Physics and computations of turbulent dispersed flows: macro - consequences from micro - interactions

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Abstract

In this paper we will use Direct Numerical Simulations of turbulence and Lagrangian Particle Tracking to elucidate the physics of teh motion of inertial particles in different turbulence instances and we will provide insight for modelling ans simulating turbulent dispersed flows important in industrial, environmental and geophysical applications.

Keywords: turbulence; particles; Direct Numerical Simulation; Lagrangian Tracking

Turbulent fluids and small particles or droplets or bubbles are common to a number of key processes in energy production, product industry and environmental phenomena. In modelling these processes, the dispersed phase is usually assumed uniformly distributed. Indeed, it is not. Dispersed phases can be focused by turbulence structures and can have a time-space distribution which barely resembles prediction of simplified averaged modelling.

Preferential distribution controls the rate at which sedimentation and re-entrainment occur, reaction rates in burners or reactors and can also determine raindrop formation and, through plankton, bubble and droplet dynamics, the rate of oxygen-carbon dioxide exchange at the ocean-atmosphere interface.

In this talk, we will review a number of physical phenomena in which particle segregation in turbulence is a crucial effect describing the physics by means of Direct Numerical Simulation of turbulence.

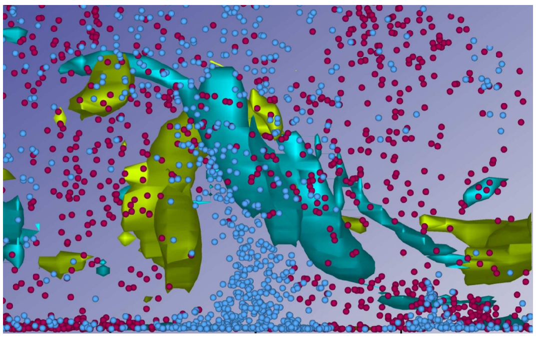

Figure 1: Vortices and inertial particles in aboundary layer. Different color for the vortices indicate clockwise or counter-clockwise rotaion in the streamwise direction. Blue particles are directed away from the wall; Purple particles are directed towards the wall

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We will elucidate concepts and modeling ideas derived from a systematic numerical study of the turbulent flow field coupled with Lagrangian tracking of particles under different modeling assumptions. We will underline the presence of the strong shear which flavors wall turbulence with a unique multiscale aspect and adds intricacy to the role of inertia, gravity and buoyancy in influencing particle motion. We will describe the role of free surface turbulence in dispersing and clustering the light particles such as plancton and the role of the distribution of dissipation in non-homogeneous turbulence to control breakage rates of brittle and ductile aggregates.

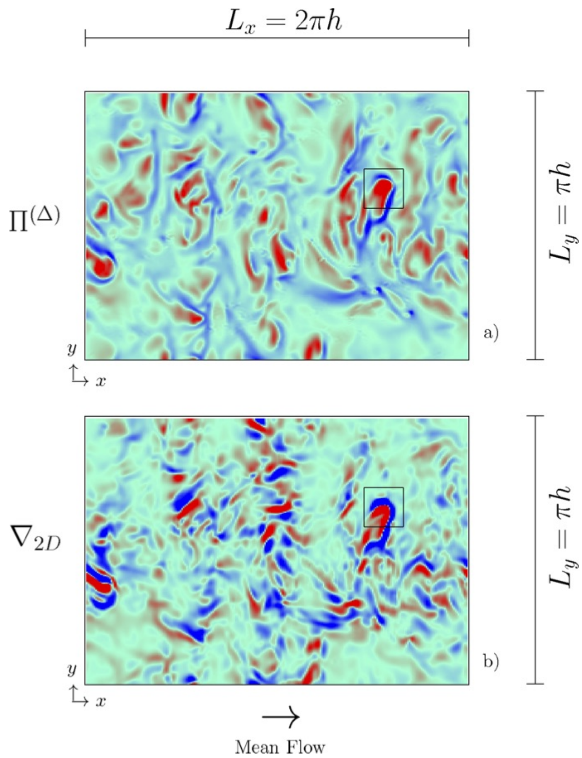

Figure 2: Contour maps of the energy flux (panel a) and of the two-dimensional surface divergence (panel b) computed at the free surface for Re = 509.

