtonian turbulent flow [6] are also discussed. A quantitative explanation of the nonhomogeneity due to turbophoresis is provided in the asymptotic regimes of small and large particle inertia.

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Phase field model for immiscible two phase flow in microfluidic junctions

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A numerical model for analyzing two phase liquid-liquid flow in different microfluidic junctions shapes is presented in this paper. The numerical model was built reposing on Navier Stokes equations describing an incompressible laminar flow added to Cahn Hilliard equation for interface tracking via phase field method. Thus, the laminar two phase flow-phase field module of the finite element method based software, COMSOL Multiphysics was used. The obtained model has proven its efficiency to describe the different regimes that may occur due to singularities encountered by the flow. Various flow regimes were observed viz. slug, bubbly and stratified flow. The parameters governing the flow patterns and the transition between different flow regimes are followed up. It was found that the appearance of slugs or bubbles, their number and dimensions are highly dependent on the inlet velocities gradient of both fluids as well as the surface tension effect between the liquid phases. The obtained numerical results are compared to relate other computational as well as experimental findings reported in literature which allows giving a deep insight on the two phases dynamics in various microfluidics topologies.

Influence of time-delayed reaction on stability and transition to self-oscillating mode of multiphase flow in porous medium

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The simulation of self-oscillating multiphase reacting flows in porous media is a very complicated problem due to multiscale physics including diffusion, convective mixing at different scales, capillary phenomena. In the framework of Darcy level models the volume averaged reaction rate is often considered to be a function of volume averaged molar densities of the chemically active components. In the general case of diffusion-limited reaction, the reaction rate is a functional, which depends on the history of the flow, in particular, the history of average concentrations. In the present work we consider the non-local in time (time delayed) kinetics of the reaction. The time delay is supposed to be small in comparison with the characteristic time scale. The self-oscillating mode of reaction front propagation in multiphase flow in the porous medium with chemically active skeleton is studied numerically. The flow represents a two-phase displacement, such that the displacing fluid and the skeleton of the porous medium have chemically active components which react with production of gaseous phase. The calculations have shown strong influence of the reaction kinetics on stability of the flow. The presence of the time delay is shown to stimulate the transition of the reaction front propagation to the oscillatory mode. Possible physical mechanisms of time-delayed reaction kinetics are discussed.

Anomalous diffusion in laminar flows

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Dispersion of particles in chaotic, turbulent or random flows has been studied for a long time. It is known that the action of advection on large spatial and temporal scales typically can be described as an (anisotropic) normal diffusion process. In random but strongly correlated velocity fields, an anomalous diffusion is possible. Anomalous diffusion is possible also in spatially regular velocity fields in the presence of Lagrangian chaos. It is less known that an anomalous transport can take place in steady two-dimensional flows in the absence of any kind of chaos. In the present talk, we discuss two examples of such behavior. The first example is the deterministic advection in spatially periodic steady two-dimensional velocity fields, which include stagnation points or solid obstacles, so that the passage time is infinite along some streamlines. The large-time asymptotics of the dispersion law is analyzed using the special flow construction (a flow built over the mapping). Depending on the type of the passage time singularity, the asymptotic dispersion law can correspond to either subdiffusion or superdiffusion. The analytical predictions match the results of numerical simulations. The second example is the diffusion- advection problem in spatially periodic, steady two-dimensional flows that contain closed cells, possibly separated by jets. The anomalous dispersion is predicted and found numerically on an intermediate time interval. On the large time case, anormal diffusion (enhanced by the flow) takes place. The dispersion displays peculiar aging properties.

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Quantized vortex lines in superfluid turbulence: how to take them into account?

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On large scales superfluid turbulence is well described by the two-fluid model of Landau and Tisza. On smaller scales the existence of quantized vortex lines is essential, and the question of how to take this into account in writing coarse-grained equations of motion is a long standing, highly debated and thorny issue. I will review the issue and explain the difficulties associated with choosing the right order parameters and the right terms in the equations of motion. The lecture will draw on experimental and simulational data and will require no prior knowledge of quantum fluid dynamics.

Convective thermal fluxes in unsteady non-homogenous flows

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We investigate the transition from homogeneous linearly stratified fluid to a cellular or layered structure in and enclosure by means of Thermoelectric generated heating and cooling device [1,2]. Patterns arise by setting up a convective flow generated by a buoyant heat flux either in the base or in a side wall of the convective enclosure [3,5]. The experiments and simulations investigate mixing using brine or sugar solutions and fresh water in order to form a density interface and low Prandtl number mixing with forced thermoelectric temperature gradients. The evolution of the sidewise convective mixing and the topological characteristics of the merging of lateral intrusions in different configurations are presented, allowing PIV and interface tracking, that is used to perform detailed comparison of mixing within different parameter spaces. The relation between structure functions, fractal analysis and spectral analysis [6] is here very useful to determine the evolution of scales. Experimental and numerical results on the mixing or non-mixing (wavy) fronts occurring at the density interface due to body forces [7-9] can be compared with the convective fronts. The numerical simulations are performed using two approaches: Finite-volume method in Open Foam versus Direct Numerical Simulation based on spectral elimination. We map the different transitions between 2D and 3D topology driven convections in an enclosure with several heat-cold driven flows. The size of the water tank is of 0.2 x 0.2 x 0.1 m and the heat sources can be regulated both in power and sign [2-4]. The thermal convective driven flows are generated by Seebeck and Peltier effects in 2 wall extended positions of 0.05 x 0.05 cm each. The parameter range of the convective cell array varies strongly along the boundary conditions. Side heat fluxes are considered and estimated as a function of Rayleigh, Peclet and Nusselt numbers, [9-10].

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INTERFACIAL DYNAMICS

One dimensional turbulent diffusion model for hydrodynamic instability mixing zone growth

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Under hydrodynamic instability a mixing zone at the interface of two fluids grows with time. We show that a simple one dimensional diffusion model with turbulent diffusion coefficient can reproduce the known growth rate of the mixing zone for Rayleigh-Taylor instability, Richtmyer-Meshkov instability and Kelvin-Helmholtz instability. The turbulent diffusion coefficient is expressed by the product of a dominant eddy size by its turbulent velocity. This size is derived using the mixing length assumption in which the dominant eddy size is a constant fraction of the mixing zone width. The turbulent velocity is formulated using physical arguments fitted for each of the instabilities.

Effect of pressure fluctuations on Richtmyer-Meshkov coherent structures

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We investigate the formation and evolution of Richtmyer Meshkov bubbles after the passage of a shock wave across a two fluid interface in the presence of pressure fluctuations. The fluids are ideal and incompressible and the pressure fluctuations are scale invariant in space and time, and are modeled by a power law time dependent acceleration field with exponent -2. Solutions indicate sensitivity to pressure fluctuations. In the linear regime, the growth of curvature and bubble velocity is linear. The growth rate is dominated by the initial velocity for weak pressure fluctuations, and by the acceleration term for strong pressure fluctuations. In the non-linear regime, the bubble curvature is constant and the solutions form a one parameter family (parametrized by the bubble curvature). The solutions are shown to be convergent and asymptotically stable. The physical solution (stable fastest growing) is a flat bubble for small pressure fluctuations and a curved bubble for large pressure fluctuations. The velocity field (in the frame of references accounting for the background motion) involves intense motion of the fluids in a vicinity of the interface, effectively no motion of the fluids away from the interfaces, and formation of vortical structures at the interface [1,2].

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Evolution of the linear Richtmyer-Meshkov instability when a shock/rarefaction is reflected

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When a planar shock hits a corrugated contact surface between two fluids, hydrodynamic perturbations are generated in both fluids that result in asymptotic normal and tangential velocity perturbations in the linear stage, the so called Richtmyer-Meshkov instability (RMI). It is important in the initial stages of target compression in inertial confinement fusion (ICF), in shock tube research, and in the interaction with turbulent flows in general, as well as in the study of matter at high energy density (HEDP). The linear problem is solved from the conservation equations and the whole perturbation history between the transmitted and reflected fronts is followed since the incident shock has disappeared. Vorticity profiles are analyzed near the contact surface. The surface ripple growth is calculated up to the asymptotic stage inside the linear regime. An asymptotic behavior for the contact surface ripple is obtained, as evidenced for the first time in [1]. Approximate expressions for the asymptotic velocities are given for arbitrary values of the shock Mach number. We present explicit solutions and exact analytical expansions of the asymptotic normal and tangential velocities for the cases in which a shock [2] or a rarefaction [3] are reflected at the contact surface. The results of the linear theory are compared to simulations and experimental work [2,3,4].

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Mixing and entrainment in variable viscosity and density round jet

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It is important from both fundamental and economical viewpoints to understand, with the aim to predict, mixing in variable dynamic viscosity (VV) and variable density (VD) flows. The particular flow considered is the round jet. The VV case concerns fluids with the same density, but with different dynamic viscosity (propane/air, for which the dynamical viscosity ratio is 3.5). The VD case involves fluids with the same dynamic viscosity, but with different densities (helium mixed with air, the ratio of densities is 7). These two representative situations are critically compared with the reference case for which both density and viscosity are the same, i.e. the passive scalar mixing (slightly heated air, mixed with fresh air). Due to the scalar active nature, simultaneous velocity and concentration measurements have been performed (using stereo-PIV and PLIF respectively). The fashion the mixing is progressively installed is described, via mixed statistics, such as joint probability density functions of velocity and scalar fluctuations, at different downstream positions. It is shown that, with respect to the reference case, mixing is rapidly enhanced for VV and VD flows, thought the physical mechanisms are different. This observation is tightly correlated to the interface (Turbulent/Non Turbulent region) and the associated physics. As an example, the entrainment ratio Ce is calculated from experiments. Whilst Ce is positive for the baseline case, reflecting an entrainment, negative values of the entrainment coefficient are noted for either VV or VD cases, corresponding to a detrainment process (the injected fluid slips off on the ambient fluid). This observation corroborates the idea of mixing quantification due to viscosity/density gradients. These effects are finally put in the context of transport equations for the entrainment ratio, obtained from the first principles.

Ejecta produced by Rychtmyer-Meshkov instability from free metal surfaces

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Due to machining, material surfaces are usually covered with the micrometer-sized perturbations. Shock wave propagation to such surfaces results in RMI and ejecting of microscopic cumulative jets which break down into particles forming an ejecta cloud. Those particles must be taken into account both in optical measurements of shocked free metal surfaces and for comprehensive simulation of target under inertial confinement fusion. Shock pressures in experiments are typically about tens of GPa, which generate jets of several km/s. The space-time evolution of such extreme phenomena is difficult to resolve using available diagnostics. The deeper understanding of instability mechanism may be given by simulation. Lagrangian meshless methods are found to fit the best the ejecting peculiarities including complex surface evolution and jet fragmentation. To study ejecta we perform the consistent SPH and MD simulations of shocked metals. Realistic surfaces are represented by adding randomness in grooves shape. The obtained mass and velocity distributions are analyzed and utilized for interpretation of optical data. Evolution of ejecta cloud, including fragmentation mechanisms, is discussed.

Gyroscopic analogy of Coriolis effect for stabilizing a rotating stratified flow confined in a spheroid

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In the investigation of the Rayleigh-Taylor instability (RTI) in a rotating frame, Chandrasekhar (1961) claimed that rotation does not affect the instability or stability of a stratified flow. However, the dispersion relation of the internal inertia-gravity wave reveals the stabilizing action of the Coriolis force. We address the suppression of the gravitational instability of rotating stratified flows in a confined geometry in two ways, continuous and discontinuous stratification. A rotating flow of a stratified fluid confined in an ellipsoid, subject to gravity force, whose velocity and density fields are linear in coordinates, bears an analogy with a mechanical system of finite degrees of freedom, that is, a heavy rigid body. An insight is gained into the mechanism of system rotation for the ability of a lighter fluid of sustaining, on top of it, a heavier fluid when the angular velocity is greater than a critical value. The sleeping top corresponds to such a state. First we show that a rotating stratified flow confined in a tilted spheroid is equivalent to a heavy symmetrical top with the symmetric axis tilted from the top axis. This tilting effect of the symmetric axis on the linear stability of the sleeping top and its bifurcation is investigated in some detail. Second, we explore the incompressible two-layer RTI of a discontinuously stratified fluid confined in the lower-half

of a spheroid rotating about the axis of symmetry oriented parallel to the vertical direction. The gyroscopic analogy accounts for decrease of the critical rotation rate with oblateness.

Tutorial: models and numerics for the Rayleigh-Taylor flows between miscible Newtonian fluids

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The goal of this tutorial is two-fold. The first goal is to point out that for a given physical situation the corresponding mathematical modeling has to be based on a simplified set of equations to avoid unnecessary stiffnesses of the PDEs. The second goal is an advocacy for the use of high-order numerical methods for the solution of these PDEs. These two statements are general but the tutorial is conducted within the specific case of the Rayleigh-Taylor instability. This instability is governed by several dimensionless parameters such as the Atwood, Mach, stratification, Reynolds, Schmidt and Prandtl numbers. From asymptotic analysis, four low- and zero-Mach-number models, which correspond to limit values of these numbers, have been derived. These are the anelastic, quasi-isobaric, Sandoval and Boussinesq models. The nature of these PDEs, including the full Navier-Stokes equations, hyperbolic, parabolic and elliptic will be discussed. These four incompressible models lead to the solution of a Stokes problem, i.e. a Helmholtz problem constrained by div (rho u) = S, while the solution of the full Navier-Stokes includes acoustic and shock waves. The errors of numerical schemes (amplitude and phase errors) will be recalled on simple examples. This leads to the use of high-order methods, which include high-order finite difference, spectral and wavelet methods. An extensive bibliography will be given and we will focus on spectral methods. Efficient spectral algorithms for subsonic compressible and incompressible models have been designed and large-scale simulation results will be reported. These simulations use an adaptive multidomain Chebyshev method in one direction. This method has also been used to solve linear and nonlinear boundary value problems. On the other hand, the turbulent regime is classically investigated with DNS and LES or implicit LES (ILES). The numerical requirements for these methods will be also discussed.

What is the final size of turbulent mixing zones driven by the Faraday instability?

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Fluids of different densities submitted to strong time-periodic accelerations normal to their interface can mix due to Faraday instability effects. Turbulent fluctuations generated by this mechanism lead to the emergence and the growth of a mixing layer. Its enlargement is progressively slowed down as resonance conditions driving the instability cease to be fulfilled. The final state corresponds to a saturated mixing zone in which turbulence intensity slowly decays. We introduce a new formalism dedicated to the Faraday instability based on second-order correlations spectra for turbulent quantities. This theory allows for the prediction of the mixing zone final size and extends results from classical stability analysis limited to weakly non linear regimes. It is then satisfactorily compared to a large set of thoroughly investigated numerical simulations.

Stability and structure of fields of a flow with a hydrodynamic discontinuity

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We consider from a far field the evolution of a hydrodynamic discontinuity separating incompressible ideal fluids of different densities, with mass flow across this interface. By solving the boundary value problem and finding fundamental solutions of linearized dynamics, we directly link interface stability to structure of the flow fields. We find that classic Landau's system of equations for the Landau-Darrieus instability has a degenerate and singular character. Eliminating this degeneracy leads to appearance of a neutrally stable solution whose vortical field can seed the instability. We further find that the interface is stable if the flux of energy fluctuations produced by the perturbed interface is small compared to the flux of kinetic energy across the planar interface. The interface is unstable otherwise. Landau's solution is consistent with the latter case.

Current-vortex sheet dynamics in magnetohydrodynamic flows

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A theoretical model is proposed to describe fully nonlinear dynamics of interfaces in two-dimensional MHD flows. Numerical calculations based on the model [1] are performed for MHD Richtmyer-Meshkov instability with sinusoidal vortex sheet strength. Nonlinear evolution of the interface is found to be determined by the Alfven and Atwood numbers. Some of their dependence on the sheet dynamics and magnetic field amplification are discussed. It is shown by the model that the magnetic field amplification occurs locally associated with the nonlinear dynamics of the current-vortex sheet. We expect that our model can be applicable to a wide variety of MHD shear flows such as MHD Kelvin-Helmholtz instability.

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On the structure of the Rayleigh-Taylor Mixing zone

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When the Rayleigh-Taylor instability (RT) development the density jump initially existing on an unstable contact boundary remains in the process of the mixing zone development in the

form of the front of the bubble domes and this ensures the undamped development of the mixing zone [1, 2]. The anomalous stability of bubble domes is associated with the effect of accelerated shear flow on the surface of bubbles [2-5]. This stability is observed both in the case of the gas-liquid interface [1-3] (the Atwood number A ~ 1), and in the liquid-liquid [4] (A = 0.007) and gas-gas cases [5]. The stabilization of the RT instability on the bubbles surface is analogous to the relaminarization of the turbulent boundary layer during acceleration of the flow [6-8]. Experiments demonstrate the possibility of accelerated flow through the mixing zone of the flows of both a denser and less dense medium. Experiments demonstrate the possibility of self-organization of fiber-like structures in the turbulent mixing zone, consisting of weakly ionized products of detonation of a gas mixture, air and dust of vegetable origin.

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A computational study for the membrane supporting grid effect on the Richtmyer-Meshkov instability

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Several mechanisms have been proposed for forming the density interface in order to experimentally investigate the Richtmyer-Meshkov instability (RMI). One way is to create the interface, which separating the two different gases, by a thin film supported by thin solid wires. However, non-agreements of the results from different experimental setups and theoretical predictions were observed. This is expected to be an effect of the perturbation that is introduced by the film and its supporting grid [1]. Thus, the objective of this work is to study the affect of the supporting grid wires in the transient dynamic of the RMI. The RMI test cases were numerically simulated by solving a (multi-fluid) variable-γ compressible Euler equation by an embedded boundary AMR code that utilizes a second order scheme and high order multi-stage reconstruction algorithm. The developed algorithms [2] were implemented under block-based AMR framework using Chombo library. The numerical experiments were performed in a two-dimensional shock tube in which a multi-mode air-SF6 interface. Several solid circular cylinders were added to mimic the effect of the thin wire by introducing small scales perturbation on the density interface, that are around two order of magnitude smaller than the interface sinusoidal perturbation. The effects of the supporting wires on mixing and growth rate will be analyzed and discussed; and validated/verified with experimental and computational results.

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Simulation of Richtmyer-Meshkov instability in the presence of thermal fluctuations using fluctuating hydrodynamics

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Thermal fluctuations in a fluid are significant in small volumes such as nano-channels and may play a key role in mechanisms triggering instabilities that in turn drive processes such as Rayleigh-Taylor mixing [1]. The fluctuating compressible Navier-Stokes equations (FCNS) provide a meso-level description of the system and account for intrinsic thermal fluctuations in the fluid by extending the deterministic Navier-Stokes equation via the addition of the divergence of a stochastic flux, which results in a system of stochastic partial differential equations (SPDEs) that we write in conservation form. Here, we develop numerical methods for the two-fluid FCNS and simulate Richtmyer-Meshkov instability to quantify the growth rate of a single-mode perturbation on the interface between Helium and Argon gas for a range of Atwood and Mach numbers. We compare the results to those obtained direct simulation Monte Carlo (DSMC) method [2] and to analytical models in literature.

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Late-time evolution of Rayleigh-Taylor instability in a domain of a finite size

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We develop the theoretical analysis to systematically study the late-time evolution of Rayleigh-Taylor instability in a domain of a finite size. The nonlinear dynamics of fluids with similar and contrasting densities are considered for two-dimensional flows driven by sustained acceleration. The flows are periodic in the plane normal to the direction of acceleration and have no external mass sources. Group theory analysis is applied to accurately account for the mode coupling. Asymptotic nonlinear solutions are found to describe the interface dynamics far from the boundaries and near the boundaries. The influence of the size of the domain on the diagnostic parameters of the flow is identified. In particular, it is shown that in a finite size the domain the flow is decelerating compared to spatially extended case. A close analysis of the shear present at the interface of the fluids is also studied both for a domain of a finite size and in the limit of an infinite domain. It is shown how the interfacial shear acts as a natural parameter to the family of solutions. The theory outcomes for the numerical modeling and design of experiments on Rayleigh-Taylor instability are discussed.

Analysis of high Atwood number Rayleigh-Taylor mixing using low-Mach number, variable density/viscosity, non-dissipative LES algorithm

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High Atwood number Rayleigh-Taylor (RT) turbulent mixing is studied using recently proposed [1] low-Mach number, variable density/viscosity, fully-implicit, non-dissipative, finite-volume LES algorithm. After showing that the algorithm is capable of capturing the dynamics of mixing at both low and moderate Atwood numbers, it is applied to high Atwood number RT instability. Since the algorithm does not rely on the Boussinesq assumption and allows density and viscosity to vary, it does not suffer from the loss of physical accuracy expected to be caused by the physical limits of the assumption at higher Atwood numbers [2]. This feature provides an obvious advantage against the pure incompressible methods based on the Boussinesq assumption, when studying RT mixing. Results obtained through systematic and rigorous runs include many diagnostics such as local mole fractions, bubble and spike penetration lengths and growth rates, mixing efficiencies, Taylor micro-scales and Reynolds numbers, Reynolds stresses and their anisotropy to quantify the effects of higher Atwood numbers. It can be preliminarily concluded that the higher Atwood numbers are characterized by increasing ratio of spike and bubble growth rates, faster development in instability due to the higher speeds of bubble and spike fronts, late time mixing values similar to each other and mixing asymmetry. Higher Atwood number runs also require higher aspect ratio domains and longer simulation times for full development of flow. In-depth analyses of results will be provided in the full manuscript.

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HIGH ENERGY DENSITY PHYSICS

On the fundamentals of Rayleigh-Taylor mixing driven by variable acceleration

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Rayleigh-Taylor (RT) mixing occurs in a variety of natural and man-made phenomena. In most instances, RT flows are driven by variable acceleration, whereas the bulk of existing studies have considered only steady and constant acceleration. Here, we analyze certain patterns of variable accelerations and discuss the symmetries and invariants of RT mixing, by assuming that the dynamics of a fluid parcel is driven by the gain and loss of specific momenta [1-5]. Analytical solutions in the balanced and imbalanced cases show the existence of two regimes -- the acceleration-driven regime and the non-universal, dissipation-driven regime. We find that the scaling, correlations, fluctuations spectra of RT mixing depart substantially from those of the canonical cases of Kolmogorov turbulence and of the self-similar blast waves of the first (Sedov-Taylor) and second (Guderley-Stanyukovich) kind. The R-T mixing exhibits greater order in comparison to homogeneous isotropic turbulence, and greater disorder in comparison with self-similar blast-waves.

