Workshop on

Science and Technology in High Reynolds Number Turbulence

Nagoya Institute of Technology
Nagoya, Japan

Feb. 21, 2025

Large-scale direct numerical simulations of isotropic turbulence using K computer and Fugaku

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Direct numerical simulation (DNS) of isotropic turbulence is an effective tool for understanding the fundamental statistical properties of turbulence and the physics of turbulent flow phenomena. We have performed a series of large-scale DNSs of turbulence using K and Fugaku. An alias-free Fourier spectral method is adopted with double-precision arithmetic. The Taylor-microscale Reynolds numbers in the DNSs are up to R_λ=2250 with $k_{max}\eta$=1, R_λ=1750 with $k_{max}\eta$=2, R_λ=1100 with $k_{max}\eta$=4, and R_λ=740 with $k_{max}\eta$=8, where k_{max} is the maximum wavenumber and η is the Kolmogorov length. Some updates of the turbulence statistics in the inertial subrange and the energy dissipation range of high Reynolds number turbulence will be given. The results of the series of DNSs reveal that we should use the DNS data effectively and appropriately, depending on the statistics and structures we want to understand.

Statistical properties of Hall magnetohydrodynamics (HMHD) turbulence depending upon magnetic Prandtl number and ion skin depth

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The satellite observations of solar-wind-plasma turbulence yield a fluid-energy spectrum $E_u(k)$ with k the wave-number, with a power-law inertial range that has a scaling exponent that is consistent with -5/3 [the Kolmogorov prediction (henceforth K41)] and a magnetic-energy spectrum $E_b(k)$ that displays (i) a first inertial range, consistent with K41, and (ii) a second inertial range that is characterized by an exponent in the range [-4, -1]. These observations also uncover intermittency and multiscaling of velocity and magnetic-field structure functions in the first inertial range, but not in the second one. It is important, therefore, to explore such scaling regions and intermittency in theoretical models, for the solar wind, such as the three-dimensional (3D) Hall magnetohydrodynamic (HMHD) equations, which have been studied via direct numerical simulations (DNSs), at magnetic Prandtl number Pr_m=1 [1]. These DNSs yield a K41-type inertial range for $E_u(k)$ spectrum and -7/3 and -11/3 scaling regimes in $E_b(k)$ in the second inertial region, with $d_i << l << \eta_d^b$, where d_i is the ion-inertial length and η_d^b the magnetic-energy dissipation length scale. There are not many studies of such scaling and intermittency in 3D HMHD turbulence when Pr_m not equal to 1.

Therefore, we present a detailed study of such turbulence at values of Pr_m that are different from unity. We compare our results for Pr_m = 0.1, Pr_m=1.0 and Pr_m=10.0, at different values of d_i, in our pseudospectral DNSs. We compute various statistical quantities to characterize 3D HMHD plasma turbulence: (i) $E_u(k)$ and $E_b(k)$, including spectra conditioned on left- and right-polarised fluctuations of the fields, to uncover ion-cyclotron and whistler waves in the second-inertial region; (ii) probability distribution functions (PDFs) of longitudinal velocity and magnetic-fields increments, their structure functions, and their flatnesses. For all values of Pr_m, there is a K41-type inertial range with $E_u(k) \sim k^{-5/3}$ and $E_b(k) \sim k^{-5/3}$. For large k, i.e., length scales smaller than d_i, we find that $E_b(k) \sim k^{-17/3}$ for Pr_m=0.1; but $E_b(k) \sim k^{-17/3}$ for Pr_m=1.0 and Pr_m=10. We present

theoretical arguments for these two different scaling behaviors of E_b (k), in this second-inertial region, and show that they can be understood using left- and right-polarised fluctuations of the fields, which lead to the dominance of either ion-cyclotron or whistler waves. Our analysis of PDFs of field increments, structure functions, and their flatnesses show that the velocity fields are less intermittent than their magnetic-field counterparts for Pr_m=1.0 and Pr_m= 10.0.

References:

[1] Statistical properties of three-dimensional Hall magnetohydrodynamics turbulence, S.K. Yadav, H. Miura, and R. Pandit, Phys. Fluids, **34**, 095135, (2022).

Advancing the super-droplet method for deep convective cloud microphysics: recent developments and applications

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Accurate representation of cloud microphysics is crucial for improving weather forecasting and understanding aerosol–cloud interactions. In this talk, we present recent enhancements to the Super-Droplet Method (SDM), a particle-based microphysical scheme integrated into the SCALE modeling framework. Our updates focus on mixed-phase processes in deep convective systems, particularly those associated with heavy rainfall events. These improvements are particularly relevant for heavy rainfall events, where cloud microphysics and underlying turbulent motions both play a role in shaping precipitation processes.