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Internal capsule defects quenching thermonuclear ignition

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The concept of inertial confinement fusion (ICF) is that a spherical capsule containing a fuel layer is imploded by irradiating its surface with high power lasers or soft x rays, thereby assembling a high-density main fuel and a low-density hot spark, triggering thermonuclear ignition. Hydrodynamic instabilities such as the Rayleigh-Taylor instability may amplify perturbations on the capsule, and finally mix the cold main fuel and capsule material into the hot spark, thereby quenching thermonuclear ignition. Surface roughness is generally considered as a primary source of the hydrodynamic instabilities, but internal capsule defects can seed perturbations on the surface, being amplified by the instabilities. Such internal defects are inevitable if capsules are made with coating technique, in which a few (but non zero) monomers of CH get together in flight and fall on the coating surface, making a seed of defects, resulting in cone like structures and domes above them. The dome is usually polished out to meet a specification of the surface roughness, but the cone structure under the dome remains unpolished. Our mixing calculations for ignition targets suggests that the internal capsule defects is large enough to quench the thermonuclear ignition, though the initial conditions are not well characterized and so they are assumed to be consistent with the microscopic observations. Thus it is quite obvious that one should adopt a new target manufacturing technique that can eliminate the internal defects. Density matched emulsion technique is completely free from the internal capsule defects. Backing in late 1980's Osaka group demonstrated extremely high density at time with polystyrene capsules made with this technique. We would urge the ICF community to adopt and improve the density matched emulsion technique to meet the ignition condition.

Scale coupling in strong shock driven Richtmyer-Meshkov flows

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Richtmyer-Meshkov instability (RMI) governs a broad variety of processes in fluids, plasmas and materials, including inertial confinement fusion, core-collapse supernova, and material transformation under impact. We systematically study RMI induced by strong shocks for fluids with contrasting densities and with small and large amplitude initial perturbations imposed at the fluid interface [1-5]. Smoothed particle hydrodynamics code (SPHC) is employed to ensure accurate shock capturing, interface tracking, and accounting for the dissipation processes. Simulations results achieve good agreement with existing experiments and with the rigorous theoretical analyses and with the novel empirical model. We find that (1) The amount of energy that can be deposited by the shock at the RM-unstable interface is restrained. Significant part of the shock energy goes into compression and background motion of the fluids. (2) The initial amplitude is key factor of RMI evolution. The initial growth-rate of RMI is a non-monotone function of the initial amplitude. (3) At late times RM flow remains laminar rather than turbulent; RM bubbles flatten and decelerate. (5) In the fluid bulk, the dynamics at small-scale is heterogeneous, and is characterized by reverse cumulative jets, non-uniform velocity fields, local micro-structures, high pressure regions, and 'hot spots'. (6) For the first time, to our knowledge, we find the maximum value of the initial growth-rate of RMI, the corresponding scale of the initial amplitude, and the maximum fraction of energy available for interfacial mixing. We show that the amplitude scale at which this maximum growth-rate is achieved is the characteristic quantity of RMI dynamics. It is independent of the shock strength and density ratio. It leads to exponential decays of the ratio of the initial and linear growth-rates of RMI.

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Hydrodynamic instability as consequence of laser action

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Laser ablation through liquid is very different from ablation in vacuum. In spite of importance of this kind of laser-matter interaction (e.g., for nanoparticles production), corresponding processes are still poorly understood. We show in the report that to produce nanoparticles the laser absorbed energy Fabs (absorbed fluence, energy per unit of area) should few times overcome the ablation threshold in the case when irradiated target contacts with vacuum. Then temperatures in the heat affected zone increases above critical temperature. Our analysis of the flow as whole with a strong shock propagating in liquid and with a rarefaction wave inside the metal target demonstrates that the contact between metal and liquid, both in their supercritical states, is hydrodynamically unstable. The instability is of the Rayleigh-Taylor type. Its dynamics is important for separation of droplets freezing soon into solid nanoparticles.

Dynamic stabilization of plasma instabilities

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The paper presents a study on dynamic stabilization of plasma instabilities, including the Rayleigh-Taylor instability, the filamentation instability and others, based on a control mechanism. The dynamic stabilization control mechanism is rather general, and so can be applied widely to plasma stabilization. Instability grows from perturbations of physical quantities in unstable systems, and the perturbation phase is unknown in plasmas and fluids. In general, it would be hard to control instabilities in plasmas and fluids. Usually the instability growth rate is employed to examine the plasma state. However, if the perturbation phase is known, the instability growth can be controlled by a superimposition of perturbations imposed actively: if the perturbation is introduced by, for example, a driving beam axis oscillation or so, the perturbation phase can be controlled and the instability growth is mitigated by the superimposition of the growing perturbations. On the one hand, a stabilization mechanism has been also studied based on the Kapitza's pendulum theory. In the Kapitza's pendulum theory the basic equation is modified by adding another term to create a new stable window. On the other hand, the feedback control mechanism has been widely employed to stabilize unstable systems. In the feedback control the perturbation phase and amplitude are detected, and the growing perturbation is compensated by the active feedback control. However, in plasmas and fluids it is difficult to measure the instability phase and amplitude, and so the perfect active feedback control cannot be normally realized in plasmas and fluids. However, if we actively impose the perturbation phase by a driving energy source wobbling or oscillation, the perturbation growth can be controlled in a similar way as the feedback control mechanism. In this paper, we present the dynamic stabilization of plasma instabilities based on the control theory.

The arrow of time and extending conventional thermodynamics from matter to antimatter

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The arrow of thermodynamic time (i.e. temporal direction of entropy increase) is most likely to be primed by a small-scale process that induces tiny violations of quantum unitarity by environmental and intrinsic mechanisms causing decoherence. The exact physical mechanism of time priming remains unknown but, as we know, direct effects of time priming may be possible to observe at least in two types of experiments: 1) as possible apparent CPT violations in CP-violating and CPT-preserving quantum systems [1] and 2) as possible differences between thermodynamic (and radiation-absorbing) properties of matter and antimatter [2,3]. The second possibility is related to two possible and mutually exclusive extensions of thermodynamics and kinetics from matter to antimatter: symmetric (CP-invariant) and antisymmetric (CPT-invariant) [2,4]. It is not known which extension of thermodynamics is real, but the antisymmetric version seems attractive since, unlike conventional symmetric thermodynamics, it favours conversion of antimatter into matter [4]. While matter is necessarily dominated by decoherence, antimatter can be dominated either by decoherence or recoherence (this corresponds to symmetric and antisymmetric versions of thermodynamics), only decoherence-neutral treatment of radiation is consistent with Einstein theory of radiation and experimental evidence [3].

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Collisionless shocks in the Large Plasma Device

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A new laser experiment to study the interaction of an energetic laser plasma with a large magnetized ambient plasma is now operational at the Large Plasma Device at University of California Los Angeles. A rapidly exploding, and super-Alfvenic (Mach > 2) plasma-plume is created by irradiating a solid target within the preformed magnetized plasma with an energetic laser pulse (200 J in 20 ns). The ambient plasma (1E13 cm-3, 5 eV, 300 G) is current free, stationary, quiescent, and large enough (17x0.5 m) to support Alfven waves. Results from experiments and 2D kinetic-fluid hybrid simulations concerning the dynamics of energetic target debris ions, formation of magnetic cavities and outgoing waves, and shocks are presented. In experiments where the debris propagates primarily across the field we directly measure the collisionless coupling between the debris and the ambient plasma and how it leads to the formation of a shock. Experiments with energetic debris ions streaming along the magnetic field investigate the excitation of electromagnetic ion-ion instabilities that can steepen into a shock. The results will be discussed in the context of debris-ambient coupling in space and astrophysical explosions and other laboratory experiments.

Effect of a relative phase of waves constituting the initial perturbation and the wave interference on the dynamics of strong shock driven Richtmyer-Meshkov flows

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While it is a common wisdom that initial conditions influence the evolution of the Richtmyer-Meshkov instability (RMI), the research in this area is focused primarily on the effects of the wavelength and amplitude of the interface perturbation. The information is hitherto largely ignored about the influences on RMI dynamics of the relative phase of waves constituting a multi-wave initial perturbation and the interference of the perturbation waves. In this work we systematically study the influence of the relative phase and the interference of waves constituting a multi-wave initial perturbation on a strong shock driven Richtmyer-Meshkov unstable interface separating ideal fluids with contrast densities. We apply group theory analysis and Smoothed Particle Hydrodynamics (SPH) numerical simulations [1-4]. For verification and validation of the simulations, qualitative and quantitative comparisons are performed with rigorous zero-order, linear and nonlinear theories as well as with gas dynamics experiments achieving good agreement. For a sample case of a two wave (two-mode) initial perturbation we select the first wave amplitude enabling the maximum initial growth-rate of the RMI, and we vary the second wave amplitude from 1% to 100% of the first wave amplitude. We also vary the relative phase of the first and second waves and consider the in-phase, the anti-phase and the random-phase cases. We find (for the first time, to our knowledge) that the relative phase and the interference of waves are important factors of RMI dynamics influencing qualitatively and quantitatively the symmetry, morphology, and growth-rate of the RM unstable interface, as well as the order and disorder in strong shock driven RMI.

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Effect of noise on Rayleigh-Taylor mixing with time-dependent acceleration

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We perform a detailed stochastic study of Rayleigh-Taylor (RT) mixing with time-dependent acceleration. A set of nonlinear stochastic differential equations with multiplicative noise is derived on the basis of momentum model and group theory analysis [1-5]. A broad range of parameters is investigated, and self-similar asymptotic solutions are found. The existence is shown of two sub-regimes of RT mixing dynamics – the acceleration-driven and the dissipation-driven mixing. In each sub-regime, statistic properties of the solutions are investigated, and dynamic invariants are found. Transition between the sub-regimes is studied.

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High energy density turbulent mixing from astrophysical collisionless plasma flows to solid-density plastic flow in metals

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Turbulent mixing occurs ubiquitously in the universe. Two very extreme cases are presented: high flow-stress interface mixing in solid density metals and high Mach number collisionless plasma interactions. We are conducting laboratory experiments at Omega and NIF with high-energy, high-power lasers to investigate the dynamics of solid-state lattice dynamics and plastic flows relevant to planetary interiors. Dynamic strength experiments utilize the growth of Rayleigh-Taylor instabilities (RTI), where the flow stress (strength) of the solid-state material can be inferred from the reduction in growth of the RTI [1]. The other experiments are high Mach number collisionless shock formation in two interpenetrating plasma streams. It is believed that in astrophysical environments such shocks are the sites where seed magnetic fields are generated on a cosmologically fast timescale via the Weibel instability. The Omega and NIF experiments were able to observe the counter-streaming flow interactions in both the collisional and the collisionless regimes as well as magnetic nature of the flow interactions [1]. We will present the results from both of these classes of experiments

[1] Park HS et al., Phys. Rev. Lett., 114, 065502 (2015); [2] Ross JS et al., Phys. Rev. Lett., 118, 185003 (2017). This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Novel regimes of hydrodynamic instabilities and mixing in high energy density settings

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New regimes of science are being experimentally studied at high energy density on the National Ignition Facility and Omega laser Facility at drive energies spanning joules to megajoules, and time scales from picoseconds to fractions of a microsecond. The ability to shock and ramp compress samples to very high pressures and densities allows new states of matter relevant to planetary and stellar interiors to be studied. Shock and acceleration driven hydrodynamic instabilities evolving into turbulent flows relevant to the dynamics of exploding stars (such as supernovae), accreting compact objects (such as white dwarfs, neutron stars, and black holes), and planetary formation dynamics are being probed. The capability to study the dynamics of magnetized plasmas relevant to astrophysics is being developed. High velocity, low density interpenetrating plasma flows are being probed for evidence of collisionless astrophysical shock formation, the turbulent magnetic dynamo effect, magnetic reconnection, and plasma particle acceleration. And new results from thermonuclear reactions in hot dense plasmas relevant to stellar and big bang nucleosynthesis are starting to emerge. Hydrodynamics instabilities in a range of geometries and high energy density (HED) regimes are being explored, with and without radiation, magnetic fields, and solid-state material strength effects. I will give examples of experiments exploring these different types of flows, instabilities, and the ensuing mixing from the NIF and Omega lasers, and provide a vision for frontier HED science in the coming decade.

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Interfacial magnetohydrodynamic instabilities in laser plasmas

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Interfacial instabilities, the Kelvin-Helmholtz, Rayleigh-Taylor, and Richtmyer-Meshkov (RM) instabilities, play a crucial role in various plasma phenomena such as astrophysical supernova explosions and inertial fusion implosions. Recently the experimental studies on these instabilities in high energy density setting have been performed intensely by using high power laser facilities. Compared with the classical instabilities in “low energy density”, various interactions should be considered in the laser plasma, which are for example the radiation, compression, kinetic effects, and magnetic fields. In this talk, I will review the recent progress in the laser experiments for the interfacial instabilities including our activity by the GEKKO laser in Osaka University. Numerical simulations are also quite important to understand the nature of the interfacial instabilities. I will introduce briefly our theoretical results on the RM instability. One of the urgent and curious questions related to the RM instability is the interaction with a magnetic field. It is known that there are two important effects brought by the inclusion of an external field, which are the amplification of the ambient field and the suppression of the unstable growth. We demonstrated by direct numerical simulations (DNS) that the magnetic field could be amplified through the stretching motions driven by the RMI. The maximum field strength is more than two orders of magnitude higher than the initial size, and it appears associated with the interface as well as the bulk vorticity left by the rippled transmitted shock. The growth of RM instability can be reduced significantly by a strong field as a result of the extraction of vorticity from the interface. A useful formula describing a critical condition for magnetohydrodynamic RM instability has been derived, and which is successfully confirmed by DNS.

Radiation of charge bunches revolving around a metamaterial sphere

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We investigate the interaction of a relativistic uniformly rotating charge with a metamaterial sphere in the microwave range. The charge revolves around the sphere at the equatorial plane. The root mean square of the radiation field for different types of metamaterial spheres is presented and its dependence on some usual parameters is considered. They demonstrate that the radiation field is concentrated near the surface and shifts towards the centre by increasing charge energy for conventional and double-negative metamaterial. The stopping and deflection forces acting on the charge are also calculated. Finally, we generalize these results to a line charge bunch. This study has potential application in the area of high-power radiation sources and accelerators

Multifluid mathematical model for the numerical investigation of high-speed interaction of metal plates

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The work is devoted to the development of three-fluid mathematical model and the correspondent computational algorithm for the modeling of the initial stage of two metal plates impact. The governing system of equations is based on (Saurel, Abgrall, JCP, 150, 1999) model. All fluids – steel plate, lead plate and the ambient air – are considered to be compressible and non-equilibrium on velocities and pressures. The governing system of equations comprises conservation laws for each fluid and transfer equation for the volume fraction of the fluid. The system has hyperbolic type but couldn't be written in the conservative form because of nozzling terms in the right-hand side terms. The computational algorithm is based on the Harten-Lax-van Leer-Contact numerical flux function (Liang et al., Comp. Fluids., 99, 2014). The robust computation in the presence of the interface boundaries is carried out due to the special pressure relaxation procedure like (Saurel, Lemetayer, JFM, 431, 2001). The problem is solved using stiffened gas equations of state for each fluid. The parameters in the equations of state are calibrated using the results of computations using wide-range equations of state for the metals. In simulations of metal plates impact we get two shocks after the initial impact that propagate to the free surfaces of the samples, the rarefaction waves after the interaction of the shocks with free boundaries. We also measure the acceleration of the interface boundary between the metals after the superposition of the rarefaction waves. The characteristics of shock waves are close (maximum relative error in characteristics of shocks is not greater than 7 %) to the data from the wide-range equations of states computations.

Vorticity and kinetic energy in Richtmyer-Meshkov like flows

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Corrugated shocks in ideal gases generate acoustic, entropic and vorticity perturbations. Hence, the velocity perturbations are essentially rotational. Velocity perturbations are obtained as a function of time and the asymptotic linear profile is derived. The vorticity distributed inside the compressed fluids is an important quantity to determine the asymptotic linear velocities at the contact/piston surfaces that drive the shocks. Usually, the vortices nearest to the piston/contact surface are the strongest and contain a significant amount of

rotational kinetic energy. The size of the strongest vortices is analyzed as a function of the compression level and the kinetic energy stored inside the vorticity field is also calculated.

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MATERIAL SCIENCE

Shock-bubble interaction near a compliant tissue-like material

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Since the discovery of tissue damage incurred by cavitation bubble collapses during intraocular surgery or shock-wave lithotripsy, the potential of harnessing the strongly localized release of thermal and mechanical energy through a collapse-induced shock wave has moved into the focus of biomedical technology. Experimental access of such configurations is extremely challenging, and thus intense research on experimentally accessible surrogate configurations and accompanying numerical simulations has developed over the past decade. Such an experimental surrogate configuration we consider in this paper (Kodama & Tomita 2000) and discuss the late stages of bubble collapse and interaction with the tissue surrogate by highly-resolved two-dimensional numerical simulations. We use a employ a recently developed multi-material regional level-set approach (Pan et al. 2016a, 2016b) to represent the sharp multi-material interfaces while employing high-resolution low-dissipation WENO schemes (Hu et al. 2010), adaptive multi-resolution (Han et al. 2014a) with a conservative interface-interaction model (Hu et al. 2009). Our aim is to understand and quantify the mechanisms observed during extracorporeal shock-wave lithotripsy or sonoporation. Therefore, late-stage dynamics of the bubble collapse and tissue penetration are presented.

Massively parallel Smoothed Particle Hydrodynamics modeling of shock-loaded spherical particles

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According to the data obtained by Photonic Doppler Velocimetry shock wave propagation through randomly packed metallic particles leads to formation of a metallic dust cloud, fragments of which possess various velocities. Without optical survey involvement it is difficult to use experimental data for obtaining reliable information about formation and composition of the disperse system. Numerical simulation may involve applying complex models of heterogeneous medium that operate averaged parameters of the layer, or it may fully correspond to real pattern of the layer observed. The second case, meso-scale modeling, allows one to obtain sizes of dust particles directly, without any averaging of simplifying assumptions, but only a careful choice of appropriate simulation method in combination with effective usage of computational resources can make a solution of such problems possible. Meshless lagrangian smoothed particle hydrodynamics method (SPH) is an optimal approach for solving hydrodynamic problems of compressible medium which imply formation of drops, caverns, and cumulative jets, because the method assume neither free surface nor contact interface tracking. Contact SPH (CSPH) formulation incorporating Riemann problem solution empowers standard SPH, allowing it to reproduce effects of particles compression and tension correctly. Method formulation simplicity encourages clear program realization, and limited particle interaction area suites well for effective parallelization via spatial decomposition approach. Through the use of our massive-parallel CSPH code based on the dynamic Voronoi domain decomposition approach we conduct direct simulation of the experiment described above using different packing of spheres. For the first time, the results of the meso-scale modeling demonstrate that fragments of fractured cumulative jets elapsing from metal spheres layers due to spheres collision are present in the metallic dust cloud.

Tapering and superheat in cylindrical continuous casting.

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The formation of an air gap in continuous casting systems is detrimental to the process efficiency as it acts to thermally insulate the cast from the water-cooled mould. By tapering the mould wall, the thermal contraction of the cooling cast can be accommodated so that the thickness of the air gap is decreased. We consider a coupled thermomechanical model to investigate the effect of mould tapering on the formation and thickness of the air gap in an axisymmetric mould. Using asymptotic techniques, the model is reduced to allow analytic and inexpensive numerical investigations while maintaining the essential characteristics of the thermomechanical process. The modelling of superheat is included, where the incoming molten metal is at a higher temperature than its melting point. The degree of superheating also affects the formation and thickness of the air gap and presents a viable alternative for control of the system. The efficacy of mould tapering in the presence of superheat is examined.

Instability of the interface between two high-speed colliding metal plates: 3D numerical simulation

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High-speed impact of lead plate with the plates of different metals the features of the processes in the near interface regions of the colliding plates are investigated numerically. The lead plate is thrown by the products of condensed explosive detonation to the steel plate under some angle with the speed several hundred meters per second. The transition of the metals to the elastoplastic state occurs due the high energy release. During about 10 ms after an impact the metals are in the elastoplastic state and behave as pseudofluids before the backward transition starts. Circumstantial proof of that fact is the existence of crateriform splashes on the surface of steel plate in the direction of lead plate. The explanation of the splashes was given on the assumption of the Rayleigh-Taylor instability development. For the numerical simulations of the problems which are described by the hyperbolic system of equations the authors developed computer code TurbulenceProblemSolver (TPS). TPS has modular structure and consists from the independent blocks responsible for different parts of the numerical method. TPS provides to the user the possibility to change numerical scheme, initial and boundary conditions and mass forces. The code is written in C++ and is parallelized using Message Passing Interface (MPI) package using domain decomposition approach. The main features of the process obtained in the natural experiment and confirmed by our numerical study: (i) The instability development on the interface of the metal plates is characterized by splashes from the metal plate with the smaller density to the plate with the greater density. (ii) The increase of the throwing plate thickness with the fixed velocity leads to the disturbance wavelength growth on the interface.

Instability of the contact discontinuity in the presence of density perturbations

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The paper presents the analytical and numerical analysis of evolution of the contact discontinuity boundary in the collision of plates. There is the initial density distribution in one of the plates. Interaction of the shock wave with the field leads to a velocity perturbation appearance. This leads to a distortion of the contact discontinuity boundary. This type of contact instability is mentioned in the work [1]. We consider the case of high velocity impact and the elastic properties of the substances we neglect (use the hydrodynamic approximation). In this paper we use the method of finding the solution using the decomposition of the field perturbations on the sound and entropy-vortex components [2]. We found theoretical dependence of amplitude of the contact discontinuity boundary of time based on nonlinear corrections. We showed that consideration of nonlinear effects leads to a difference in the growth of bubbles and spikes similarly Richtmyer-Meshkov and Rayleigh-Taylor instabilities [3]. A comparison with the case of the classical Richtmyer-Meshkov instability is conducted. These results are in agreement with numerical calculations.

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Hydrodynamics of nanofilms with melting and re-crystallization non-equilibrium phase transitions of the first order under action of laser pulse

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Modern laser techniques combine sophisticated manipulations with photon cloud and refined target design together with ultrafast isochoric transfer of solid into WDM state. Photon cloud is just 10s micron long and one micron thick when it is focused in the diffraction limited regime onto a thin film 10-100 nm thick. In one case the spherical or cylindrical lenses produces a hot spot with maximum in the central point, while in the other case a spiral phase plate is used. Then illumination field has a hole in the center and bears angular momentum to the target. We create a simulation package including two-temperature (immediately during and for some time after a fs pulse the electrons are much hotter than lattice) 2D hydrodynamics code and multiprocessor molecular dynamics approach with Monte Carlo description of strong thermal conductivity of metal and analyze absorption, melting, capillary dynamics of hot melt and it freezing into solitary nanostructures.

Shock compressibility of two-phase liquid-vapor mixture of metals at high temperatures

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Modeling of thermodynamic properties and phase transitions of materials is needed for analysis of processes at high energy density. Reliability of predictions is determined mainly by adequacy of equation of state for materials in question. In the present work, a multiphase equation of state for metals is considered. Thermodynamic potential Helmholtz free energy is written with taking into account solid, liquid and gas phases. Equation-of-state calculations have been carried out for aluminum, tantalum and some other metals over a broad region of the phase diagram. Obtained results are compared with available data from experiments at high energy densities. Shock compressibility of high-temperature two-phase liquid-vapor mixture of metals in equilibrium is studied particularly. Stability of shock waves in the mixture is discussed.

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Dynamics of turbulent melting from below driven by thermal convection

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Melting and solidification coupled with convective flows are fundamental processes in the geophysical context; such as ice melting in the Arctic pack during summer season or fusion in magma chambers. Similar to the Rayleigh-Benard system, for sufficiently large vertical temperature gaps a convective instability develops which exhibits a rich dynamics as the

Rayleigh number is increased. However, Due to the dynamic nature of top boundary layer (solid-to-liquid melting interface), which is under transformation at the pace of the local heat flux across the fluid layer, the resulting shape of the lead may in turn modify the organization of flow structures with a feedback on the heat transport. We investigate such a model system by means of numerical tools by performing Direct Numerical Simulations built on a enthalpy based Lattice Boltzmann algorithm to address the high Rayleigh number regime both in two- and three-dimensional setups. We focus on the scaling of global quantities, Nusselt and Reynolds numbers, and on the characterization of the geometry of the melting lead.

The effect of passivation and strain on quantum transport of Molybdenum disulfide armchair nanoribbons

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Molybdenum disulfide (MoS2) is layered transition-metal di-calcogonide (TMDC) which in its monolayer form has the direct bandgap of 1.8eV and is good material for using in transistors. We investigated the effect of passivation, width and strain on quantum transport for MoS2 armchair nanoribbons. For these calculations we used QUANTUM ESPRESSO package and WANNIER90 code. Our calculation indicates MoS2 armchair nanoribbons-passivated are good candidate for transistors even with strain.

Instability and fragmentation of liquid jets: molecular dynamics and smoothed particle hydrodynamics simulations

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Even flat surfaces of materials have micrometer-sized imperfections like grooves. Shock wave reflecting from such surface generates the microscopic cumulative jets because the Richtmyer-Meshkov instability. It is too difficult to resolve space-time evolution of such jets in experimental conditions. However, the process of jet formation can be reproduced in details by atomistic molecular dynamics (MD) and smoothed particle hydrodynamics (SPH) methods. We demonstrate that the consistent MD and SPH simulations provide similar jet velocity profiles and mass distributions during jet formation. Further evolution of shock-induced ejecta from metal surface obtained by both MD and SPH, including mechanisms of jet fragmentation, are discussed. Simulation of ejecta is divided onto two parts: the short-time formation of jet until it reaches its final mass, and the long-time evolution of jet towards its fragmentation. The second part utilizes the mass and velocity distributions obtained at the end of the first part of simulation. MD simulation results for liquid jets of tin with different surface tensions, obtained using two embedded atom method potentials, are presented. We show that fragmentation of ejecta in forms of cylindrical and planar jets happens via different ways. While the cylindrical jets decay to droplets after reaching a critical length due to the Savart–Plateau–Rayleigh instability, the plane jets are stable against the small perturbations of jet shape. But a plane jet with free boundary is found to be unstable. A complicated fragmentation mechanism via boundary instability of plane jets is discussed.

ASTROPHYSICS

On the multidimensional character of core-collapse supernova explosions

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A core-collapse supernova (CCSN) represents the explosive evolutionary endpoint of a massive star's life. On a time scale of a few seconds, the star's iron core collapses to nuclear densities and launches a shock wave that eventually disrupts the massive star in a CCSN explosion — enriching the Universe with heavy elements and leaving behind a compact object (neutron star or black hole). While the details of the explosion mechanism remains uncertain, detailed neutrino radiation hydrodynamics simulations have revealed that fluid instabilities (neutrino-driven convection and the standing accretion shock instability) play an important role in shaping the explosion. These fluid instabilities also drive turbulence in the critical neutrino heating region between the proto-neutron star and the supernova shock wave. The role of turbulence in CCSN explosions is now frequently debated in the literature (e.g., [1]). We will discuss recent results from CCSN explosion simulations obtained with the Chimera code [2,3]. In particular, we discuss results from a resolution study using full neutrino radiation hydrodynamics simulations aimed at assessing the impact of turbulence on supernova dynamics.

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Cosmological evidence that the turbulence problem is solved

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Space telescopes in all frequency bands prove that the classical "turbulence problem" is finally solved Gibson (1996). The solution is revolutionary in many areas, from fluid mechanics to particle physics, and is comprehensive. Cosmology models must be revised back to the time of the hot big bang. Turbulence is defined by the inertial vortex force v x w so that the cascade of turbulent kinetic energy MUST always be from small scales to large, contrary to the standard misconception of Taylor and Richardson that the turbulence cascade is from large scales to small. Universal similarity theories of turbulence and turbulent mixing can now be easily explained by rejecting the failed idea of collisionless fluid mechanics, starting with Planck scales of temperature, length, time and entropy. Misconceptions such as cold dark matter, black holes, massive stars, and dark energy are dispelled. The 2011 Nobel prize in physics is falsified. The dark matter of galaxies is shown to be PGC (proto-globular-star-cluster) clumps of > 10^12 Schild (1996) earth-mass dark matter rogue planets. All stars form by mergers of Schild planets within such PGC clumps (eg: Pleiades) that are interpreted as Jeans-mass proto-galaxies formed at 0.03 Myr during the plasma epoch along big bang fossil turbulence vortex lines. Stars and first life formed soon after the plasma gas transition at 0.3 Myr, hosted by > 10^8 Schild planets produced by the big bang, and mixed by Wickramasinghe cometary panspermia as explained in journalofcosmology.com.

Effect of large-scale vorticity perturbations on shocks undergoing nuclear dissociation

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In the context of core-collapse supernova explosions, the interaction of standing accretion shocks with upstream vorticity perturbations is investigated by linear theory analysis. The nuclear dissociation, taking place behind the shock front, affects the amplification of the perturbations impinging on the front. Likewise, the energy employed in the nuclear dissociation that depends on the shock strength, is also affected by the upstream perturbation field, thereby conforming a coupled interaction. For upstream disturbances, whose characteristic size is much larger than the post-shock dissociation-layer thickness, the effect of nuclear dissociation can be reduced to that of considering the global endothermic effect. The linear interaction of the shock with divergence-free vorticity perturbations is carried out in the large-scale limit. Analytical expressions for the time-dependent shock evolution and for the perturbation field downstream are provided.

Primordial magneto-hydrodynamic turbulence and its signatures

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Observations show that galaxies have magnetic fields with a component that is coherent over a large fraction of the galaxy with field strengths of order microGauss. These fields are supposed to be the result of the amplification of initial weak seed magnetic fields of unknown nature. There are two scenarios for their origin under current discussion: a bottom-up (astrophysical) one, where the needed seed field is generated on smaller scales and, a top-down (cosmological) scenario where the seed field is generated prior to galaxy formation in the early universe on scales that are large now. In our present study we assume that seed magnetic fields have been generated in the early universe. We show that these seed fields lead to primordial MHD turbulence development. We will discuss different classes of turbulence, its evolution, and observational signatures including gravitational waves, effects on cosmic microwave background, large scale structure formation, etc.

Cascades and scaling in two-dimensional compressible turbulence

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Motivated primarily by interest in large-scale turbulence effects in galactic disks, we carried out direct numerical simulations of driven compressible turbulence in 2D. The simulations employ white-in-time random solenoidal forcing at intermediate scales in a doubly periodic square domain with grid resolutions up to 16384^2. Large-scale isothermal compressible turbulence consists of planar vortices and acoustic waves. Separately, wave turbulence usually produces a direct energy cascade, while solenoidal 2D turbulence transports energy to large scales by an inverse cascade. The simulations cover regimes with finite Mach numbers when interaction between acoustic waves and vortices is substantial and show how both direct and inverse energy cascades are formed starting from the energy injection scale. The inverse cascade of kinetic energy eventually produces vortices with velocities approaching the speed of sound, creating shock waves which provide for a compensating direct energy cascade. The resulting steady state contains a system-size pair of long-living condensate vortices connected by a system of shocks. Thus 2D compressible turbulence processes energy via a closed loop: most energy first goes to large scales via vortices and is then transported by waves to small-scale dissipation. Below the injection scale, energy spectra follow classical predictions of Kraichnan (1971) and Kadomtsev-Petviashvili (1973) since at very low Mach numbers the acoustic energy and enstrophy cascades are fully decoupled. Above the injection scale, we recover acoustic energy spectra reminiscent of Zakharov-Sagdeev (1970) theory, while the kinetic energy spectrum is dominated by vortical modes and scales as k^(-2). The simulations employ a state-of-the-art 7th-order accurate finite-difference method with strict dissipation control.

Numerical modelling of convection

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Convective motions can be found in a variety of physical situations, if a liquid, gas or plasma in an external (e.g. gravitational, magnetic, centripetal) force field is unable to transport the heat through it by radiation, thermal conduction or by thermal expansion. Convection is a fundamental process in fluid dynamics, which occurs (or can be induced) in nearly any fluid or plasma, starting with boiling water in a teapot or air over a radiator in a room, in planetary interiors, in Earth's and planetary atmospheres, leading to thunderstorms, and ending with largest astrophysical scales, such as solar and stellar convection zones and accretion disks around black holes. Nevertheless, despite its nature being fundamental, this process is not understood well. This lack of understanding comes from the complexity of the system of non-linear Navier-Stokes equations. A further level of complexity is added to the equations and to the dynamics of fluid, if it is sensitive to an externally induced or locally generated magnetic field, or if radiative energy transport is included in the system. In my presentation, I will review a variety of situations, from astrophysical to technological, in which convection occurs. I will discuss numerical techniques used for modelling of three-dimensional (magneto) convection and show the effects of numerical resolution and numerical viscosity on the flow pattern. Furthermore, I will show presence and analyse dynamics of vortex features generated in convection, their interaction with magnetic field in magnetoconvection, and demonstrate effects of Prandtl number on development of convective patterns.

Mixing as relaxation

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We explore the application of the concept of violent relaxation from far-from-equilibrium states, proposed in the context of stellar dynamics, to a range of other mixing processes. Considered in phase space, the Kelvin Helmholtz instability can be seen as a form of violent relaxation process, rapidly transforming ordered motion to a quasi-thermal distribution. A variational treatment based on configurational entropy gives a good description of the late-time density distribution in stratification-confined buoyant turbulence. Similar processes apply to other phase spaces, e.g. quantum level populations.

MAGNETO-HYDRODYNAMICS

Linear analysis of magnetohydrodynamic Richtmyer-Meshkov instability in converging geometry

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Richtmyer-Meshkov instability (RMI) occurs when an incident shock impulsively accelerates the interface between two different fluids. RMI is important in many technological applications such as Inertial Confinement Fusion and astrophysical phenomena such as supernovae. It is well established that RMI is suppressed by an externally applied seed magnetic field. An analytical solution of incompressible 2-D magnetohydrodynamics (MHD) RMI of an impulsively accelerated interface with a finite magnetic field normal to the interface was investigated by Wheatley et al. [1]. It was found that although the initial growth

rate of the interface is unaffected by the presence of magnetic field, the late-time amplitude of the interface asymptotes to a constant value. On the other hand, for a transverse magnetic field [2] the amplitude of the interface oscillates in time. In cylindrical geometry, we will present an analytical investigation in to the behavior of an impulsively accelerated interface separating conducting fluids of different densities. We investigate the influence of radial/azimuthal magnetic field on the growth rate of the interface. This is accomplished by solving the linearized initial value problem using numerical inverse Laplace transform. In converging cylindrical geometry, the RMI is followed by a Rayleigh-Taylor (RT) phase. Our analysis does not account for the RT phase of the instability but is valid for the duration of the RMI phase. We compare results of the incompressible analysis with linear compressible MHD simulations.

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Is helicity everywhere or nowhere? The case of rotating stratified magnetohydrodynamic turbulence

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In homogeneous rotating turbulence, local turbulent patches, snapshots, or special flow realizations containing helicity are often observed in direct numerical simulation (DNS) studies. Nonetheless, the rise of statistically significant helicity spectrum is never found in the absence of ad hoc initialization or forcing. Even when considering weak turbulence propagating from a blob, or cloud, of vorticity [1], coexisting pairs of inertial waves with opposite polarities yield exactly zero helicity. On the other hand, spontaneous generation of kinematic helicity in rotating turbulence is only found in the presence of solid boundaries [2]. In the presence of coupled effects, as in rotating stably stratified turbulence, helicity is not a conserved quantity, and the creation of net helicity can be expected [3,4]. This spontaneous generation is not confirmed by a study of baroclinic turbulence, with an accurate control of finite-size-box effects, which includes mean shear in addition to stratification and rotation [5]. In the latter context, one can however introduce a statistical quantity similar to MHD cross-helicity [6], and show a significant preference for positive cross-helicity related to a new alignment mechanism [5]. What happens for actual MHD turbulence and `true' cross-helicity? Rotating MHD with mean magnetic field [7] gives a new scenario for creating net 'bulk' (without explicit boundaries or artificial forcing) helicities (cross-helicity, then magnetic and kinetic ones): a subtle interplay is found between linear effects of magneto-Coriolis waves and nonlinearity of the Lorentz force in MHD equations. DNS of homogeneous MHD turbulence are in progress for quantitative results. Theoretical analysis is based on anisotropic Lin-type equations for all angle-dependent spectra.

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On cascade reversal in extended MHD

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There has been a great deal of attention in recent times focused on plasma turbulence at "small" scales, i.e., scales smaller than the electron/ proton gyroradius (or skin depth). The two most notable examples in astrophysics are the Earth's magnetosphere and the solar wind, respectively. To gain the relevant understanding it is necessary to work with models such as extended MHD (XMHD) that captures the microscopic effects of Hall drift and electron inertia. The model is endowed with topological invariants – two helicities which can be determined through the Hamiltonian Energy-Casimir method. We have computed dissipation rates for the helicities and showed [1] that in the limit of infinite Reynolds number, the dissipation rates vanish when the Beltrami conditions are satisfied. Previous investigations of MHD exhibited curious behaviour of the inverse cascade of magnetic helicity: the latter flowing to large scales. Inverse cascade is often invoked to explain the dynamo, a mechanism for large-scale generation and maintenance of magnetic fields, such as the Earth and Solar magnetic fields. However, we have shown [1] analytically that the inverse cascading at the electron skin depth is suppressed. It happens at a microscopic scale relevant when electron inertia becomes dominant where it appears that the cascade reverses direction. The criticality of the transition has not been investigated yet, as approximations were used. Naturally, results still require confirmation in numerical simulations and observations/experiment. Our ongoing investigations focus on a simplified 2D case, which is more amenable to numerical analysis. The preliminary analytical queries reveal similar behaviour to 3D cascade reversal so we are confident that 2D case study can be representative.

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Singularity formation in gas-dynamic and fast magnetohydrodynamic shocks

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New results on the nonlinear dynamics of plane propagating gas-dynamic and fast magnetohydrodynamic (MHD) shocks are discussed [1]. Using a pseudo-spectral numerical method applied to the full equations of geometrical shock dynamics (GSD) for both gas-dynamic shocks and fast MHD shocks in a neutral plasma in the presence of a uniform, upstream magnetic field, numerical evidence is presented supporting the hypothesis that a smooth initial perturbation to either a planar gas-dynamic shock or a planar fast MHD shock in a neutral plasma will lead to the production of a shock-shock, or shock wave traveling along the shock, in a time inversely proportional to the initial perturbation amplitude. This corresponds physically to the spontaneous formation of a triple point following a perturbation of arbitrarily small amplitude. For gas dynamic shocks, a spectral-based, a closed-form solution of the equations of GSD is discussed that predicts the time to loss of analyticity in the profile of an initially perturbed planar shock for both strong and weak shocks. This is equivalent to singularity formation on the shock profile. Following an initial spatially periodic but arbitrary continuous perturbation, the shock shape remains analytic only up to a finite, critical time that is also inversely proportional to the initial perturbation amplitude. The relation between this critical time and the numerical detection of the time to formation of shock-shocks will be discussed. It is also shown that this analysis can also be applied to strong, fast MHD shocks in the presence of an external magnetic field parallel to the unperturbed shock.

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Stably and unstably magnetized stratified weak wave turbulence

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Unsteady turbulence in stably and unstably stratified-magnettized flow is analysed using the linear spectral theory. In this work we investigate the energy partition, scale by scale, in Magnetic Archimedes weak wave turbulence for a Boussinesq fluid. Complete linear solutions for the spectra are obtained analytically, and their characteristics, including the short- and long-time asymptotic, are examined in detail. For stably stratified magnetized turbulence, it has been found that at small scales, such that (k >> 1), the ratio of the buoyancy energy spectrum Sp(k,t) to kinetic energy spectrum Sk(k,t) behaves like 1/k, and the ratio Sk(k,t)/Sm(k,t) is equal to the unit, while at large scales, there is an equipartition of energy between kinetic and magnetic components. For unstably stratified magnetized turbulence, at large scales, the ratio Sp(k,t)/Sm(k,t) behaves like k^(-2), while at small scales, this ratio is constant. We conclude that the instabilities generate the phenomenon of dilution of the magnetic energy, which is proposed as a possible mechanism to heat the Sun's corona to millions of degrees by transporting energy from the photosphere into the diffuse corona.

Experimental study of heat transfer enhancement in liquid metal by rotating magnetic field

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This study focuses on some applied aspects of flow of electrically conducting liquid such as liquid metal (LM) under the influence of electromagnetic force known as Lorentz force. The research focuses on benefits for nuclear applications of the MHD phenomena, such as a rotating magnetic field (RMF) which generates a rotating motion of LM. The mentioned phenomenon is used for two different purposes: transportation of LM by MHD pumps and amplification of heat and mass transfer. In the current project we study, on the one hand, (a) the designing of a helical induction MHD pumps, and on the other hand, (b) utilization of a RMF for heat transfer enhancement. Particularly: (1) A small scale prototype pump built specifically for experimental research in order to test and verify the theoretical formulas derived for the design of a large scale model that will be built in the following steps of this project. The pump will be installed in a neutrons production facility, currently under development, for radiotherapy applications. (2) Beam of protons with high kinetic energy hits the LM target, the protons are absorbed in the LM and their kinetic energy is converted to heat. Extremely concentrated heat release causes high temperatures in the LM and leads to non-homogenous temperature distribution. The irradiated target face is covered by thin vulnerable metallic foil. Insufficient heat dispersion results in high temperature gradients on the foil's surface which may cause significant damage to the foil and to the whole target. To resolve this problem, the use of RMF was suggested in order to produce turbulence flow of the LM and to force heat convection resulting in a more homogenous distribution of the LM temperature on the irradiated surface. The results of the numerical simulation based on the analytical model have been verified by the experiments results.

Heat transfer enhancement in liquid metal targets by rotating magnetic field

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High heat flux removal is an acute and challenging problem in the design of the liquid metal (LM) targets for production of radioisotopes for medical applications. This problem is considered one of the major obstacles in the development of such targets for linear proton accelerator. An insufficient heat removal may cause significant damage to the target, such as cracks in the target material. The radio-isotope production targets are designed for high specific activity of small amount of the produced material which does not make it possible to use external circulation system for LM mixing inside the target. Thus, nonintrusive methods for enhancing the heat transfer have to be explored. The rotating magnetic field was used for this purpose. Analytical approximate solution for the rotating magnetic field has been developed and used in parametric study and optimization of the inductor design. Additionally, the rotating magnetic field was computed by the commercial code ANSYS MAXWELL and plugged into the ANSYS FLUENT code as a user defined function. Different simulations were conducted in order to test the dependence of the LM flow and temperature distribution on the parameters of rotating magnetic field. The main goal was to obtain a maximum flow circulation in the region exposed to high heat flux and the maximum reduction of the fluid temperature due to highest turbulent mixing.

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Evolution of structures during electric explosion of conductors

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During the electric explosion of conductors complex structures with very different spatial scales are formed. It is known that at nanosecond electric explosion of micron wires, the substance can be at the same time in different states: inner layers are the dense weakly conducting core, and outer layers are the hot plasma corona. The parameters of the substance in them are significantly different, respectively, the instabilities leading to the formation of structures in the core and corona, develop in different ways. Dense core at the time of formation of a plasma corona can be in the liquid state. When the current is redistributed into the corona formed from the outer layers of the wire, the magnetic pressure that compresses the material to the axis of the wire is reduced. Compressed matter begins to expand intensively; this can lead to the fact that the substance of the liquid core falls into an extended metastable state, which will then decay into a stable two-phase state of droplet-vapor [1]. In the process of this disintegration, various structures appear: small droplets, pieces of the liquid shell destroyed at development of the instabilities. At the same time, various modes of MHD instabilities develop in the plasma corona [2]. It is difficult to model such processes in the electric explosion of a single wire, because they vary greatly in both of spatial and temporal scales. Much more scales vary during the implosion of wire assemblies when a submicrosecond current pulse flows through them.

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Anisotropic particle diffusion in field-guided magnetohydrodynamic turbulence

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Magnetohydrodynamic (MHD) turbulence with a background magnetic field is relevant to many astrophysical processes such as solar wind transport. We investigate how a mean guided-field alters the Lagrangian transport of tracer particles in MHD turbulence. We find that the mean-squared-displacement grows linearly with time, indicating a diffusive behavior. As the strength of the guided-field increases, the diffusion becomes anisotropic with larger diffusivity in the field-parallel direction. Interestingly, associated with such transition are changes in the behavior of the Lagrangian velocity correlation function. The Lagrangian velocity decorrelation time exhibits a power-law scaling with the root-mean-squared velocity. The scaling exponent shifts from -1 to -2 as anisotropic diffusion develops in the system, signalling a switching from the hydrodynamic-like regime to the weak MHD turbulence regime of interacting Alfven waves.