Unlike traditional bulk or bin schemes, SDM explicitly tracks the distribution and trajectories of aerosol particles, offering a more detailed perspective on cloud development, precipitation formation, and hydrometeor interactions. Building on prior work, we incorporate data from the Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) by the Indian Institute of Tropical Meteorology (IITM) to validate and refine our model. Comparisons with radar observations indicate that SCALE-SDM achieves strong consistency in hydrometeor representation and effectively captures key cloud processes.

These findings underscore SCALE-SDM's capability for accurately simulating deep convective environments, marking a significant step forward in high-resolution cloud modeling and advancing our understanding of cloud microphysics in weather and climate studies.

Effects of shape anisotropy of high enstrophy regions on small-scale statistics in isotropic high Reynolds number turbulence.

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In high Reyolds number (Re) turbulence, the shapes of high enstrophy (squared vorticity) regions are highly anisotropic. Each is like a tube or a banana, but not a sphere or an apple. The ratios of their characteristic length scales along vortex lines to those perpendicular to the lines can be much larger than unity, and the ratios are generally larger in the higher enstrophy region. The shape anisotropy can coexist with the statistical isotropy of the orientations and the distributions of the regions, and is presumably linked to the singular nature of the solution of the Navier-Stokes equation in the limit of Re $\rightarrow\infty$. After a brief review of some quantitative aspects of the anisotropy known from direct numerical simulations, this talk will discuss the implications of the anisotropy for the small-scale statistics in high Re turbulence, based on a simple model.

Deterministic turbulence?
Exploring the stochastic nature of turbulent flows

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Despite the deterministic nature of the Navier-Stokes equations, the turbulent velocity fields are typically treated as random variables and are most often characterized by their statistical properties. In this study, we seek to ascertain whether turbulence is truly random—or stochastic—or if it is to some extent deterministic. Through a series of experiments conducted in the Variable Density Turbulence Tunnel at the Max Planck Institute for Dynamics and Self-Organization (MPI-DS) for Rλ between 150 and 500, we show that the larger scales of turbulent flows are deterministic and reproducible, while the behavior observed in the inertial range is consistent with a purely random flow. Furthermore, we have identified a novel approach to calculate the integral length scale of turbulence, which is interpreted as the scale where the velocity field is no longer reproducible. These findings provide crucial insights into the fundamental aspects of turbulent flows, including their random nature and their characteristic scales.

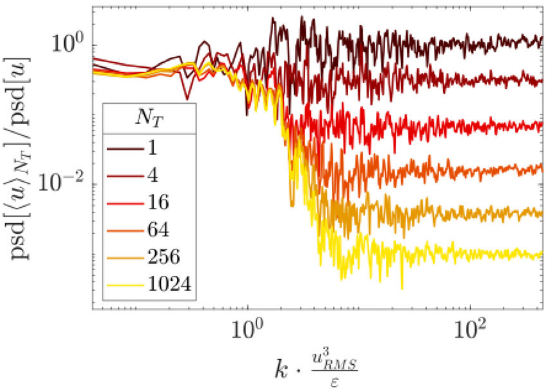

Figure 1 Left: The Variable Density Turbulence Tunnel (VDTT) at the Max Planck Institute for Dynamics and Self-Organization. Right: The ratio between the energy spectrum of the ensemble averaged velocity signal of N_T consecutive repetitions of the same experiment to the energy spectrum of one full experiment.

Turbulence statistics and friction factor in high Reynolds number actual flow facility (Hi-Reff)

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The experimental facility for high Reynolds number turbulent pipe flow, known as the High Reynolds Number Actual Flow Facility (Hi-Reff), is introduced in this presentation. This facility is uniquely designed to achieve highly accurate flow rate measurement. A series of experiments conducted at this facility are presented, including measurements of the friction factor, mean velocity, turbulence intensity profiles for all three velocity components, turbulent kinetic energy, and spectrum distributions, up to Ret=20000.

Probability density functions of energy dissipation rate, enstrophy and their 1D surrogates in isotropic turbulence

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Relation between the probability density functions (PDFs) of the three dimensional (3D) energy dissipation rate, enstrophy and their one dimensional (1D) surrogates in the incompressible isotropic turbulence is theoretically derived and verified by the direct numerical simulations. The relations indicates that the PDFs of the 1D surrogates have the longer tail than those of the PDFs of 3D energy dissipation and enstrophy and that their long tails are the stretched exponential with the same stretching exponents. It is shown that the ratios of the moments of the 3D dissipation (enstrophy) to those of the 1D surrogates grow rapidly with the order but is independent of the Reynolds number.