PLASMAS

Ohms law and the collision of magnetic flux ropes

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Magnetic flux ropes are bundles of twisted magnetic fields and their associated current. They are common on the surface of the sun (and presumably all other stars) and are observed to have a large range of sizes and lifetimes. They can become unstable and resulting in coronal mass ejections that can travel to earth and indeed, have been observed by satellites. Single and multiple flux ropes have been reproducibly generated in the LArge plasma device (LAPD) at UCLA. Using a series of novel diagnostics the following key quantities, B, Vp, u, n, Te (u is the plasma flow and Vp the plasma potential) have been measured at more than 48,000 spatial locations and 7,000 time steps. The construction and deployment of the diagnostic probes conditional averaging techniques and calculation of relevant quantities will be presented. From these measurements,the total electric field,plasma currents, pressure, the magnetic Helicity, and Qusai Seperatrix Layer (QSL) are derived from the data. Every term in Ohm's law is evaluated across and along the local magnetic field and the plasma resistivity derived. Ohms law does not yield a physically meaningful resistivity and the data meets a condition for non-local. The Kubo AC conductivity, at the flux rope rotation frequency, is evaluated will be presented. This yields meaningful results for the global resistivity. The temporal variation of helicity transport into the QSL is used to calculate the resistivity in the narrow reconnection region. The contribution to the power density, J x E from the region in which reconnection occurs is compared to heating in the current channels. Time domain structures (spiky electric fields) are observed to move from the reconnection region to the edges of the current channels.

Turbulence spreading and avalanch dynamics in fusion plasmas

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Transport in magnetized plasmas in fusion devices such as tokamaks is usually modeled by diffusive process caused by linearly unstable local turbulence. However, there exists a variety of phenomena from experiments and simulations which cannot be explained by those simple models. Outstanding examples include turbulence spreading from linearly unstable zone to the stable zone and avalanch-like transport events which possess characteristics of self-organized-critical systems. This presentation will review direct numerical simulation results, simple theoretical models, and their implications for future fusion devices' performances.

Laser generated Richtmyer-Meshkov and Rayleigh-Taylor instabilities and nonlinear wave-vortex paradigm in turbulent mixing

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Three-dimensional Richtmyer-Meshkov (RM) and Rayleigh-Taylor (RT) instabilities generated by the laser pulse of Gaussian-like power profile on metal target with multimodal initial perturbation in the semiconfined configuration (SCC) have been studied. The SCC enables extended lifetime of a hot vapor/plasma plume to the microsecond scale and formation of the fast multiple reshocks. The RMI/RTI structures stay frozen permanently after pulse termination making possible a posteriori study. The RMI/RTI morphology is different in the Central Region (CR) and in the Near Central Region (NCR) of Gaussian-like spot. In the CR, the shock ($P \sim 1.2$ GPa, Mach $\lesssim 5$) causes formation of irregular web with RMI jet-spikes at the nodal points. Jet spikes generated by strong shock are broken up leaving small remnants and random set of collapsed bubbles. Development of 3D turbulent mixing layer represents unsteady stochastic process which causes pressure pulsations and generates small-scale structures near the nodal points of the web. In the NCR the RMI is followed by the reversal of pressure and density gradients causing the RT instability and the evolution of damped, spherical and ellipsoidal mushroom-shape spikes. Density interface is transformed into the large-scale, quasi-periodic web with RTI mushroom spikes and the coherent structures - line solitons and vortex filaments which make polygonal “walls”. The change of morphology results from decrease of the Atwood number A from the CR ($A \sim 1 – 0.8$) to the NCR ($A \sim 0.8 - 0.6$) and of the momentum transfer from the maximal $M \sim M\text{max}$ (CR) to $M \sim (0.60 - 0.70)$ Mmax (NCR). Instead of the stochastic small-scale structures, the NCR shows formation of chaotic, large-scale, low-mixing wave-vortex ones.

The dynamics of 2D turbulence in magnetically confined tokamak plasmas and statistical properties of the resulting transport

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The large temperature and density gradients present in magnetically confined high-temperature fusion plasmas provide free energy that drives electrostatic and electromagnetic turbulence. The resulting turbulent transport convects and mixes particles, energy and momentum at rates that typically vastly exceed that from neoclassical collisional processes alone. The interface region between the magnetically confined closed flux surfaces and open field lines presents a unique and specific challenge due to exceptionally large gradients, complex geometry, and strongly driven turbulence and other instabilities. The magnetic field direction in a fusion system defines a nearly ignorable coordinate, with the primary turbulent transport dynamics occurring at small scales perpendicular to the confining field. This long-wavelength turbulence is measured in the crucial 2D radial and poloidal (perpendicular to the field) directions using collisionally-excited fluorescence of a hydrogenic heating neutral beam whose intensity is proportional to local density with a Beam Emission Spectroscopy diagnostic on the DIII-D tokamak, allowing for direct imaging of turbulent density fluctuations. Application of spatiotemporal velocimetry image analysis techniques to the radially and poloidally resolved measurements allows for extraction of the trajectory of turbulent eddies and inference of critical dynamical properties, such as radially-sheared poloidally-symmetric flows, Reynolds stress, and density transport via correlated density and flow fluctuations. Fast poloidal velocity analysis indicates the presence of radially sheared flows that have been shown to mediate the saturated turbulence amplitude. Statistical parameters will be compared with simulations to better understand and validate them. Understanding and predicting the behavior of turbulence is crucial to developing fusion energy systems, wherein the confinement and performance are limited by turbulent transport.

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Turbulent thermal mixing in multiple interacting magnetised electron temperature filaments

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Results are presented from basic heat transport experiments and numerical simulations of multiple magnetized electron temperature filaments in close proximity. This arrangement samples cross-field transport from nonlinear drift-Alfven waves and large scale convective cells. Experiments are performed in the Large Plasma Device at University of California. The setup consists of three biased CeB6 crystal cathodes that inject low energy electrons (below ionization energy) along a strong magnetic field into a pre-existing large and cold plasma forming 3 electron temperature filaments embedded in a colder plasma, and far from the machine walls. The cathodes are mounted on separate probe drives for variable positioning and each have a separate power supply that allows for individual DC voltage biasing capabilities. A triangular spatial pattern is chosen for the thermal sources and multiple axial and transverse probe measurements allow for determination of the cross-field mode patterns and axial filament length. It has previously been reported that single thermal filaments exhibit spontaneous excitation of thermal waves [1], and that the temperature gradient drives drift-Alfvén waves that lead to enhanced cross-field transport [2]. We have characterized these waves on an individual filament when a single source is activated. When the 3 sources are activated, and in close proximity, a complex wave pattern emerges due to interference of the various wave modes on each filament, thus leading to turbulent thermal mixing and enhanced cross-field transport. Detailed eigenmode analysis of the tri-filament configuration and comparison with nonlinear gyrokinetic simulations of will be reported.

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Time domain structures in a colliding magnetic flux rope experiment

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In general, plasmas in space are neither featureless nor Maxwellian. Satellites have observed density depressions and enhancements both along and across ambient magnetic fields that occur on vast spatial scales. Sometimes, concomitant with these features are Time Domain Structures (TDS), which are packets of intense electric field spikes that have significant components parallel to the local magnetic field. The TDS are frequently observed in studies of auroras, planetary magnetospheres and laboratory experiments, and they include various forms such as double layers and electron phase space holes, which are regions of positive potential that are on the scale of the Debye-length. In addition, various non-linear processes such as instabilities and parametric wave processes may give rise to different kinds of TDS. In an ongoing investigation at UCLA, TDS were observed on the surface of two magnetized flux ropes produced within the Large Plasma Device. A barium oxide (BaO) cathode produced a 18 m long magnetized plasma column and a lanthanum hexaboride (LaB6) source created two 11 m long kink-unstable flux ropes. Using two probes capable of measuring the local electric and magnetic fields, statistical analysis was performed on tens of thousands of these structures, and we present their propagation velocities, wavenumber spectrum, probability distribution function and spatial distribution. The TDS become abundant as the flux ropes collide and appear to emanate from the reconnection region in between them. In addition, a preliminary analysis of the permutation entropy and statistical complexity of the data suggests that the TDS signals may be chaotic.

This work is performed at the US Basic Plasma Science Facility, which is supported by the US Department of Energy and the National Science Foundation.

Nonlinear interactions of kink-unstable flux ropes and shear Alfven waves: creating smaller-scale structures from larger ones

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Magnetic flux ropes and shear Alfven waves occur simultaneously in plasmas ranging from solar prominences, to the solar wind, to planetary magnetospheres. If the flux ropes evolve to become unstable to the kink mode, interactions between the kink oscillations and the shear waves can arise, and may even lead to nonlinear phenomena. Experiments aimed at elucidating such interactions are performed in the upgraded Large Plasma Device at University of California, Los Angeles. Flux ropes are generated using a 20 cm x 20 cm LaB6 cathode-anode discharge (with L = 18 m and plasma beta ~ 0.1.) The ropes are embedded in an otherwise current-free, cylindrical (r = 30cm) ambient plasma produced by a second, BaO cathode. Shear Alfven waves are launched using externally fed antennas having three separate polarizations. The counter-propagating, kink-unstable oscillations and driven shear waves are observed to nonlinearly generate sidebands about the higher, shear wave frequency (evident in power spectra) via three-wave coupling. This is demonstrated though bi-coherence calculations and k-matching. With a fixed kink-mode polarization, a total of six daughter wave patterns are presented. Energy flow is shown to proceed from larger to smaller perpendicular wavelengths. Future work will focus on increasing the plasma beta and wave amplitudes in the quest to observe an evolution to a turbulent state.

The work is performed at the US Basic Plasma Science Facility, which is supported by the US Department of Energy and the National Science Foundation.

PHYSICS of ATMOSPHERE

Propulsion generated by diffusion-induced flows on a plate and a wedge

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Spatial non-uniformity of density distribution in non-homogeneous media produces molecular diffusion flux which, as broken on an impermeable motionless obstacle, initiates specific fluid motions, or so-called diffusion-induced flows on topography. Such flows are a wide-spread phenomenon in biology, medicine, and environmental systems, since diffusion-induced flows inevitably occur in any non-homogeneous media, including different solutions, suspensions, mixtures, etc. Study on diffusion-induced flows around obstacles is based on the fundamental equations set which is solved numerically in the full nonlinear formulation using finite volume method. The numerical simulation reveals a complex multi-level vortex system of compensatory circulating flows around a motionless obstacle, which structure is strongly dependent on position of a body relative horizon. The flow structure and dynamics is analyzed around motionless obstacles immersed into a stably stratified medium, including a sloping plate, a wedge-shaped obstacle, a disc, and a circular cylinder. The most intensive and extended high-gradient horizontal interfaces are attached to sharp edges or poles of obstacles and are clearly observed in the both numerical computations and laboratory experiments. The numerical results obtained are compared with the available analytical and experimental data. Diffusion-induced flows form intensive pressure deficiency zones around an obstacle, which may lead to generation of propulsion mechanism resulting in self-movement of neutral buoyancy bodies in a continuously stratified fluid, e.g. horizontal movement of a wedge, rotation of a sloping plate, etc. The diffusion-induced flow structure and dynamics are studied for different geometric parameters of a wedge and a plate. This allowed to find optimal values for opening angle, length and curvature of the wedge and thickness, length and sloping angle of the plate, which provide the most intensive propulsion.

Helicity distribution in convective vortical flows

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Experimental and numerical study of the steady-state cyclonic vortex from isolated heat source in a rotating fluid layer was carried out. The structure of laboratory cyclonic vortex is similar to the typical structure of tropical cyclones. Here we focused our attention on differential characteristics of the convective flow, mainly helicity which is a scalar production of velocity and vorticity vectors. Helicity is an invariant and its generation or conservation may change energy cascade in a developed turbulent media. The problem of helicity of turbulent flows is very complex for studying because it requires measurements of 3D velocity field in a volume or high-resolution numerical modelling. Even realization of the flow with substantial value of helicity is a complicated problem. Here, we consider helicity in a laboratory hurricane-like vortex. The flow in our experimental system is not fully turbulent but the structure of large-scale flow with high correlation of vertical vorticity and vertical velocity is very promising for helicity formation. Helicity distribution in rotating fluid layer with localized heat source was analysed. Two mechanisms which play role in helicity generation were found. The first one is the strong correlation of cyclonic vortex and intensive upward motion in the central part of the vessel. The second one is due to large gradients of velocity on the periphery. It was shown that besides of these mechanisms there is one more factor that can be a crucial part in helicity generation. It is a system of secondary flows appearing over the heating area. The integral helicity in a considered case is substantial and relative level of helicity is high. It proves that chosen configuration is very promising and requires further detailed studies for a wide range of governing parameters.

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Turbulence in rotating fluids and the Nastrom & Gage spectrum

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An analytical theory of turbulence, the quasi-normal scale elimination, has been developed for neutrally stratified rotating flows. The theory provides near-first principle framework for the representation of flow anisotropization under the actions of rotation. The anisotropization reveals itself in the emergence of different eddy viscosities and eddy diffusivities in different directions and directional dependence of the kinetic and potential energies spectra. In addition, there are also phenomena of componentality (eddy viscosities are different for different velocity components resulting in the existence of 4 different eddy viscosities) and the onset of the inverse energy cascade. The anisotropization increases with increasing scale. The characteristic scale for the crossover between the turbulence and inertial wave domains is the Woods scale which is analogous to the Ozmidov scale in flows with stable stratification. Rapid rotation renders the horizontal eddy viscosity negative, and in order to preserve it positive, a weak rotation limit is invoked. Within that limit, an analytical theory of the transition from the Kolmogorov to a rotation-dominated turbulence regime is developed. The dispersion relation of linear inertial waves is unaffected by turbulence while all one-dimensional energy spectra undergo steepening from the Kolmogorov -5/3 to the -3 slope. The longitudinal and transverse spectra are congruent with the famous atmospheric spectra by Nastrom & Gage. Thus, for the first time, these spectra are derived within an analytical theory. The theory explains the latitudinal dependence of the spectra and other aspects and lends itself for practical applications in simulations of atmospheric and oceanic flows as it produces closed expressions for the eddy viscosities and eddy diffusivities. It will also be shown that the Nastrom & Gage spectra apply to the oceanic flows as well.

Determination of size and concentration of water droplets in experiments with Wilson chamber

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The processes of water evaporation and condensation play a defining role in many atmosphere phenomena. Kinetics of condensation determines the character of the development of such phenomena as thunderstorms and tornado. An experimental facility based on Wilson chamber was constructed for experimental verification of theoretical models of condensation processes. The chamber in the installation differs from the original one by the way of air expansion: air expands in the atmosphere with initially elevated pressure instead of expanding in the vacuum. Visual supervisions of the condensation process permitted to suppose that the higher initial pressure in the chamber is, the more drops are in the volume unit, and the less their size is. The size and concentration of drops are calculated according to the results of measuring of temperature inside the chamber and weakening of the detector signal that registered the dispersion of laser ray by drops. The circuit for the dynamic temperature measurement consisting of amplifier thermocouple, precision operational amplifier and two thermocouples chromel-alumel was developed. Research of the dependence of thermal inertia index of thermocouple diameter was held and the technology of application of thin thermocouples in the experiments was worked off using this circuit. The size and droplets concentration that condensed in the chamber were investigated. To confirm the obtained results the droplets that condensed inside the chamber were registered by photo projection method. This method allows to register the particles with a size of 5,6 micron and more. The obtained data are used for verification of the theoretical model of the kinetics of condensation.

Towards a solution of the closure problem for convective atmospheric boundary layer turbulence

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We consider the closure problem for turbulence in the dry convective atmospheric boundary layer (CBL). Transport in the CBL is carried by small scale eddies near the surface and large plumes in the well mixed middle part up to the inversion that separates the CBL from the stably stratified air above. An analytically tractable model based on a multivariate Delta-PDF approach is developed. It is an extension of the model of Gryanik and Hartmann [1] (GH02) that additionally includes a term for background turbulence. Thus an exact solution is derived and all higher order moments (HOMs) are explained by second order moments, correlation coefficients and the skewness. The solution provides a proof of the extended universality hypothesis of GH02 which is the refinement of the Millionshchikov hypothesis (quasi-normality of FOM). This refined hypothesis states that CBL turbulence can be considered as result of a linear interpolation between the Gaussian and the very skewed turbulence regimes. Although the extended universality hypothesis was confirmed by results of field measurements, LES and DNS simulations (see e.g. [2-4]), several questions remained unexplained. These are now answered by the new model including the reasons of the universality of the functional form of the HOMs, the significant scatter of the values of the coefficients and the source of the magic of the linear interpolation. Finally, the closures predicted by the model are tested against measurements and LES data. Some of the other issues of CBL turbulence, e.g. familiar kurtosis-skewness relationships and relation of area coverage parameters of plumes (so called filling factors) with HOM will be discussed also.

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On sheared wind-driven air-shallow water turbulent boundary layers using LES

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We consider the canonical case of a turbulent Couette boundary layer flow driven at the interface by the transient traction generated by a Poiseuille turbulent boundary layer above, where such interface is formed between two highly stratified fluids, at a Reynolds Number of 171. Similar cases have been studied [1], although for boundary layers of only one type (Couette or Poiseuille), whereas here we study an intermediate configuration that can serve as an archetype in applied disciplines. This particular configuration is more likely to be of interest in physical oceanography and limnology, and physical meteorology, since it represents a large class of environmental flows that interact through a sheared interface, i. e. wind-driven circulations in the ocean. Numerical experiments using LES show a thinning of the Couette-type boundary layer due to the increased Reynolds stress interaction at the flat interface. Furthermore, the larger near-interface streaks produced at the Couette flow are passed to the wall-like Poiseuille boundary layer, where they seem to persist over the vertical. This enforces the notion that near-interface behavior on the ABL is dominated by coherent structures emanating from the interface in the denser fluid side, i. e. the ocean. Despite this, first-order and second-order statistical moments in the Poiseuille boundary layer remain largely unaltered compared to wall-bounded turbulence due to the fluid's lower inertia. On the other hand, large discrepancies are seen in the Couette boundary layer statistics when compared with canonical cases in literature. Numerical simulations using higher values of Reynolds number should elucidate the role of the elongated Couette streaks on the Poiseuille flow above it.

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Relaxation from rotation and what it reveals about turbulence physics and modeling.

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It is well known that external rotation inhibits the energy cascade and results in reduced decay rates for the turbulent kinetic energy. Less well known is how rotated turbulence behaves after the system rotation is stopped. This work is a variation on the familiar return-to-isotropy experiments that look at the behavior of strained turbulence after the strain is removed. But rotation is particularly revealing (compared to strained turbulence) because rotation produces almost no anisotropy in the Reynolds stresses (velocity fluctuations) and only produces anisotropy in the two-point correlations (turbulent length scales). In this work, direct numerical simulations of physically initialized isotropic turbulence at a variety of Reynolds numbers and rotation rates are used to explore the relaxation-from-rotation problem. We show that immediately after rotation ends, decaying turbulence has an exponential decay law. Exponential turbulent decay is unusual. All other turbulent decay process obey a power-law. Exponential decay results from a constant turbulent timescale and its presence provides us with some useful new insights into the energy cascade process. Some implications for the modeling of the turbulent decay process are also discussed.

Simulation of turbulence mixing in atmosphere boundary layer and fractal dimension

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We analyse Atmospheric Boundary Layer (ABL) structure, using Large-Eddy Simulation (LES) in order to improve pollution topology and diffusion [1]. Many processes are highly intermittent with spiky measures and non-uniformities in Weibull PDF's. For example, distribution of turbulent kinetic energy dissipation rates is intermittent and cannot be described by typical moment methods. Therefore, a multifractal analysis is required. Multifractal dimension was applied to the results of LES and One Eddy Equation turbulence model for neutral and stable ABL in OpenFoam. The filtered incompressible Navier-Stokes equations within a rotating frame of reference were used to perform additional simulations. Boussinesq approximation for buoyancy was included with an explicit additional term [2]. The size of the numerical domain was 3000x1020x3000 m, meshes with 150x51x150, 300x102x300 cells were used. The initial conditions for the stable case were: wind speed U0=8 m/s with direction 2700, the height at which mean wind (U0) was maximum is 100 m; initial potential temperature at bottom 300 K, at top 305 K; the height of the middle of the inversion was 750 m; the initial turbulent kinetic energy 0.1 m2 /s2; the potential temperature gradient above the inversion was 0.003 K/m. The Prandtl number is 0.7, the turbulent Prandtl (or Schmidt) number 0.33, molecular viscosity 1.0E-5 m2/s, and latitude of the Earth 41.30 degree. Fractal objects are irregular in shape but their irregularity is similar across many scales, and we applied these advances in fluid visualization as SFIV [3]to investigate different scale to scale properties of flow through iterative box-counting algorithms for different values of velocity and vorticity. Multifractal techniques were used to evaluate intermittency and structure functions [4]. Maximum fractal dimension D(RI) as a function of Richardson's number, selected among velocity and vorticity modules which is a good indicator of the flow's complexity.

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Single-particle dispersion in stably stratified turbulence

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One of the main properties of turbulent flows is the efficiency to transport and mix quantities advected by the fluid. In particular, in stratified turbulence, a proper understanding of transport processes is relevant, e.g., to correctly model the diffusion of pollutants in the atmosphere, the suspension of cloud droplets, and hail formation. In these flows the presence of restitutive forces associated with the stratification allow excitation of internal gravity waves, which interact between themselves and with eddies, modifying the dynamics and, in particular, the transport of particles. We performed simulations of stably stratified turbulence with Lagrangian particles, varying the Brunt-Väisäla frequency (corresponding to the frequency of internal gravity waves, and associated with the degree of stratification of the fluid), and the external mechanical forcing. We show that the Lagrangian vertical velocity spectrum is compatible with a Garrett-Munk spectrum, as observed in the ocean, and with a maximum in the frequency of internal gravity waves. This spectrum can be explained from the statistics of waiting times considering that vertical motions are dominated by internal gravity waves. We also derive a simple model for the evolution of the probability density function of particle displacements in the horizontal direction, using a continuous random walk model that also takes into account the presence of horizontal winds in the flow.

Energy and mass turbulent fluxes in a salt marsh in southeastern South America Argentina

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Salt marshes are coastal wetlands located in preferential areas for urban settling which therefore are vulnerable. They produce great amount of biomass, and also are of great interest because of the ecosystem services they provide. Among these services the carbon storage stands out. In my work I intend to study the energy and mass turbulent fluxes between an ecosystem and the atmosphere. I particular I have been working in a salt marsh located in southeastern Buenos Aires province (Argentina) and characterized its net ecosystem production. A field campaign was carried out from February 2014 to March 2015. Sensible heat, water vapor (H2O) and carbon dioxide (CO2) fluxes were measured with eddy covariance technique at 6m height over a Spartina densiflora canopy. Fifty five percent of data were lost due to equipment malfunction, data screening and a freshwater flood that prevent field access. A combination of gap filling techniques allowed estimating monthly

mean values of net ecosystem exchange, gross primary production and ecosystem respiration. Latent heat fluxes during December consumed up to 85.6% of the available energy possibly due to the flooding event. Pre-flooding conditions produced a sensible heat flux reversal at the end of winter when the air was slightly warmer than the soil. Unlike other environments, this southern salt marsh behaved as a CO2 sink throughout the year. The net ecosystem production from March 2014 to February 2015 was approximately -15 ton of CO2 ha-1 yr-1 which is greater than reported results for other wetlands. These preliminary results are the first ones reported in the Southern Hemisphere for S. densiflora salt marshes.

Analysis of flow structural elements around obstacles in thermodynamically non-equilibrium media

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Due to combined effects of medium inhomogeneity and action of external forces, i.e. Earth's gravitation, electro-magnetic forces, global rotation, etc., a stable stratification is formed. In a stratified fluid, known to be a thermodynamically non-equilibrium system, molecular diffusion flux of a stratifying agent always exists in direction opposite to vector of an external force. When encountering an impermeable surface, the diffusion flux is broken, that results in a substance redistribution and extensive mixing processes. At the same time, under action of buoyancy force, fluid particles, assigned initially to their own horizons, start oscillating around the initial positions when disturbed. All the effects mentioned give rise to a number of specific fluid motions which are wide-spread phenomena in the environmental and life systems. The stratified flow structure around a sloping plate is analyzed numerically for different angles of its inclination in a wide range of Reynolds numbers. The flow structure is classified into typical flow regimes, depending on prevailing structural components in the flow, such as vortices, which are common for all kinds of fluids, and internal waves, upstream perturbations, and thin interfaces, which are specific for stratified media. The analysis starts from ultra-slow diffusion-induced flows, when a complex multi-level vortex system of compensatory circulating flows are formed around motionless obstacles, up to complex, multiscale and essentially transient flows at relatively high Reynolds numbers, when the physical process is accompanied by mutual interactions between large and fine scale flow components and the free stream, which are characterized by their own geometries, spatial and temporal scales, manifestation level, and dissipation rate. The calculated flow patterns are compared with exact solutions of the analogous linearized problem and Schlieren images of stratified flows around both motionless and moving obstacles.

GEOPHYSICS and EARTH SCIENCE

Circulation in the atmospheres of gas giant planets and in the Earth's outer core due to small-scale convection

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Theoretical and experimental results showing that a small-scale convection generates a large-scale circulation on the rotating planets are presented. A key feature of the convection is a misalignment of the buoyancy force acting on the buoyant parcels and the direction of the planetary rotation. The resulting large-scale circulation has two components, namely a geostrophic thermal wind and an ageostrophic flow which occurs due to the component of buoyancy perpendicular to the rotation axis. A theoretical model is offered to explain the observed cyclonic offset in the atmospheric circulation of Saturn and Jupiter. The model predicts the equatorial jet as well as oppositely flowing jets at the flanks of the equatorial one. When applied to the Earth's outer core composed of convecting liquid metal, the model predicts a westward flowing jet at the tangent cylinder. The existence of this jet was previously demonstrated by the observations of the change in Earth's magnetic field - the secular variation. Laboratory experiments on the rotating table where an altimetric imaging velocimetry was used in parallel with a particle imaging velocimetry and thermal measurements of the surface temperature field showed multiple cyclonic and anticyclonic vortices generated by convection. The vortices are dynamically similar to those observed in the spacecraft images of Jupiter and Saturn. Similar to the planetary vortices, the laboratory ones are embedded in the circumpolar circulation which also includes alternating zonal jets.

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Gas flow in unconventional gas reservoirs using space fractional transport models

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A one-dimensional fractional transport model for the flow of gas in unconventional gas reservoirs using space fractional derivatives is developed [1,2]. The apparent velocity U and the apparent diffusivity D are functions of the pressure and the pressure gradient and other parameters such as the porosity and permeability. Using an implicit finite volume method that we have developed, we investigate numerically different models for U and D, and a parametric study for each such model for a range of fractional derivative alpha is carried out. We match the results against experimental data from pressure pulse decay tests through shale rock core samples to obtain best estimates for rock properties. We compare with the results from the conventional model developed by the authors [3]. Key questions that we address are, can fractional models reproduce the experimental results? If so, can simplified models for U

and D perform well? What are the optimal range of fractional derivatives that perform the best?

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Large eddy simulation of a marine turbine in a stable stratified flow condition

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The development of efficient renewable energy technologies is already a technological challenge for engineers and scientist all over the world. In particular, oceans and sea are a consistent source of kinetic energy that could be converted in electricity. Countries like U.S., Scotland and Great Britain began to invest considerable amount of resources for the exploitation of tidal and marine currents using marine turbines. As for the wind farms, the wakes behind the rotors cause a reduction of velocity and, as a consequence, decrease in power production [1]. Finding the optimal configuration is of huge importance in order to capture as much energy as possible. For this purpose many studies have been carried out in the field of wind farms, but even if there are a lot of analogies between the wind and the marine application, in the case of marine turbines it is necessary to take into account specific phenomena that characterize the marine environment. Among them, since the atmospheric boundary layer differs from the marine boundary layer, marine density stratification should be considered in order to represent as closest as possible the real physics of the flow. Moreover, the effect of marine density stratification is an issue that hasn’t yet been adequately investigated [2]. Large eddy simulation coupled with a model for turbines is performed in order to determine whether marine stratification could influence the downstream rotor wake, this is important for the arrangement of a cluster of turbines, since the efficiency and the energy production could be affected by this event.

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Large eddy simulation of turbulent flow in a sharp meander bend

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The knowledge of hydrodynamic of meandering rivers is a major topic in environmental engineering. It has many practical consequences, i.e. it affects the bank stability and the channel navigability, and hence it is the subject of a number of recent experimental and theoretical studies. In meanders, the flow undergoes centrifugal forces, which make the flow field highly three-dimensional. Its principal feature is a transverse inclination of the free surface which varies along the bend producing the establishment of a centrifugal secondary flow that deeply influence the flow behaviour. On the numerical side, Reynolds Averaged Navier Stokes equations are commonly in use in literature for the investigation of the meandering flows, although increasing interest is emerging in the use of Large Eddy Simulation (LES). Here we use LES to study turbulence in a sharp curved single-bend open channel flow. We take as reference the experimental work of Blanckaert [1], dealing with the interaction between the bed topography and the flow field in a strongly bent laboratory flume (193°) over an equilibrium scour bed. We start with a simplified geometrical configuration characterized by flat bed, representative of the early phase of bed erosion. In order to simulate a high Reynolds number flow, our LES model is used in combination with a wall-modelling approach. The objective of the present work is to explain the main flow and secondary flow characteristics and the role of turbulence in a sharp meandering flow. In summary, we can define the meander wave evolution essentially as the result of the combination of downstream migration and outward migration.

[1] Blanckaert K, Water Resour. Res. 46, W09506 (2010)

Turbulent boundary layer and mixing of waters of confluensing rivers

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We consider the turbulent transport near free liquid boundary where the shear stress profile is linear, which corresponds to the liquid flow downhill an inclined plane and rivers. We derive transport equations for a passive scalar in these systems. Consistent consideration of turbulent viscosity and turbulent diffusion allows one to calculate the profiles of the average flow velocity and the effective diffusion coefficient. We find that, for the dimensionless equation of diffusive transport, all the coefficients are equal to 1, if the scale of the coordinate downstream the river is by two orders of magnitude larger than that of the transversal coordinates. For the zone near free liquid boundary (where the bed does not effect the turbulent diffusion) the mixing of waters of confluensing rivers is self-similar. We obtain the self-similar solution for the concentration field of a passive admixture; this solution is valid away from the banks and bed of the river. The problem of the visual color of rivers with limited transparency is considered as well. The dependence of the width of the mixing zone on the coordinate downstream the river was found. This dependence varies from the square-root dependence, observed near the point of confluence, to the quadratic one, observed in the region where the scattering distance of light in water is small in comparison with the characteristic width of the mixing zone.

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Geostrophic turbulence and the formation of large scale structure

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Low Rossby number convection is studied using an asymptotically reduced system of equations valid in the limit of strong rotation. The equations describe four regimes as the Rayleigh number Ra increases: a disordered cellular regime near threshold, a regime of weakly interacting convective Taylor columns at larger Ra, followed for yet larger Ra by a breakdown of the convective Taylor columns into a disordered plume regime characterized by reduced heat transport efficiency, and finally by geostrophic turbulence. The Nusselt number--Rayleigh number scaling in the ultimate regime of geostrophic turbulence is predicted and confirmed using direct numerical simulations of the reduced equations. These simulations reveal that geostrophic turbulence is unstable to the formation of large scale barotropic vortices, via a process known as spectral condensation. The details of this process are quantified and its implications explored.

Neutral-plasma interactions in ionosphere: Rayleigh-Taylor turbulence, mixing and non-equilibrium wave dynamics

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Since the discovery of the plasma irregularities that occur in the nighttime equatorial F-region ionosphere, and which are revealed by rising plumes identified as large scale depletions or bubbles, considerable effort has been invested in the development of computer models that simulate the generation and evolution of the Equatorial Spread F disturbances. The combination of the effects of gravity and electric fields, in the presence of a vertical density gradient, can generate Rayleigh-Taylor (RT) plasma instability and turbulence in the nighttime F-region equatorial ionosphere. RT instabilities and turbulence cause density irregularities, which are commonly referred to as the equatorial spread F. We present statistical analysis of the amplitudes of GPS scintillations observed using the satellite radio occultation measurements of the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC). The scintillations signatures were found to be coherent with the atmospheric ultrafast Kelvin (UFK) planetary waves characterized by the zonal wind measurements. These UFK waves are as important as the solar and geomagnetic drivers in forcing the day-to-day variations of the occurrence of equatorial spread F. The results also revealed UFK wave modulations, reinforcing the importance of Kelvin waves in the coupling between the neutral and ionized atmosphere. We describe non-equilibrium effects and scintillations induced by the trapping and modulation of Kelvin waves and RT bubbles and their impacts on local ionospheric dynamics and mixing. The results on time frequencies and amplitude variations will be compared with observations.

Filtration by porous media: the role of flow disorder

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Considerable ongoing efforts aimed at understanding transport and deposition behavior (filtration) of colloids and microbial particles in porous media, have been carried forward. The reason lies on the common intent to prevent waterborne disease and enhance bio-remediation, riverbank filtration and protection of drinking water. Complex transport behaviors has been observed in many colloid transport experiment in porous media: long tailing phenomena and spatial distribution of deposited particles are two crucial aspects affecting the macroscopic transport, mixing and mixing mediated processes that are not captured by classical approach, named classical filtration theory (CFT). Cardinal point of CFT is the estimation of the attachment rate, assumed constant and empirically estimated by a posteriori fitting the data with the context of advection-dispersion theory. Stochastic approaches are also invoked to recover consistency with experimental data, but without a direct link with the processes taking place at the pore scale, where filtration takes place. In the present work we point out the role of the pore-scale flow heterogeneity in filtration process looking at two different level. At micro-scale level, both 2D particle tracking simulations and microfluidics experiment will bring out local properties of microscopic transport and filtration (attachment/detachment). To provide an upscaled view of the macroscopic filtration process we develop a Continuous Time Random Walk [1] numerical method based on the parameters directly measured via pore scale numerical simulations and microfluidics experiments.

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A reduced model for salt-finger convection in the small diffusivity ratio limit

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A simple model of nonlinear salt-finger convection in two dimensions is derived and studied. The model is valid in the limit of small solute to heat diffusivity ratio and large density ratio, which is relevant to both oceanographic and astrophysical applications. Two limits distinguished by the magnitude of the Schmidt number are found. For order one Schmidt numbers, appropriate for astrophysical applications, a modified Rayleigh-Bénard system with large-scale damping due to a stabilizing temperature is obtained. For large Schmidt numbers, appropriate for the oceanic setting, the model combines a prognostic equation for the solute field and a diagnostic equation for inertia-free momentum dynamics. Two distinct saturation regimes are identified for the second model: The weakly driven regime is characterized by a large-scale flow associated with a balance between advection and linear instability, while the strongly driven regime produces multiscale structures, resulting in a balance between the energy input through linear instability and the energy transfer between scales. For both regimes, we analytically predict and numerically confirm the dependence of the kinetic energy and salinity fluxes on the ratio between solute and heat Rayleigh numbers. The spectra and probability density functions are also computed.

COMBUSTION

Computational fluid dynamics modeling and simulation of combustion dynamics in a coal gasification process

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Carbon capture and other emission control processes are producing a vast possibility for development and implementation of clean coal technologies. Gasification is an important, clean coal technology, and numerical simulations are playing a vital role in its improvement. Various mathematical modeling techniques have been proposed and explained in the literature. In this research, an efficient numerical approach is suggested to calculate the fractions of different species because of volatile break-up during gasification. The volatile component of a solid fuel like coal consists of Carbon, Hydrogen, Nitrogen, Oxygen, and Sulfur. Mass of these elements in the evaluated species is balanced with their particular masses in the original solid fuel composition. Computational fluid dynamics simulations for gasifier is implemented comprising volatile break-up estimated using finite volume method. The reaction rates are calculated using the Finite rate/Eddy dissipation reaction model. The projected syngas composition and exit temperature are compared with the experimental results. The simulation data is within 10% of precision compared to the experimental data.

Dissipation element analysis of premixed and non-premixed turbulent flames

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The dissipation element analysis [1] is a well tested method for analyzing scalar fields in turbulent flows. Dissipation elements are defined as an ensemble of grid point whose gradient trajectories reach the same extremal points. Therefore, the scalar field can be compartmentalized in monotonous space filling regions. Dissipation elements can be described by two parameters, namely the Euclidean distance between their extremal points and their scalar difference in these points. The joint probability density function of these two parameters is expected to suffice for a statistical reconstruction of the scalar field. In addition, normalized dissipation element statistics show a remarkable invariance towards changes in Reynolds numbers and flow configuration. In the present work, dissipation element statistics of mixture fraction and temperature fields are analyzed for different flow configurations including non-premixed [2] and premixed [3] turbulent flames and non-reacting turbulent flows. Furthermore, the Reynolds number scaling of the dissipation element parameters is assessed.

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The description of the acceleration of the spherically expanding hydrogen/air flames

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A review of models for describing the acceleration of the flame front is given. It includes the power-law dependencies of the flame front position on time, fractal flame structures, flame instabilities, stretch and turbulent approaches. A series of experiments on the flame propagation in a hydrogen-air mixtures of varying composition in a cylindrical envelope of 4.5 cubic meter volume were carried out. The interpretation of the obtained results using the acceleration model of turbulent gaseous flames based on the Kolmogorov-Obukhov law identified the need to adjust this model. Model of accelerating turbulent gaseous flames based on the Kolmogorov-Obukhov law with constant specific turbulent energy dissipation rate is of a good description of the flames, accelerating according to a power law with an exponent of 1.5. Numerous experiments with different gas mixtures in the different geometry show flame acceleration with an exponent of 1.01 to 3. Modification of the model with the possibility of changes in the specific turbulent energy dissipation rate is presented. It allows the application of Kolmogorov-Obukhov approach to describe the flames accelerating by a power law with an exponent different from 1.5 [1].

[1] Golub, V.V., Korobov, A.E., Mikushkin, A.Yu., Solntsev, O.I., Volodin, V.V., International Journal of Hydrogen Energy, Available online, http://doi.org/10.1016/j.ijhydene.2017.03.177, (2017).

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Rayleigh-Taylor unstable flames: connecting local and global properties

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In this talk, we will discuss the fundamental physics of Rayleigh-Taylor (RT) unstable flames, focusing on the two properties most important to the study and simulation of Type Ia supernovae – flame speed and flame width. These properties are set by the complex interplay of the Rayleigh-Taylor instability, self-generated turbulence, burning, and the secondary Kelvin-Helmholtz instability. We know from our previous research that the flame speed is higher than the predicted Rayleigh-Taylor flame speed, and that RT unstable flames are thinner than expected. We investigate these two surprising findings by measuring local properties, like curvature and local flame width, and then using these local measurements to better understand the global flame behavior.

Mathematical modeling of adiabatic shear bands formation under dynamical loading

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Adiabatic shear bands are narrow regions of high shear deformation and appear in crystalline materials under fast dynamic loading. The process of its formation concentrates homogeneously distributed over entire material sample shear deformation in micrometer size region, which causes its high heating and strongly influences material behavior under loading. In this work we consider a mesoscopical model of material behavior under dynamical loading, which takes into account dislocations motion, twins' formation, its mutual interaction and influence of grain boundaries. This model was implemented in finite-element code LS-DYNA, what allows us to describe some experiments on dynamic loading of metals and high explosives.

Investigating flame length and time scales and flame response to oscillations using TARDIS with realistic chemistry

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Transient premixed flames expanding or contracting through inhomogeneous fuel distributions and subjected to stretch and pressure oscillations are investigated numerically using a novel direct method TARDIS (Transient Advection Reaction Diffusion Implicit Simulations) [1,2,3]. TARDIS couples the compressible flow to the comprehensive chemistry and detailed multicomponent transport properties, resolving all the time and spatial scales in the stiff thermochemical system – a 'realistic' simulation. Comprehensive chemical schemes for H2/air and for CH4/air are used to model the chemistry. The impact of increasing positive and negative stretch is investigated through the use of planar, cylindrical and spherical geometries. A key finding is that the flame speed scales non-linearly with the local stretch – different to current linear theories. Furthermore, the flame relaxation number (is the time that the flame takes to return to the mean equilibrium conditions after initial disturbance; is a flame time scale) decreases by 10% in negatively stretched contracting H2/air flames, in contrast to the two positively stretched expanding H2/air and CH4/air flames where decreased by 40% appears to much more sensitive to variations in positive/negative curvature than to the thermo-chemistry of different flame types may thus be a useful indicator of the strength of flame-curvature coupling. We explore the thermochemical structure of stretched laminar flames through simulations of eight premixed flames at atmospheric pressure and at stoichiometric mixture levels: expanding and contracting H2/air and CH4/air flames in axi-symmetric and spherical geometries. The aim is to find consistent methods of characterising the flame thickness and time scales.

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Contribution to experimental and numerical study of a full developed fire in an enclosure, with emphasis on flashover phenomenon

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A building fire generally follows three phases, ignition-growth, full-development and extinction. During these phases some phenomena can occur of which the most dreaded is flashover as perceived by firefighters. In this work, we carry out an experimental and numerical study on this phenomenon. So, a mini-room of dimensions 0.50 x 0.50 x 0.50 m with an opened door was designed and equipped with 11 temperature sensors connected to a data acquisition system (Agilent 34970A) and a probe of gas analyser (Testo 320). Two masses, 0.65 g of gas-oil and 0.62 g of kerosene, were used as fire source during the experiment. A Computational Fluid Dynamics Code, named ISIS (Fire Computation for Safety), implemented on the mathematical platform Pelicans, including some models of combustion (chemistry) like the Eddy Break-Up model and the standard k- epsilon for turbulence (mixing), is used for numerical simulations. Results show that fire with gas-oil, which lasted on average of 480 seconds, presents the three phases of fire, without reaching the Flashover level which, according to literature, occurs around a temperature of 800 K. During gas-oil experiment, the maximum released value of Carbon monoxide is about 165.8 ppm with a maximum temperature of 480 K; measured at a door's height of 0.40 m. On the other hand, fire with kerosene, which had an average duration of 240 seconds, does not present the phase of full-developed because of total consumption of fuel within the growth phase. By doubling the mass of kerosene, the flashover appears to start after 180 seconds under a temperature of 700 K with a value of CO of 407 ppm. Simulation, in conformity with the experiment, allows us to have more details on dynamics of temperature and speeds of gases inside the enclosure.

Atomistic and mesoscopic simulation of detonation initiation in porous explosives

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Sensitivity and initiation of detonation in condensed explosives by shock compression or by ultra-short laser pulse are determined by material flow and chemical reactions induced in hotspots. Molecular dynamics (MD) simulation of reactions is feasible at sub-nanosecond timescale, and it indicates that the most energetic reactions accomplish within several tens of picosecond. Different types of hotspots were found in our MD simulation of AB model explosive. Those types are categorized according to ratios between a characteristic time of reactions, an acoustic time and a time of hotspot formation. The characteristic time of reaction is determined in isochoric thermal decomposition at different densities. MD simulation of hotspot, where its formation time is the shortest, shows that a critical radius of this type of hotspots is defined by equality of reaction and acoustic time of the hotspot. A simple model of decomposition based on a local thermodynamic and chemical equilibrium approximation is developed from the picosecond time evolution observed in MD. It can be utilized in hydrodynamic simulation of real explosive with porous structure, because the microseconds required for experimental shock-to-detonation transition. Hydrodynamics modeling of AB samples by smoothed particle hydrodynamic (SPH) code are compared with MD results. A Lagrangian representation used in SPH is natural for tracking changes in material triggered by

complex flow behind an ensemble of collapsing pores. Collapse of pores and energy release in hotspots produce a fluctuating pressure field just behind a shock front.

Numerical investigation of turbulent flow through cooling channels of a PEM fuel cell with metal foam as flow distributor

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Fuel cell system is a device that uses an electrochemical reaction and converts fuels directly into electrical energy. Temperature has a significant impact on the performance of polymer electrolyte membrane (PEM) fuel cell. The electrolyte in fuel cells should be wet enough to conduct the protons well, however, the cell performance at high temperatures dries the membrane, increases its Ohmic resistance and leads to contraction and rupture of the membrane. On the other hand, low temperature causes reduction in the rate of reactions, voltage, output power, and condenses the water in cathode side. Furthermore, non-uniformity of temperature can also lead to variable rate of electrochemical reactions in different parts of the cell. It creates hot spots in some parts and eventuated in lower lifetime of the cell. Hence, rejecting the heat from the cell and keeping it in an appropriate range of temperature is very essential for PEM fuel cells. This paper presents a 3D numerical simulation of the fluid flow in cooling plates and investigates the capability of metal foam porous media to thermal management of a fuel cell. The effect of porosity on the cooling performance is investigated. The coolant flow in porous metal foam is modeled as a turbulent flow. Darcy- Forchheimer equation is used to analysis the flow field in porous media and k-epsilon model is employed for turbulence studies. Local thermal non-equilibrium model is also utilized to obtain the temperature field and heat transfer. The numerical results indicated that by increasing the porosity of metal foam, the pressure drop and the rate of heat transfer both are decreased. The obtained results are in good agreement with available experimental data. This confirms that CFD with selected turbulence model is able to truly predict the flow field in cooling channels of a PEM fuel cell.

Large-eddy simulation of mild flame in non-premixed bluff-body burner

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The large-eddy simulations of non-premixed turbulent bluff-body flames were carried out to show a turbulent mild combustion which is formed in the conditions of ambient temperature of 300k and oxygen volume fraction of 20% instead of canonical mild condition of high temperature and low-oxygen dilution. The simulations were based on the Sydney bluff-body HM1e flame. In the first case, exactly the HM1e flame, we validated the mathematical model and numerical method in details, and the results were all in good agreement with measurements. Then we reduced oxygen volume fraction into 20% with N2 dilution in air-coflow, while kept the flow boundary conditions fairly same as in HM1e flame. In the diluted case, formaldehyde (CH2O) marked pre-ignition produced significantly in neck zone and

sustained further downstream, which led to dramatic reductions of NOx and CO production. This process is much of like what happened in a mild flame, in which there were low NOx and CO, and the pre-ignition process stabilized the mild flame that was the essential factor. Therefore, we regarded the diluted bluff-body flame as a mild flame. These results give us a hint that the mild combustion could be formed in extended conditions, which would simplify the complexity of industry equipment and expand the mild combustion's application.

MATHEMATICAL ASPECTS of NON-EQUILIBRIUM DYNAMICS

The dynamics of selfish flocks

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Many well-known models of collective motion focus on the asymptotic behaviour of groups. Such results are not accurate representations of non-equilibrium systems where the short time scale motion produces the most interesting dynamics. These same models tend to incorporate some form of mutually compatible goal or mimicking of neighbours eventually concluding that a global order can emerge for an appropriate choice of parameters. We highlight several situations where dynamic behaviour is dominated by the presence of predators leading one to consider that self interest, and not cooperation, is the key driver for the pattern formation. We build on the notion of a selfish herd, first proposed by Hamilton in 1971, using an interaction network defined by the Delaunay triangulation and inertial social forces that aim to minimise the individual's Voronoi cell, which is used as a proxy for each individual's positional danger. Numerical simulations of self propelled particles illustrate that the biologically motivated selfish avoidance of a predator can lead to realistic and seemingly cooperative motion resembling that of a swarm of midges. Allowing the particles to foresee future configurations, a pseudo-intelligence, transforms a swarm into a flock.

About the application of fractional calculus to non-equilibrium process dynamics

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The study of non-equilibrium processes in terms of the principle of local non-equilibrium requires to consider memory effects (non-locality in time) and spatial correlations (coordinate non-locality) and the development of innovative analysis methods. The standard approach to account non-local effects results in appearance of an integral operator in differential equations, and the kernel of the integral operator contain the information about non-locality nature. To solve such equations it is required to present the integral operator as a series of differential operators with the ascending rate of differentiation. Obtained equations appear to be too complex and not always can be solved. In this context the technique of fractional order is the subject of interest. Derivatives of fractional order present a new approach in the theory of non-local differential equations [1-3]. Here we present the results of our recent studies on the generalization of statistical physics with fractional order derivatives. In particular, we consider some problems of non-isothermal filtration and heat transfer processes in fractal media and present the generalization of thermodynamics in formalism of fractional derivatives. The physical meaning of the fractional derivative factor is also discussed.

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Scale-similarity of particle clustering in inertial range of turbulence

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Scale-similar clustering of heavy particles is found in the inertial range of turbulence from both phenomenological and analytical approaches, where −4/3-power law of the pair-correlation function (PCF) is predicted in the inertial range. Dimensional analysis is applied to PCF with the help of Kolmogorov's theory (1941), where PCF in the inertial range shows the −4/3-power law as universality free from both large and small-scale clustering. In order to understand dynamical aspects of the clustering, the Lagrangian renormalized approximation (LRA) theory, a branch of the renormalized perturbation theory, is applied to the number-density spectrum with a non-Gaussianity extension in the preferential concentration term. Not only reproducing the -4/3 power law of PCF (1/3 power in its spectrum), but LRA identifies its proportional prefactor of the power-law. Furthermore, an underlying physics behind the scale-similarity is revealed; the -4/3 power law can be understood from the dynamical balance between turbulence mixing and the preferential-concentration mechanism. Turbulence mixing causes the spectral flux which carries number-density variance from larger to smaller scales, expressing the clusters will be broken into smaller pieces due to turbulence mixing. In terms of the spectral flux, LRA solution predicts the forward cascade of clusters. Reminding the energy cascading causes intermittent structures of turbulence in the smaller scale, cascading picture of clusters may also bring a hint to understand the intermittent structure of the small-scale clustering and its Reynolds-number dependence.

Rogue waves and Talbot carpets: Dynamics driven by modulation instability

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Rogue waves are giant waves that sporadically appear and disappear in oceans and optics. Talbot carpets are elaborate recurrent images of light and plasma waves. We bring the two together and discuss the role of modulation instability and chaos in their generation.

Low-symmetric coherent structures and dimensional crossover in Rayleigh Taylor flows driven by time dependent accelerations

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We investigate the nature of the dimensional crossover i.e. transition between the nearly isotropic 3D periodic flows with group p4mm (square) to highly anisotropic 2D periodic flows with group p2m1 in Rayleigh Taylor (RT) instability [1-4]. Power law time dependence of the acceleration is considered with the emphasis on sub-regime, where the behavior is the RT type. We consider flow with group p2mm (rectangle) and obtain the 3D square and 2D limits with leading order rectangular corrections. Regular asymptotic solutions evolve as power law and form a two parameter family parametrized by the principal curvatures of the bubble. The bubbles with near circular contour separate the 2-dimensional solution space into two sub-regimes having distinct properties under the dimensional crossover. In one sub-regime, the elongated bubbles transform to 2D solutions, whereas in the other they flatten. 3D square bubbles are universally stable whereas 2D bubbles are unstable with respect to 3D modulations, implying that the dimensional crossover is discontinuous. We find that the time dependence affects the growth/decay of perturbations and has no consequence on the overall stability properties of the solution.

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Analytical solutions for the nonlinear regime of the Rayleigh-Taylor and Richtmyer-Meshkov instabilities at arbitrary Atwood number

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Recently, Banerjee and co-workers [1] have studied the behavior of a two fluid interface experiencing the Rayleigh-Taylor instability (RTI). They have examined the development of bubbles and spikes in the nonlinear regime for arbitrary Atwood number using the well-know Layzer [2] approach with a second harmonic in the velocity potential. Including such an additional potential is new, but their numerical work did not allow the authors to derive analytically the asymptotic (i.e. large time) time-dependence of the interface. In this paper, the non-linear differential system is solved analytically. We provide the exact dependence of the solution in terms of time and Atwood number and the asymptotic behaviors of bubbles and spikes are derived. This work is also extended to the case of the Richtmyer-Meshkov instability. Comparisons are made with the results obtained from other models.

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Editors' comment: The authors have been informed that: (i) The results of Banerjee et al 2013 reproduce a particular case of general solution given in 2003 Phys. Fluids 15, 2190 & 2003 Physics Letters A 317. (ii) There is no a Layzer's solution; there is only a first-order Layzer's approximation (1992 JETP Letters 55, 521).

Exact time-dependent solution to the Euler-Helmholtz and Riemann-Hopf equations

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The exact analytic solution of the Cauchy problem in unbounded space is obtained for the three-dimensional Euler-Helmholtz (EH) equation in the case of a nonzero-divergence velocity field. The solution obtained describes the inertial vortex motion of an ideal compressible medium and coincides with exact solution to the three- dimensional Riemann-Hopf (RH) equation which stimulates turbulence without pressure (Chefranov, 1991). A cloused description of the evolution of the enstrophy and the all other moments of the velocity and vortex fields is given, i.e., the basic problem of theory of turbulence is solved exactly. A new analytic smooth solution of the Cauchy problem for the three-dimensional Navier-Stokes equation is obtained. This solution coincides with above-mentioned solution to the EH and RH equations, which take into account the viscosity effect of a compressible medium and also the sufficient condition of positive definiteness of the growth rate of the integral entropy in the form of a linear relation between pressure and divergence of the velocity field.

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Scaling laws due to fractal and non-fractal multi-scale space-filling geometries in physical systems

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It is well known that physical systems that possess fractal and multi-fractal scales over an extended range of scales produce scaling laws different to conventional single scale scaling. Mathematically, this phenomenon is related to the space-filling nature of the underlying fractal and multi-fractal geometry, quantified by various fractal dimensions (Hausdorff, Kolmogorov capacity). But are all space-filling geometries characterized by non-zero fractal dimensions? Here we examine different types of multi-scale space-filling spiral geometries, in the context of a flamelet model of combustion, some of which possess fractal dimensions equal to zero, and show that the scaling laws for the global burning rate associated with the different space-filling geometries are different [1]. This is important because it shows that non-fractal multi-scale space-filling systems can also produce non-trivial scaling laws – a point often neglected.

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Quasi solution method in a vortex dynamics problem

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There are few general methods for proving existence of solutions to nonlinear systems of equation. However, if one can obtain numerically or otherwise, an approximate representation of solution, then there exists general method for proving existence of solution in a small neighborhood of such an approximate solution. Furthermore, when the solution representation is efficient, the steps in the proof are transparent with minimal computer assist. We illustrate application of this general method to a vortex dynamics problem. A canonical problem in 2-D vortex dynamics is a translating pair of oppositely rotating vortex patches. These have been calculated numerically by Pierrehumbert in the early eighties. These arise for instance in the roll up of vortex sheet behind an aircraft. The theoretical mathematical problem of showing existence of solution is limited to near circular shapes when the translating pairs are far apart. However, the vortices are quite distorted when the distance between the centroids is smaller. The nonlocal integro-differential equation arising in this problem is transformed in a way that makes such analysis possible. We use an efficient analytical expression of an approximate solution, obtained through numerics, and prove that there is an actual solution in the neighborhood of this solution in a suitable space of functions for which non-local, non-linear terms can be controlled. There are no theoretical restrictions on how distorted the shapes are, and the approach can be generalized to other vortex configurations, and for that matter many other interfacial problems.

On vortex catastrophe and nonlinear stability for plane circulations of an ideal fluid

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Uniqueness and stability of plane stationary vortex flows of an ideal incompressible fluid encountered in sea coastal zones, blood circulations, river ducts and near fluid contact interfaces are treated below as delivered by the Euler hydrodynamic equations in a rectangular or periodical strip with boundary normal velocity and inflow vorticity prescribed. Each flow in hand is found to be unique among vector fields which components are analytical functions and non–unique among infinitely smooth non–analytical vector fields satisfying the same boundary conditions as the unique analytical flow if the later has a sufficiently power vortex zone. And even with the presence of vortex zones the analytical flows turn out to be non–linear stable.

Turbulent diffusion of inertial particle pairs such as in pollen and sandstorms

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A non-local theory of fluid particle pair diffusion has recently been proposed [1]. From application point of view, particles with inertia are much more common in nature, such as sandstorms, dispersion of pollen and mixing in the chemical industry. It is surprising that whereas turbulent diffusion of single particles has been well studied [2], investigation of inertial particle pairs is almost non-existent, only Bec et al. [3] has been reported. Here, we investigate inertia particle pair diffusion numerically using Kinematic Simulations (KS) [4,5], in the limit of small Stokes' drag. As with fluid particle diffusion, the main goal is to obtained scaling laws for the inertial pair diffusivity Ki. Tp is the particle response time. The Stokes number is, St=Tp /tk, and tk is the Kolmogorov time scale, l(t) is the distance between particles in a pair. The ensemble rms of l(t) is s(t). Following Richardson 1926 we assume that Ki scales with s i.e. Ki=Ki(s). Unlike fluid particles, there will be more than one regime of diffusion. For short times, the energy in the small scales of turbulence does not affect the particle relative motion, thus we expect ballistic regime, Ki ~ s, for tines less than some time T*. At very large times the pair separation is also large and the turbulent energy will be dominant, and the diffusion will approach fluid pair diffusion, Ki ~ s*(1.53) [1]. We expect an intermediate transition regime determined by when the local Stokes number, St(l*)=Tp /T* =1. Numerical simulations were carried out using KS, and our results confirms the existence of all three regimes.

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Laws of the wall for velocity and temperature in supersonic turbulent boundary layers

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A supersonic turbulent boundary layer on a plate in zero longitudinal pressure gradient is considered. A rational asymptotic theory is developed, which includes the following main elements: (a) closure conditions relating the turbulent shear stress and turbulent heat flux to mean velocity and enthalpy gradients, (b) a special change of variables in the boundary-layer equations, which enables us to seek the solution in the form of asymptotic expansions at high values of the logarithm of the Reynolds number based on the boundary-layer thickness, (c) solving the compressible Reynolds equations in three characteristic regions (a viscous sublayer, a logarithmic sublayer, and an outer region) with subsequent asymptotic matching. The theory does not invoke any particular hypotheses about the nature of turbulent exchange and in fact is based on first principles. For the particular case of incompressible fluid it is presented in [1] (see also [2]). The laws of the wall for the velocity and temperature for compressible gas flow are established, the law of the wall for temperature having been formulated for the first time. It occurs that the known Van Driest formula yields only a leading term of the asymptotic expansion for the velocity profile in the logarithmic sublayer. The exact asymptotic solution contains additional terms of order unity, which provide better agreement with experiments particularly in case of heated or cooled walls. Besides the von Karman constant and the turbulent Prandtl number in the logarithmic region, which are known for incompressible flow, three new universal constants appear in the theory. They are determined by the processing of experimental data.

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A fully homogenized model for a non-equilibrium two-phase flow in double porosity media with thin fissures

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We consider a two-phase incompressible immiscible non-equilibrium flow in fractured porous media in the framework of the termodinamically consistent Kondaurov model that is the mobilities and capillary pressure depend both on the real saturation and non-equilibrium Kondaurov's parameter satisifying a corresponding kinetic equation. The fractured medium is regarded as a porous medium made of two superimposed continua, a connected fracture system, which is assumed to be thin of order hL, where L is the relative fracture thickness and an h-periodic system of disjoint cubic matrix blocks. We derive the global behavior of the fractured medium by passing to the limit as h approaches 0 (homogenization), assuming that the permeability of the blocks is proportional to the square of hL, while the permeability of the fractures is of order 1, and obtain the global L–model, i.e. the homogenized model with the coefficients depending on L. In the L-model, we linearize the cell problem in the matrix block and letting L approaches 0 obtain the macroscopic model exhibiting the twice non-equilibrium phenomenon and which does not depend on h, L. It is fully homogenized in the sense that all the coefficients are calculated in terms of given data and do not depend on the additional coupling or cell problems. The numerical tests show that for L sufficiently small, the exact global L-model with a non-linear cell problem can be replaced by the fully homogenized one without loss of accuracy.

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Remarks on the Clebsch representation of fluid mechanics and turbulence

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The ideal fluid equations have a noncanonical Hamiltonian structure when represented by the conventional Eulerian fluid variables (like the density, flow velocity, entropy, etc.) [1]. The noncanonicality is due to the "topological constraints" that foliates the phase space V of the fluid variables by the leaves (level-sets) of conserved quantities. The helicity is such a constant of motion, which is known to play an important role in creating vortical structures in fluids ---in the language of Hamiltonian mechanics (Poisson algebra), such a constant of motion is called a Casimir invariant. Unlike usual constants (such as a momentum) in a Hamiltonian system, which are related to some "symmetry" of the Hamiltonian, a Casimir invariant is independent of any specific choice of a Hamiltonian. A natural thought is that a Casimir invariant may be related to some "gauge symmetry" of the system. We consider an underlying phase space X of fundamental variables, and assume that the physical variables (member of V) are represented by some specific combinations of the fundamental variables. If the map X --> V is redundant, gauge freedoms occur. Then, a Casimir invariant is a Noether charge of the gauge symmetry. In fact, the helicity is shown to be a Noether charge pertinent to a gauge group acting on the Clebsch parameterization [2]; we may identify the Clebsch fields as the fundamental field, and the fluid mechanics is a reduced (classical) realization of the Heisenberg algebra dictating the Clebsch fields. We discuss the application of the Clebsch-parameterized fluid models in understanding various structures and turbulence, ranging from classical to quantum regimes[3,4].

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STOCHASTIC PROCESSES and PROBABILISTIC DESCRIPTION

A Lagrangian fluctuation-dissipation relation for scalar turbulence

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We present an exact formula -- dubbed a "Lagrangian fluctuation-dissipation relation" (LFDR) -- for scalar dissipation in terms of the variance of the scalar inputs (initial conditions and boundary data) acquired along random perturbed fluid trajectories. As an important application, we study the connection between anomalous scalar dissipation in turbulent flows for large Reynolds and Péclet numbers and the spontaneous stochasticity of the Lagrangian particle trajectories. The latter property corresponds to the Lagrangian trajectories remaining random in the limit Re, Pe approaching infinity, when the noise kicking the particles formally vanishes but the advecting velocity field becomes rough. For flows on domains without boundaries (e.g. tori, spheres) and for wall-bounded flows with no-flux Neumann conditions for the scalar, we prove that spontaneous stochasticity is necessary and sufficient for anomalous scalar dissipation. The LFDR provides a representation of scalar dissipation also in flows where present experiments suggest that dissipation is tending to zero as Re,Pe approaches infinity. We discuss an illustrative example of Rayleigh-Bénard convection with imposed heat-flux at the top and bottom plates. Our formula here shows that the scalar dissipation is given by the variance of the local time densities of the stochastic particles at the heated boundaries. The "ultimate regime" of turbulent convection predicted by Kraichnan-Spiegel occurs when the near-wall particle densities are mixed to their asymptotic uniform values in a large-scale turnover time. The current observations of vanishing scalar dissipation require that fluid particles be trapped at the wall and remain unmixed for many, many large-scale turnover times.

This talk presents joint work with Gregory Eyink.

Anomalous superdiffusive transport and Levy walks

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I present a new single integro-differential wave equation for the probability density function of the position of a classical one-dimensional Levy walk with continuous sample paths. This equation involves a classical wave operator together with memory integrals describing the spatiotemporal coupling of the Levy walk. It generalizes the well-known telegraph or Cattaneo equation for the persistent random walk with the exponential switching time distribution. Several non-Markovian cases are considered when the particle's velocity alternates at the gamma and power-law distributed random times. In the strong anomalous case we obtain the asymptotic solution to the integro-differential wave equation. I implement the nonlinear reaction term into our equation and develop the theory of wave propagation in reaction-transport systems involving Levy diffusion. I also propose a model of superdiffusive Levy walk as an emergent nonlinear phenomenon in systems of interacting individuals. I introduce microscopic mean-field kinetic equations in which I combine two key ingredients: (1) alignment interactions between individuals and (2) non-Markovian effects. This interacting run-and-tumble model leads to the superdiffusive growth of the mean-squared displacement and the power-law distribution of run length with infinite variance. The main result is that the superdiffusive behavior emerges as a cooperative effect without using the standard assumption of the power-law distribution of run distances from the inception.

Anomalous transport on scale-free networks

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We model transport of individuals across a heterogeneous scale-free network where a few weakly connected nodes exhibit heavy-tailed residence times. Using the empirical law of the axiom of cumulative inertia and fractional analysis, we show that 'anomalous cumulative inertia' overpowers highly connected nodes in attracting network individuals. This fundamentally challenges the classical result that individuals tend to accumulate in high-order nodes. The derived residence time distribution has a nontrivial U shape which we encounter empirically across human residence and employment times.

Localization of convective currents under frozen parametric disorder and eddy transport of passive scalar

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We address a problem which is mathematically reminiscent of the one of Anderson localization, although it is related to a strongly dissipative dynamics. Specifically, we study thermal convection in a horizontal porous layer heated from below in the presence of a parametric disorder [1]; physical parameters of the layer are time-independent and randomly inhomogeneous in one of the horizontal directions. Under such a frozen parametric disorder, spatially localized flow patterns appear, which are in focus of our study. Our interpretation of the results of the linear theory is underpinned by numerical simulation for the nonlinear problem. The nontrivial effect of weak advection on the localized patterns is also studied. The results presented are derived for a physical system which is mathematically described by a modified Kuramoto-Sivashinsky equation and therefore they are expected to be relevant for a broad variety of dissipative media where pattern selection occurs. The problem of transport of a passive scalar in the system [2,3] is considered as an example of process where the appearance of localized current patterns and their localization properties play a decisive role. For physically relevant parameter values the localized patterns are reported to be able to enhance the efficiency of transport by 1-2 orders of magnitude and characteristics of this transport are shown to be controlled by the localization properties. The problem addressed is not only interesting from the viewpoint of mathematical physics but also important due to ecological and technical applications. Irregularity of convective currents and the role of eddy transport link this research, in general, to turbulent mixing.

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Stochastic subgrid models for inertial particles dynamics in highly turbulent flow

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The practical interest in turbulent flows with dispersed inertial particles motivated a large number of laboratory studies. A significant part of these studies is aimed at describing the interaction between individual particle and flow. If the Reynolds number is high, the flow is

highly-intermittent on small length-scales, which are usually unresolved in computation. In our work, the objective was to account for effects of those discarded but important scales on the particle motion. This is done in the framework of two different approaches. An update of the resolved flow by stochastic simulation of flow structure at subgrid scales was the first one. To this end, the recently revisited LES-SSAM approach (Stochastic Subgrid Acceleration Model) - to be reported in ETC-16 - was applied. This approach is based on decomposition of the total instantaneous acceleration of the fluid particle on its resolved and residual part. The stochastic model for the latter one comprised two processes: one for the norm of residual acceleration (log-normal process), another one for its direction (the Ornstein-Uhlenbeck process on the unite sphere in Stratonovich calculus). Thereby the corrected flow, “seen” by the particle, was directly introduced in the particle motion equation. In the second approach, we proposed to describe the particle motion directly as a stochastic equation, in which the impact of high frequencies is linked to stochastic properties of the viscous dissipation along the particle path. The both approaches are assessed. Two proposed approaches showed extended tails in the acceleration PDF, the short-time correlation of the acceleration and the long-time correlation of its norm, as was observed in measurements.

Efficient uncertainty quantification in computational fluid dynamics using polynomial chaos approach

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The application and use of aeronautical components such as engines, wings, or complete airplanes are all subject to uncertainties. These uncertainties can have an important effect on the performance (output) of these components. The presence of uncertainties brings several difficulties to the shape optimization process as well. Polynomial chaos is a recent methodology to account for uncertainties that can be described by a distribution function. The method allows to obtain the distribution of the output for given input distributions. A problem of the method is the so-called curse of dimensionality, i.e. exponential growth of the simulation times with the number of input uncertainties. It is the main drawback of all classical stochastic methods. Some alternative methodologies such as sparse polynomial chaos, sparse numerical quadrature method, compressive sampling and reduced models in the polynomial chaos framework have been investigated to overcome the curse of dimensionality. In the present work a cure for the curse of dimensionality is discussed and applied to several stochastic test functions and to a stochastic computational fluid dynamics problem, transonic flow over the RAE2822 airfoil under uncertainties.

Dynamics of singularities, wavebreaking and turbulence in 2D hydrodynamics with free surface

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2D ideal fluid hydrodynamics with free surface is considered. Time-dependent conformal transformation maps free fluid surface into the real line and fluid domain into the lower complex half-plane. Fluid Dynamics is fully characterized by complex singularities in the upper complex half-plane. Initially flat surface with the pole in the complex velocity turns over arbitrary small time into the branch cut connecting two square root branch points. Lowest branch point approaches fluid surface with the exponential law corresponding to the formation of the fluid jet producing wavebreaking in the form of plunging jet. The use of the additional conformal transformation to resolve the dynamics near branch points allows to analyze wavebreaking in details. Formation of multiple Crapper capillary solutions is observed during overturning of the wave contributing to the turbulence of surface waves. Another way of wavebreaking is the slow increase of Stokes wave amplitude through nonlinear interactions until the limiting Stokes wave forms with subsequent wavebreaking. Square-root branch point is the only singularity in the physical sheet of Riemann surface for non-limiting Stokes wave. The corresponding branch cut defines the second sheet of Riemann surface after crossing the branch cut. The infinite number of square root singularities is found in the infinite number of non-physical sheets of Riemann surface. Increase of the steepness of the Stokes wave results in simultaneous approach of all singularities to the real line from different sheets of Riemann surface forming together 2/3 power law singularity of the limiting Stokes wave. It is found that non-limiting Stokes wave at the leading order consists of the infinite product of nested square root singularities which form the infinite number of sheets of Riemann surface. The conjecture is well supported by high precision simulations.

Turbulent and financial time series analysis

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Some of the characteristics of turbulence are its randomness, nonlinearity, diffusivity, and dissipation, just to name few. But couldn’t we characterize financial data in the same way? The answer is no, not exactly. Some of the extra descriptions for financial data, which makes it different than the steady experimental turbulence, are its Markovity and non-stationarity.

A comparison of realizable and regularized Markovian and non-Markovian inhomogeneous turbulence closures with ensemble averaged direct numerical simulations for general geophysical flows far from equilibrium.

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We compare non-Markovian and Markovian variants of a regularised direct interaction approximation formulated for the interaction of mean fields, Rossby waves and inhomogeneous turbulence over topography on a generalized β-plane. The closures have a one-to-one correspondence between the dynamical equations, Rossby wave dispersion relations, nonlinear stability criteria and canonical equilibrium theory on the generalized β-plane and on the sphere. The dynamics, kinetic energy spectra and mean field structures are

compared with the ensemble-averaged results from direct numerical simulations (DNS) at moderate resolution for a series of numerical experiments examining the generation of Rossby waves when eastward large-scale flows impinge on a conical mountain in the presence of moderate to strong two-dimensional turbulence. The Markovian variant, based on a modified fluctuation dissipation theorem, is shown to be realisable and stable, even in the initial stages where the large scale stationary Rossby wave develops, and to closely compare to the non-Markovian and ensemble averaged DNS calculations.

Ability of using a backpropogation neural network for problems of two streams with different properties

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An artificial neural network (ANN), also called a simulated neural network (SNN) or just a neural network (NN), is an interconnected group of artificial neurons that uses a mathematical or computational model for information processing based on a connectionist approach to computation. Nowadays neural network algorithms are widely used in many fields of life as pattern recognition, economics, medicine, Control theory etc. The main point of this work is searching for an ability of using neural network algorithms for researching of mixing processes of two liquid streams with different properties. In particular, neural network was created and trained for a problem of hot and cold streams mixing in a domestic crane. The problem of mechanism research of PT mixing zones is also interested.

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Effect of noise on Rayleigh-Taylor mixing with space-dependent acceleration

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We analyze, for the first time by our knowledge, the effect of noise on Rayleigh-Taylor (RT) mixing with space-dependent acceleration by applying the stochastic model. In these conditions, the RT mixing is a statistically unsteady process where the means values of the flow quantities vary in space and time, and there are also the space and time dependent fluctuations around these mean values. The stochastic model is derived from the momentum model and is represented by a set of nonlinear differential equations with multiplicative noise [1-4]. The models equations are solved theoretically and numerically. Investigating a broad range of values of acceleration, self-similar asymptotic solutions are found in the mixing regime. There are two types of mixing sub-regimes (acceleration-driven and dissipation-driven respectively), each of which has its own types of solutions and characteristic values with the latter saturating to a value on the order of one. It is also observed that the

representation of the dynamics in an implicit form is noisier as compared to the case of an explicit time-dependent form.

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Investigation of stabilities and instabilities at tokamak plasma behavior and machine learning with big data

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We investigate the problem of stability and instability at tokamak plasma behavior. Generally, Jaynes maximum entropy method and Bayesian decision can be applied for recognizing the shape of the plasma . In the case of the power law behavior and the instabilities of plasma we introduce a new method. The maximization of mathematical expectations for events and fuzzy entropy are used for applications of fuzzy Bayesian neural networks for optimization and simulation without assumption on recurrence. In this case, it is possible to consider also the non-Gibbsian probability distribution functions with the power law case.

Symbolic approaches to characterise complex dynamics

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Turbulent mixing was the original paradigmatic application which motivated the development of time delay reconstruction methods for a dynamical system for an observed scalar time series. That is, suppose that the underlying equations of the dynamical system are hidden and we only have access to a sequence of instantaneous scalar observations. Delay reconstruction ensures that the original dynamics can be reconstructed faithfully (generically and up to topological deformation) from these observations. Since then, these methods have been widely applied to experimental time series data that was believed to be chaotic. Methods have developed to estimate dynamical invariants (such as Lyapunov exponents) from such data. However, the methods are data hungry and typically limited to low dimensional chaotic systems. In recent years, symbolic methods have been developed which are far more pragmatic in the face of high dimensional dynamics and noise and these methods are again finding potential application in such complex systems. In this talk I will outline our advances in designing such data-based methods to characterise invariants of dynamical systems and give examples of the application of these methods. While some of these applications remain in the realms of low dimensional dynamics - finite systems of ordinary differential equations, laser dynamics and electronic circuits - these methods are now also being applied to systems with much more complicated dynamics: globals weather patterns and spatio-temporal chaotic dynamics in heart and brain. In essence these methods work by quantising state space in a robust way and counting transitions between quantised regions of state space. From this transition between quantised states we construct a weighted transition network, and from this network we are able to estimate dynamic invariants.

Multi-level segment analysis and the applications in fluid turbulence

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The interaction of different scales is among the most interesting and challenging features of turbulence. Existing approaches used for scaling analysis such as structure-function and Fourier spectrum method have their respective limitations, for instance scale mixing, i.e. the so-called infrared and ultraviolet effects. To make improvement in this regard, a new method, multi-level segment analysis (MSA) based on the local extrema statistics, has been developed [1]. Data test results show that MSA can successfully reveal different scaling regimes in complex systems such as Lagrangian and two-dimensional turbulence, which have been remaining controversial in turbulence research. In principle MSA can generally be applied to various data sources.

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Processes formation of microporosity at initial stage of phase transition

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Physical and chemical processes leading to degradations of properties of materials of objects of a cultural heritage under the influence of natural factors can be considered on a model example of porosity in the thin layered media combining crystal and amorphous layers or layers porous ceramics. Computer simulation of non equilibrium plasmas [1] allows us to see the overall picture of initial stage of phase transition in detail the behavior of defects origin, retention of vacancy-gaseous bubbles into lattice. The defects accumulate into thin layers near surface, they combined to structures which leads to following harmful effects: porosity, swelling, flaking and other. Random fluctuations of the defects trajectories associate with the system Ito-Stratonovich stochastic differential equations [2-3] and the Kolmogorov equation with non-linear coefficients. Stochastic molecular dynamics give us a powerful tool for detection structures of defects. The passive thermography [4] of buildings with porous structure sandstone morphology was performed The example of porosity calculation, 1/f noise distribution and stresses in layers semiconductor due to pores accumulation during Xe++ irradiation allows to valuate gradients of stresses in lattice due to structure defects formation , this model can be applied to the porosity prediction. This work is partially supported by the grants RFBR 15-01-05052 and by the Department of Mathematics of the RAS N 3 (3.6)

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N 40. P. 4842-9; [3] Zmievskaya, G. I., Averina, T. A., Bondareva, A. L. (2015)Applied Numerical Math.,93, 15-29; [4] Galina I. Zmievskaya, Anna L. Bondareva, Tatiana V. Levchenko, and Giuseppe Maino (2015) AIP Conference Proceedings 1648, 230003

ADVANCED NUMERICAL SIMULATIONS

Admixture distribution around a wedge in a continuously stratified fluid

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The natural systems are mostly stratified as a result of the effect of the Earth's gravitation. Very interesting is the fact that a stable stratification enables transport of dissolved substances and self-displacement of neutral buoyancy solids in even in the absence of evident external mechanical influences. This widespread phenomenon which is called diffusion induced flows can be observed at natural conditions and in laboratory experiments in form of horizontal extended streaky structures which are formed due to interruption of natural diffusion flux of stratifying agent on topography. An increase of characteristic velocities lead to transformation of structures into just much more complicated and thinner ones such as quasi-stationary high-gradient interfaces separating different types of disturbances, vortex wake and internal waves. Vortices and waves in non-homogeneous media exist simultaneously and interact actively with each other together with the flow fine structure which affects the processes of substance transfer, flow components separations and increase in local concentration of admixtures. A great practical interest lies in computations of diffusion induced flows on asymmetric obstacles which enable producing self-motion under action of the buoyancy forces. Being intensified by additional substance fluxes due to the natural metabolism such flows play an important role in the dynamics of self-movement of phyto- and zooplankton ("diffusion fish"). In the present work we investigate the 2-D problem on evolution of continuously stratified flow on an impermeable horizontal wedge. The mathematical model and numerical method of implementation, allowing simultaneous studying all the elements of the internal multi-scale stratified flows was proposed. The calculation results of flows in a stratified fluid around the stationary and moving wedge are shown.

Application of program package TurbulenceProblemSolver (TPS) to the modeling of the development of hydrodynamic instabilities

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An important part of computational fluid dynamics is the numerical simulation of the growth and development of hydrodynamic instabilities. The results of numerical simulations of the development of Richtmeyer-Meshkov (RMI) and Rayleigh-Taylor (RTI) instabilities are presented in the work on the example of well-known experiments [1], [2]. The complexity and specificity of the problems, as well as the possibility of comparison with experimental data, allow us not only to comprehensively investigate the phenomenon, but also to use such problems for the investigation of computational methods and the verification of hydrodynamic codes. For simulation the software package TPS (Turbulence Problem Solver) was used, which allows a universal solution approach to the wide range of hydrodynamic problems described by hyperbolic equations. Modeling was carried out using the large-particle method and the second-order ENO scheme based on approximate Riemann Solver of Roe.

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Rayleigh-Taylor turbulent mixing layers for miscible Newtonian fluids from Boussinesq approximation to fully compressible Navier–Stokes model

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We present recent results on Rayleigh-Taylor (RT) turbulent mixing layers obtained from Boussinesq approximation to fully compressible Navier–Stokes equations (NSE). Large-scale direct numerical simulations of the Boussinesq and anelastic models and the full NSE have been carried out with a self-adaptive multidomain spectral numerical method. These models, with the Sandoval and the quasi-isobaric models, have been recently derived with asymptotic expansions versus dimensionless parameters (Mach number, stratification, ratio of specific heats, etc.). Results about linear stability analysis, essentially on the full NSE and on the Boussinesq approximation, will be discussed and compared. Many conclusions have been obtained within the Boussinesq and the Sandoval models. In particular, it has been shown that the RT-turbulent mixing layers exhibit a self-similar behavior although several length scales are present with different temporal evolutions. Concerning the kinetic energy spectrum, the k^(-5/3) KO is preferred but the k^(-2) is not excluded. The mean dissipation rate and the enstrophy behave as t^() and t^(1/2), respectively. Inside the mixing layer, RT-turbulence shares some characteristics with IHT. Large-scales have a Gaussian behaviour, but vorticity PDFs show large departure from Gaussianity, associated to intermittency. On the other hand, intermediate scales of the velocity field and mixing are isotropic, while small scales remain anisotropic. Compressibility effects will be discussed in particular with the Kovasznay mode decomposition and by using the Favre-averaged equations. The temperature field appears to be the slave of the mixing. This conclusion has been drawn from the comparison of power spectra, anisotropy spectra and statistical quantities. There is however a significant time lag between the density and temperature evolution. Perspectives on future investigations of the Rayleigh-Taylor instability will also be drawn.

Blended and nudged Navier-Stokes equations

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The talk concerns the coupling of Large Eddy Simulations with Reynolds Averaged Navier Stokes computations, (hybrid LES/RANS), and the integration of Experimental and Computational Fluid Dynamics, (EFD/CFD data assimilation). There is a strong analogy between them: hybrid LES/RANS algorithms that blend turbulent RANS and LES models, and nudged Navier-Stokes equations driven by experimental data have been recently applied with success. In the talk the author will examine and compare these simple approaches both to the assimilation in time of EFD data with CFD and to the soft landing in space from LES to RANS in different zones. We remark that blending is usually expressed by an algebraic relation that matches two different models or two different databases, while nudging consists in the simplest form in a relaxation term added to an equation in order to synchronize the evolution of a database with another. In the talk the evolutionary equations associated to a simple blending relation are derived formally, and blended and nudged versions of the Navier-Stokes equations are compared.

Coarse grained simulation of turbulent material mixing

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Turbulent flow conditions cannot be reproduced with single laboratory or computational experiments, nor can they be fully simulated from first principles, and the impact of this inherent under-resolution on predictability must be addressed. In coarse grained simulation (CGS) [1] – including classical and implicit large-eddy simulation, small-scales are presumed enslaved to the dynamics of the largest, and the spectral cascade rate of energy (the rate limiting step) is determined by the initial and boundary condition constrained large-scale dynamics. Beyond the complex multi-scale resolution difficulties of equilibrium turbulence, we must also address the challenging issues of unsteady non-equilibrium flow transitions dependent on initial conditions (IC) – e.g. at material interfaces. CGS predictability is examined for under-resolved mixing driven by under-resolved velocity fields, and then also in conjunction with under-resolved IC. We revisit evidence for small-scale enslavement of high Reynolds-number (Re) scalar mixing in isotropic forced turbulence and material mixing in shock-tube experiments. Turbulence metrics are used to show that a well-designed CGS can accurately capture the mixing transition and high-Re self-similar asymptotic behaviors, when suitable subgrid realizability constraints are effectively built into the scalar-mixing modeling [1]. Robust CGS for dissipative turbulent phenomena is achievable with large enough scale separation and well-resolved IC. However, late-time predictability for high-Re phenomena cannot be robust when coarse-grained (computational and laboratory) measurements are constrained by characterization and modeling of IC specifics [1]. Ensemble averaging covering the relevant IC variability thus becomes strategy of choice.

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Development and validation of a five-equation multicomponent model with viscous, thermal and species diffusion

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When conducting direct numerical simulations of compressible turbulent mixing problems using interface-capturing finite volume methods, typically the composition of the mixture is determined using conservative transport equations for species mass fractions. It has been well documented however that using this set of equations results in spurious pressure/temperature oscillations being generated across contact surfaces, which pollutes the numerical accuracy of the solution. These can be removed by adding quasi-conservative transport equations for species volume fractions, such as the five-equation model of Allaire et al. [1] for inviscid flows, however currently there is no set of quasi-conservative governing equations for viscous, diffusive, miscible gases. Here we extend the five-equation Allaire model to include species diffusion, enabling more efficient DNS of miscible, multispecies flows. A numerical method is derived to solve the governing equations at second order accuracy in space and time and formal convergence studies are used to demonstrate the expected order of accuracy is achieved, as well as the advantages over the conservative four-equation model. These advantages are further demonstrated with simulations of a two-dimensional Richtmyer-Meshkov instability between air and SF6.

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Comparison of conjugate heat transfer in forward facing step using various turbulence models, considering variable thermophysical properties of the working fluid

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Flows through sudden contraction and expansion are found in many industrial applications and equipment such as cooling of electronic components, operation of compact heat exchangers, heat transfer enhancements etc. Such geometries are the best modelled through the backward-facing step or the forward-facing step. Flow in these devices are characterised with adverse and favourable pressure gradients, which leads to flow separation, reattachment and recirculation. Local heating phenomenon can cause the failure of equipment in certain cases, which may be caused by such separation and reattachment process. The forward-facing step (FFS) is more complex one, in which one or two recirculation regions may form, one on the downstream and the other at upstream of the step, depending on the boundary layer thickness to step height ratio. Use of proper turbulence model is very important for prediction of fluid flow and heat transfer characteristics in FFS. No published work dealing with this topic is currently available. In the present work, conjugate heat transfer from a FFS is analysed considering various turbulence models viz., k-epsilon, k-omega SST, v2-f and LES. The open source CFD code OpenFOAM is used for this analysis. OpenFOAM (Open Source Field Operation And Manipulation) is a C++ library, which contains numerous solvers, which could be used to solve problems in engineering applications. The code is suitably modified to

carry out the present analysis. Influence of (i) Reynolds number, (ii) Prandtl number, (iii) step height and (iv) ratio of thermal conductivity of metal to that of liquid on wall shear stress and heat transfer coefficient are presented. The entire analysis is then repeated considering temperature dependent thermophysical properties of the fluid, which is also a new result. It is seen that results with variable properties are much closer to the benchmark results and are markedly different from those with constant properties.

Energy fluxes and spectra for turbulent and laminar flows

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Turbulence is a classic problem with more unsolved issues than the solved ones. The most popular theory of turbulence is by Kolmogorov. According to Kolmogorov, the energy cascade rate or the energy flux is constant, and the one-dimensional energy spectrum E(k) shows -5/3 exponent in the inertial range. Further, Kolmogorov's spectrum for the hydrodynamic turbulence has been generalised so as to include the dissipative range that includes the dependence on the kinematic viscosity. Two well-known turbulence models to describe the inertial and dissipative ranges simultaneously are by Pao[1] and Pope[2]. In this paper, we report energy spectrum E(k) and energy flux computed using spectral simulations on grids up to 4096^3, and show consistency between the numerical results and predictions by the above models. The aforementioned models for turbulent flows, however, have certain deficiencies. The hump in the energy spectrum near the beginning of dissipation range related to the bottleneck effect is not captured by either of these models. Also, the energy flux of DNS differs from the model predictions in the dissipative regime by a small amount. Thus, the models of Pao and Pope need some revisions. In this paper, we also present a new model for the energy spectrum and flux of laminar flows. According to our model, the energy spectrum and flux exhibit exponential behaviour. We verify these model predictions using numerical simulations. We also show that the shell-to-shell energy transfers for the turbulent flows are forward and local for both inertial and dissipative range, but those for the laminar flows are forward and nonlocal. The modelling for energy spectrum and flux for the entire length scale, i.e., from inertial range to dissipative range, will enhance the understanding of turbulence mixing.

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Sweeping errors in turbulent particle pair diffusion in kinematic simulations

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Ref [1] and others have suggested that the large scale mean sweeping effects make the Lagrangian properties in Kinematic Simulations (KS) [2] unreliable. Here it is shown through a novel analysis based upon analysing pairs of particle trajectories in a frame of reference moving with the large energy containing scales of motion that the normalized integrated error E(l) in the turbulent pair diffusivity, K, due to the sweeping effect decreases with increasing pair separation l. There is an intermediate range of separations in which the error E(l) remains negligible. Simulations using KS show that in the swept frame of reference, this intermediate range is large, covering almost the entire inertial subrange simulated and showing that the deviation from locality observed in KS cannot be attributed to sweeping effect. This is important for pair diffusion theory and modeling because since Richardson 1926 all pair diffusion theories have been based upon the idea of locality; these results suggest that non-local effects may also be important.

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Computer simulation of the initial stage of condensation with the fragmentation of charged melt drops

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This article describes the model of a nonequilibrium stage of a first-order phase transition in the process of condensation silicon carbide (SiC) melt vapor. The production of condensate droplets of a given size is an important process preceding the solidification of the melt. Dispersing of charged droplets of silicon carbide melt is of interest in production nanocomposites (e.g., Si3N4/SiC, SiC/polymer), high-temperature and high-power semiconductors, in strengthening materials for Al, Al2O3, Mg, and Ni, etc. The processes of nucleation and condensation can be described using the equations of the Fokker-Planck-Kolmogorov kinetic theory and their stochastic analogs, the Ito-Stratonovich equations [1,3]. The stability of numerical methods for modeling the processes of obtaining nanostructured materials is studied in connection with the creation of new algorithms and modification of existing ones. The numerical experiments carried out refine the understanding of the nonequilibrium initial stage of cluster formation, taking into account the collisional process that changes the diffusion stochastic process and demonstrate the possibilities of applying the SDE theory to the problems of gas dynamics, dust plasma and colloidal media. Investigation of the stability of the algorithm for solving stochastic equations for models of nonequilibrium phase transitions expands the possibilities of studying the kinetics of nonequilibrium environment.

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A numerical study of decay of vortex rings in confined domains

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Vortex rings are fluid structures of concentrated vorticity having a toroidal shape. Vortex ring-like structures have been found to be formed inside the chamber, when the fuel is injected in a gasoline engine. The behavior of these rings affects mixing of fuel and air, which in turn decides the quality of combustion. Such cases of vortex rings in confined domains have also been encountered when vortex rings are used for extinguishing fire in oil and gas wells, and during the flow of blood from left atrium to the left ventricle of the heart during early diastolic filling. A knowledge about the decay patterns of these confined vortex rings are necessary, for identifying the optimal vortex rings in the respective cases. The available report on the decay of vortex rings in radially confined domains indicates the importance of confinement ratios (ratio of the vortex ring diameter to confinement diameter). A theoretical model for this confined viscous ring was also developed on a later study. In this work, we study the effects of various parameters of the vortex ring and the confinement on decay, using Lattice Boltzmann Method with Bhatnagar–Gross–Krook approximation for collision process. Initial vorticity distribution inside the vortex core is assumed to be Gaussian. The decay is recorded in terms of circulation, maximum core vorticity and kinetic energy of the vortex ring. Contrary to the earlier observations in the literature, this study suggests that the non-dimensional parameter confinement ratio, alone can not determine the decay rates. The details of the computation and inferences of the study will be presented at the time of conference.

Hierarchical wavelet-based modeling of turbulent flows

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Since the inception of Computational Fluid Dynamics, turbulence modeling and numerical methods evolved as two separate fields of research with the perception that once a turbulence model is developed, any suitable computational approach can be used for the numerical simulations of the model. Latest advancements in wavelet-based numerical methodologies for the solution of partial differential equations, combined with the unique properties of wavelet analysis to unambiguously identify and isolate localized dynamically dominant flow structures, made it possible to develop a cardinally different framework for modeling and simulation of turbulent flows with the tight integration of the numerics and physics-based modeling. The integration is achieved by combining spatially and temporally varying wavelet thresholding with hierarchical wavelet-based turbulence modeling. The resulting approach provides automatic smooth transition from directly resolving all flow physics to capturing only the energetic/coherent structures, leading to a dynamically adaptive variable fidelity approach. The self-regulating continuous switch between different fidelity regimes is accomplished through spatiotemporal variation of the wavelet threshold and two-way feedback mechanism between the modeled dissipation and the local grid resolution. This defines a new concept of model-refinement. The ability of the proposed methodology to

capture the flow-physics at the desired level of fidelity is demonstrated for the benchmark problem where the fidelity of turbulence simulation, measured by the ratio of the SGS and total dissipations, automatically adjusts to time-varying user prescribed levels. Finally, the implementation of the proposed model-refinement concept within classical LES methodology and possible feedback mechanism to incorporate a filter-width/model adaptation, preferably coupled with adaptation of the numerical resolution, are also discussed.

Wavelet methods in computational fluid dynamics

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Wavelet methods in Computational Fluid Dynamics is a relatively young area of research. Despite their short two decade-long existence, a substantial number of wavelet techniques have been developed for numerical simulations of compressible and incompressible Euler and Navier--Stokes equations for both inert and reactive flows. What distinguishes wavelet methods from traditional approaches is their ability to unambiguously identify and isolate localized dynamically dominant flow structures such as shocks, flame fronts or vortices and to track these structures on adaptive computational meshes. This lecture will provide a general overview of wavelet methods for solution of partial differential equations and describe different numerical wavelet-based approaches for solving the Navier-Stokes and Euler equations in adaptive wavelet bases as well as provide the background how to use wavelet-based methods for flows in complex geometries. Recent developments such as space-time adaptive wavelet collocation method for solution of partial differential equations and variational data assimilation problems as well as wavelet methods with mesh and anisotropy adaptation will be also discussed. Perspectives on using wavelet methods for modeling and computing industrially relevant flows will be also given.

Turbulence and scaling in high performance computing

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Direct numerical simulation is well-known to be a powerful but resource-intensive tool for advancing fundamental understanding in turbulence, provided requirements such as scale resolution and statistical sampling are appropriately met. Advances in computing power offer new possibilities for higher Reynolds numbers, improved scale resolution, wider parameter spaces, more complex boundary conditions, etc., with the central goal being to achieve greater physical realism in the computations. However, effective usage of leading high performance computing platforms is often not trivial, leading to challenges in the scalability of parallel algorithms when run on machines with hundreds of thousands of Central Processing Unit cores. In this talk we discuss two examples of recent success in achieving high scalability in simulations tested up to 8192-cubed grid points. The first involves tracking of over 100 million fluid particles for a study of Lagrangian statistics in isotropic turbulence at high

Reynolds number. The second involves turbulent mixing at very high Schmidt number, which poses resolution requirements much more stringent than that needed for the velocity field.

Computer simulation of Brownian diffusion of gaseous defects in silicon carbide under influence of Xe++ radiation

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The formation of porosity in thin layers of coating under its processing with high-energy Xe++ ions fluxes is a first-order phase transition. The initial stage of the phase transition is a nucleation of vacancy-gaseous defects (VGD). This effect considered as the superposition of the two random processes: diffusion in the phase space of sizes of defects clusters and their Brownian motion (BD) (defect diffusion in the material lattice) [1-3]. The motion is initiated by the indirect elastic interaction between defects due to acoustic phonons of the lattice. The diffusion depends on the long-range potential. The model is described by the kinetic equations of Kolmogorov-Feller for the clustering of VGD and the Einstein-Smoluchowski for the Brownian motion. The kinetic equations are related with the system of Ito-Stratonovich stochastic differential equations which are solved using stable algorithms. The result is the kinetic distribution function (DF) of defects which 3D visualization is produced effectively. The DF depends on sizes and depth of their penetration into the material under the irradiation. Values of defect concentration, diffusion coefficients and porosity-induced stresses in the material were calculated for various Xe++ radiation fluences. Thus, the damaging of silicon carbide layers can be predicted by means of computer experiments aimed at analyzing the diffusion in the lattice.

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EXPERIMENTS and EXPERIMENTAL DIAGNOSTICS

Three-wave resonance in water surface waves

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Three-wave resonance is one of the most fundamental energy-transfer mechanisms that can occur among weakly nonlinear surface waves. Here we show experimentally that if two source waves are propagating at an angle with respect to each other, the conditions for three-wave resonances are satisfied and a third resultant wave is produced. We reconstruct 3D surface waves using the Free-Surface Synthetic Schlieren method, which removes the need for the addition of a light-diffusing agent, thereby retaining the surface tension and density properties of water. For three triads, we compute the average temporal power spectral density (PSD) using the Welch method on the surface heights. We then compare the results of taking the average spatial PSD of the wave heights to the ones graphically obtained by plotting the gravity-capillary water wave dispersion relation for each triad component in w-k space.

About the possibility of cumulation stability investigation of the investigation on the hydraulic model of cylindrical implosion

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Hydraulic model of cylindrical implosion in the form of a liquid ring dynamically created on a flat horizontal surface is described [1]. When the axisymmetric flattening of a ring under the action of gravity, the inner boundary of the flow symmetrically converges, while the velocity of the boundary of the ring increases with decreasing radius, demonstrating the phenomenon of implosion and cumulationA well-known example of energy cumulation of implosive type is Rayleigh's problem of collapsing a hollow bubble in a liquid [2]. According to the book [3], until the bubble collapses moment -tf, at a radius r ~ 0, the motion of the bubble boundary is described by the dependence r ~ (tf-t) alpha with constant exponent alpha (0 < alpha <1), and in the incompressible fluid approximation the cumulative index alpha is 0.4 (alpha = 0.4). The experiments [4] on the model in the form of a water ring with internal and external radii of 6 and 9.6 cm and a height of the ring h = 1.4 cm have shown that the flow in the model [1] has a similar character with alpha = 0.73 - 0, 81Calculations based on the STAR-CCM + program and the results of experiments on the model [1], the possibilities of investigating the stability of cumulation in the collapse of the inner boundary of a ring are discussed.

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Results from the Göttingen Variable Density Turbulence Tunnel

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I shall report recent results on measurements in Göttingen Variable Density Turbulence Tunnel for Taylor micro-scale Reynolds numbers up to 6500.

Editors’ comment: This is the post-deadlne submission.

Turbulent gaseous mixing induced by the Richtmyer-Meshkov instability at the shock and reshock phase: shock tube experiments and 3D numerical simulations

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We investigate the turbulent mixing of 2 gases (air and SF6) arising from the Richtmyer-Meshkov instability, firstly when a Mach number 1.2 shock wave in air impulsively accelerates a discontinuous air/SF6 interface, and secondly as the initial mixing zone is excited when the Mach number 1.3 reflected shock in SF6 impulsively decelerates it. The 5 m long vertical shock tube has a square 0.13 m cross-section throughout. The compressed air filled 1 m long driver is at the bottom. The first part of the air filled at atmospheric pressure test section is 3 m long, the SF6 filled second part has a variable length from 0.1 to 0.3 m. We can then study the effect of the length of SF6 (hence the reshock time) on the turbulent mixing. Air and SF6 are initially separated by a thin 0.5 µm nitrocellulose film in sandwich between two square grids (wire spacing 1, 1. 8 and 12.1 mm). The lower grid prevents the membrane from bulging due to the weight of the SF6; the upper grid breaks the membrane at shock passage. We study the effect of the wire spacing of both grids on the turbulent mixing. The diagnostics are based on high speed camera Schlieren visualizations and laser-doppler velocity measurements for estimating the turbulent kinetic energy. The effects of the lower and upper grid spacing and of the length of SF6 on the evolution of the turbulent mixing zone thickness before and after reshock were investigated. The velocity measurements were hindered by the membrane fragments remaining in the mixing zone. The simulations are performed using the 3D Eulerian code TRICLADE which does not treat the membrane nor the grids. Thus two options for the treatment of the initial conditions have been explored. Agreements and disagreements with the experimental results were found.

Experimental and numerical investigation of the Rayleigh-Taylor instability of the Newtonian and dilatant fluids system

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The present work is devoted to the Rayleigh-Taylor instability (RTI) of dilatant and Newtonian fluids. The main aim of this work was to carry out experiment, numerical simulation of mixing of two media, and making a comparison between gained data. The experiment was carried out in a flat rectangular vessel, where liquid (an aqueous solution of starch) and air are mixed. The problem is considered two-dimensional with the Atwood number almost equals to 1. Parameters of a single-mode initial perturbation of the contact boundary are given: the wavelength and its amplitude. The intermixing was shot by a high-speed video camera and processed by the program of the camera frame by frame. In this way, the ascent velocities of the air bubble and the acceleration of the fluid spikes are determined. The experiment is modeled using a numerical simulation program. The experimental andnumerical results are compared achieving good agreement.

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Interaction between shock wave and turbulent wake

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Experiments on a spherical shock wave propagating across turbulent cylinder wake are conducted in a wind tunnel. The overpressure of the shock wave and the velocity of the wake are simultaneously measured using a piezoelectric pressure transducer and an I-type hot wire probe, respectively. The cylinder is installed horizontally for generating partially turbulent flows, across which the shock wave passes. The measurements are repeated for different vertical distributions of turbulence layer formed behind the cylinder by changing the height of the cylinder. This enables us to investigate the effects of the thickness and the location of the vertical turbulence layer on the peak-overpressure observed on the bottom wall. The mean value of the peak-overpressure decreases for the turbulence layer with larger thickness across which the shock wave propagates. The spatial velocity distribution behind the cylinder is estimated with the Taylor hypothesis. We calculate the correlation coefficients between the peak-overpressure fluctuation and the spatial distribution of the low pass filtered turbulent velocity fluctuation with a wide range of the filter size. The results show that the peak-overpressure fluctuation is correlated with the velocity around the shock ray from the open end of the shock tube to the pressure transducer location.

Development of methods for investigating the stability of the pop-up bubble dome in case of small Atwood number

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The stability of bubble domes in the RT-mixing zone on the unstable gas-liquid interface can be explained by the action of analog of the relaminarization effect [1-3] associated with the accelerated flow of a fluid along the surface of the emerging bubbles [4]. In experiments [4], the effect of relaminarization was observed in the case of air Taylor bubble floating in the water. In this case, the Atwood number A is close to 1; and it is of interest to study the effect of the relaminarization for small values of the Atwood number. The development of a methodology for investigating this problem has begun in experiments in which a bubble was created from pure water, emerging in salt solution. The first results showing the stabilization of RT instability on the dome of a pop-up bubble with the Atwood number $A = 0.007$ or less are obtained. An intensive development of the Kelvin-Helmholtz instability on the lateral surface of the bubble is observed. The results of the experiments demonstrate the possibilities of visualizing the flow in the bubble and in the neighborhood of the bubble with the help of various types of markers with a median density approaching the liquid density (dyed trickles, hard markers, laser sheet method). The development of computational modeling of the problem under the STAR-CCM + program has begun.

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Stochastic model of turbulent mixing layer and its use for explanation of peculiarities of aerodynamic noise generated by turbulent jet

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Recently, a new experimental method based on the azimuthal decomposition of sound was used to measure the noise of a turbulent jet. The obtained data make it possible to extract various noise components associated with different types of turbulent pulsations. The results indicate at an absence of the so-called shear noise component, that is in contradiction with the standard theory based on the statistics of the random field of quadrupole sound sources, and the expression for the Green's function of the convective wave operator in the mean flow. In this paper, an attempt is made to interpret these experimental data as manifestation of intermittency. To this end, the turbulent mixing layer is represented as 2D gas from randomly distributed point vortices. Despite the simplicity of this model, it retains the main features of the turbulent flow, important for the correct description of the interaction of equivalent sound sources with the background flow. It is shown that the acoustic radiation of a quadrupole source located in a stochastic mixing layer differ from the solution of the classical problem in which the mixing layer is modeled by a stationary mean flow. The obtained results demonstrate the important role of correct modeling of the background flow in describing the process of noise generation by turbulence. In particular, this concerns intermittent turbulent flows, where the vorticity field breaks up into separate intense vortex structures separated by regions of almost potential flow. Thus, the proposed concept, validated by acoustic measurements, allows us to formulate a new procedure for describing sound generation by turbulent flows and to confirm the intermittent nature of intense shear layers in turbulent jets in a non-contact manner.

Physical characteristics determination of the products of the shock wave-induced surface destruction: Optoheterodyne Doppler measurements

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Optoheterodyne Doppler velocimetry was widely used in the last decade to study the dynamic processes. One of the advantages of this method is the possibility of simultaneous recording of the velocities of many objects in a probing zone. This process takes place when a shock wave reaches the sample surface and the destruction products are formed during the process of spallation of the surface layer. The results of optoheterodyne Doppler measurements of the ballistic expansion of the surface destruction products submitted in this article. To interpret the spectral data of the optoheterodyne Doppler measurements the transport equation for the function of the mutual coherence of the multiple scattered field is used. The Doppler spectra of the backscattered signal are calculated using the theoretical model of the dust cloud that appears when the shock wave reaches the sample surface. The qualitative changes are found in the spectra depending on the optical thickness of the dust cloud. The obtained theoretical results are in the agreement with the experimental data. The carried out analysis shows that

the optoheterodyne Doppler measurements of the free surface velocity of metal samples subjected to shock-wave loading can be used to determine the physical characteristics of the destruction products.

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Visualization of some unstable fluid flows by means of solid and liquid markers

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An overview of the methods for hydrodynamic flows visualization developed in the SarFTI hydrodynamic laboratory of the NRNU MEPhI is presented. These include: (i) The method of solid markers, in which the flow is visualized by solid polystyrene beads, whose density is close to the density of water. This method serves to visualize the flow and determine the flow rate [1-3]. (ii) The method of 'liquid markers' - the flow is visualized with the help of dyed trickles, the density in which is close to the density of the liquid under study [3,4] (a technique similar to that used by Reynolds in his classical work). (iii) The 'falling curtain' method - the flow is visualized with the help of many adjacent dyed trickles. These methods were used in the study of the following problems: (a) Investigation of the possibility of increasing the density of the kinetic energy of the water flow by means of a system of guiding structures [1-3]. (b) Spiral rise of small air bubbles in the water (visualization using the "falling curtain" method). (c) A solid cylinder floating in the water [4]. (d) Liquid bubble emerging in a denser liquid [5].

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Effect of double diffusion phenomenon on solutal advective flow

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The structure and stability of the solutal advective flow in a horizontal shallow channel are experimentally studied. The flow is produced by an initial longitudinal step-like density distribution due to dissolution of (i) one solute with different concentration or (ii) two different solutes. In both cases it is found that an increase of density difference or channel thickness give rise to the main flow instability which results in appearance of the longitudinal convective rolls in near-wall regions. We show that the phenomenon is originated from the Rayleigh-Taylor instability which develops near both upper and lower horizontal boundaries where unstable density stratification takes place due to no-slip boundary condition. It is shown that solutal Péclet number, which reflects the relative strength of advection and diffusion, has to exceed the critical value Pe~300 for the instability to set in. This non-dimensional parameter uniquely determines as well the spatio-temporal characteristics of the secondary flow, wavelength and formation time, which allows us to combine all the results obtained for different substances and cuvettes into unified dependences. In the case of two solutes there is an additional complicating mechanism caused by cross-diffusion mechanisms, i.e. an additional convective motion appears due to the difference in the diffusion coefficients of the dissolved substances. It is shown that under certain conditions, the cross-diffusion mechanisms can have either destabilizing or stabilizing effect on the secondary flow depending on the ratio of the diffusion coefficients.

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Enhanced turbulence and mixing in a controlled Taylor–Couette flow

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Due to its many interesting academic and industrial applications, the Taylor–Couette flow problem is considered one of the most important in modern physics. The problem is encountered in numerous industrial areas such as catalytic reactors, electrochemistry, photochemistry, biochemistry, polymerization and mass transfer operations (extraction, tangential filtration, crystallization and dialysis). We present a numerical and experimental study of a Taylor–Couette flow with a radial pulsatile motion superimposed on the rotative inner cylinder. The simulations are implemented on the FLUENT code where a three-dimensional, incompressible flow is considered. The results are experimentally validated and indicate that the proposed active control strategy strongly modifies the flow behavior in such a way that turbulence is substantially enhanced with earlier laminar-to-turbulence transition. The first instability is observed at a Taylor number of Ta=17 instead of Ta=41.33 corresponding to the uncontrolled case. It is conjectured that the control strategy induces a momentum transfer mechanism from the mean velocity and vorticity fields to the corresponding fluctuating components. This is confirmed by the measured rms values which are found to be several orders of magnitude greater (up to 25 times) than the uncontrolled case. This central result is consistent with a considerably intensified mixing and thus enhanced heat, mass, and momentum transport.

Richtmyer-Meshkov shock induced fractal mixing

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Turbulent mixing generated by gravitational acceleration in low Atwood number incompressible experiments using fluids is studied in detail The role of local turbulence is studied and different experiments were compared using advanced visualization to analyse the fractal and multi-scale instabilities leading to mixing due to Rayleigh-Taylor and Richtmyer-

Meshkov instabilities [1-3].The evaluation of the scale to scale transfer of energy and other descriptors of great importance in mixing processes use higher order structure function analysis in combination with Extended Self Similarity and other methods [6-8]. In particular we present the evolution of fluxes as molecular mixing takes place using fast reactive indicators such as Phenoftalein, which provides 3D visual indication of the complexity of shock and buoyancy driven flows. We present a practical application in order to compare shocks. The physical mechanism producing the instability is easily done [3] with the sudden stop of a tank in a falling frame of reference with vertical railing. We can resolve 2D velocities in a LIF plane or image sequence in mixing produced by either Rayleigh-Taylor instability, Richtmyer- Meshkov Instability or Kelvin-Helmholtz billows. Even when viscosities are small the two fluids are stirred and interpenetrating each other developing initially mushroom type structures that degenerate into extremely thin and twisted filaments [3-6], even the large Reynolds number flows keep some memory of the intermittent forcing.

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Interaction of a turbulent boundary layer with isotropic turbulence behind an active grid

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We report experiments that study the interaction between high intensity (~9%) isotropic free stream turbulence (FST) behind an active grid and a turbulent boundary layer (TBL) on a flat plate. The TBL with FST generated behind a passive grid as well as the TBL in the absence of any grid are also considered. The wind tunnel is of open-type and is of low (~0.3%) noise. The Taylor's microscale based Reynolds number for the FST is over 250 for the active grid case and is about 50 for the passive grid case. The active grid is operated in the double random mode, which is optimized for isotropy and eliminates the spike in the energy spectrum at low frequencies as seen with a single-random mode. Both hot-wire anemometry (HWA) and particle image velocimetry (PIV) are used to obtain detailed velocity statistics. Velocity profiles, correlation functions, velocity spectra, and PDFs of velocity differences are reported and the effect of FST on TBL is shown through these statistics. The increased growth rate of TBL with increased intensity of FST is confirmed. It is seen that the effect of FST on TBL is felt deep within the boundary layer, to a depth that is proportional to the intensity of FST; for the highest intensity the effects are seen even at y/delta of 0.25. The effects are surmised to cause a suppression of wall-towards motions in the TBL, thus enhancing the growth of the TBL in the presence of FST.

Instabilities and mixing in internal waves attractors

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Internal wave attractors may serve as a laboratory model of high amplitude internal waves, when almost all the energy of the monochromatic external forcing (which may correspond to tidal forcing) accumulates along certain paths. Wave attractors were first described in trapezoidal domains. In this work we describe cascades of instabilities, arising inside the trapezoidal domain due to focusing of the waves on the inclined boundary. With the help of Fourier analysis, Hilbert transform, bispectra and other tools sequences of triadic resonances were studied. For higher forcing amplitudes there may occur overturning and intensive mixing, which depends on spacial wave lengths. And on the other hand for even higher forcing there may begin intensive interaction of the waves with the walls which has as a result multi-folded structures propagating from the boundaries inside the domain and interacting with the mean oscillatory flow. Another important question is stability of wave attractors in three-dimensional cases with localized wave-makers. Numerical simulations show, that in presence of inclined surfaces, even for localized wavemakers (one tenth of the domain size in transversal direction) the final structure of the attractor is close to two-dimensional, which was quantitatively described with the help of correlation functions

Turbulence and mixing generated by 3D sparse multi-scale grid

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It is known that flat 2D fractal grids alter turbulence characteristics downstream of the grid as compared to the flat regular grids with the same blockage ratio and mass inflow rates [1]. Recently, a new 3D sparse multi-scale grid design (3DSGT) in co-planar arrangement has been proposed [2] such that each generation of length scale of grid elements is held in its own frame. A critical motivation here is that the effective blockage ratio in the 3DSGT design is significantly lower than in the flat 2D counterpart – typically the blockage ratio could be reduced from say 21% in 2D to 7% in the 3DSGT. This has excited interest in the turbulence community because if this can be realized in practice, it could greatly enhance the efficiency of turbulent mixing and transfer processes. Work has begun on the 3DSGT exper-imentally using Surface Flow Image velocimetry (SFIV) [3] at the European facility in the Max Planck Institute for Dynamics and Self-Organization located in Gottingen, Germany and at the Technical University of Catalonia (UPC) in Spain, and numerically using Direct Numerical Simulation (DNS) at King Fahd University of Petroleum & Minerals (KFUPM) in Saudi Arabia and in University of Warsaw in Poland. Many variables will be investigated for optimal mixing conditions. For example, the number of scale generations, the spacing between frames, the size ratio of grid elements, inflow conditions, etc. Quantities of interest include high order velocity structure functions, correlations, mixing characteristics and timescales.

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Passive scalar mixing in temporally developing grid turbulence

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We perform the direct numerical simulation of temporally developing grid turbulence with a mean scalar gradient. The temporal grid turbulence is a counterpart to the spatially developing grid turbulence, in a similar spirit to the temporal counterparts studied for free shear flows. This temporal approach allows us to simulate the grid turbulence in a periodic box. We show that the temporal evolution of turbulence statistics in the present DNS agrees well with wind tunnel experiments. In virtue of the periodic boundary conditions in three directions, we can directly evaluate three dimensional turbulent kinetic energy spectrum E(k) in the grid turbulence. It is shown that E(k) is proportional to k^2 for small wavenumbers confirming that the grid turbulence simulated in this study is Saffman turbulence. We also investigate the passive scalar mixing process in the grid turbulence with particular attention to spectral properties.

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