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Through a number of physical examples of practical interest such as boundary layers, free-surface and stratified flows, we will show that a sound rendering of turbulence mechanisms is required to produce a physical understanding of particle trapping, segregation and ultimately macroscopic flows such as surfacing, settling and re-entrainment.

The talk will start focusing on the role of inertia on a single particle in a vortex to discuss the effects of the wall vortices present in a turbulenyt boundary layer on particle deposition and re-entrainment. Specifically, we will give precise identification of coherent structures responsible for particle sedimentation and reentrainment [5]. A simulation snapshot elucidating this concepts is presented in Figure 1.

However, turbulence features change according with the geometric features of the flow. Some significant environmental problems are relative to free surface turbulence. The free surface turbulence, albeit constrained onto a two-dimensional space, exhibits features which barely resemble predictions of simplified two-dimensional modelling. In particular, in a three dimensional open channel flow, surface turbulence is characterized by upscale energy transfer which controls the long term evolution of the larger scales. This can be demosbtrated by associating downscale and upscale energy transfer at the surface with the trace of the velocity gradient tensor. A simulation snapshot elucidating this concepts is presented in Figure 2.

The presence of the inverse ebergy cascade at the free-surface is crucial in determining the pattern evolution of floaters and planctonc species. In particular it is possible to demonstrate that that particle buoyancy induces clusters that evolve towards a long-term fractal distribution in a time much longer than the Lagrangian integral fluid time scale, indicating that such clusters overlive the surface turbulent structures which produced them [1]. A simulation snapshot elucidating this concepts is presented in Figure 3.

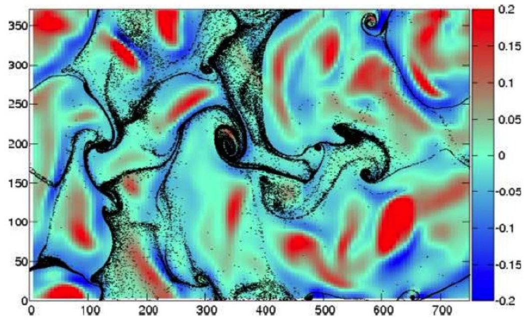

Figure 3: Light particles floating on a flat shear-free surface of a turbulent open water. This configuration mimics the motion of buoyant matter (e.g. phytoplankton, pollutants or nutrients). Correlation between floater clusters and surface divergence ∇_{2D}. Floaters segregatein $\nabla_{2D} < 0$ regions (in blue, footprint of subsurface downwelings) avoiding footprint of sub-surface upwelings). Particle buoyancy induces clusters that evolve towards a long-term fractal distribution in a time much longer than the Lagrangian integral fluid time scale, indicating that such clusters over-live the surface turbulent structures which produced them [4].

We will also discuss the effects of thermal stratification [6, 7] on the distribution of passive and active planctonic species and swimmers.

A final issue which will be addressed in this talk is the local shearing action induced by turbulence on the rupture of aggregates. Brittle and ductile aggregates will be examined and physics and statistical features of the rupture will be discussed [2, 3]. A simulation snapshot elucidating this concepts is presented in Figure 4.

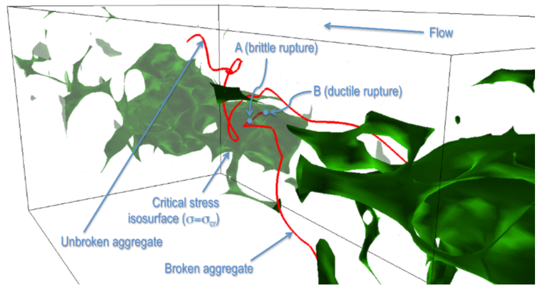

Figure 4: Rendering of brittle and ductile rupture in turbulent flow. The trajectory of two different aggregates is shown, superimposed onto the isosurface of the critical stress ?=?cr required to produce brittle rupture or activate ductile rupture. The broken aggregate trespasses the ?cr isosurface at point A (potential brittle rupture) and undergoes ductile rupture at point B (where the breakage condition $E > E_{cr}$ is met). The unbroken aggregate avoids all regions where $\sigma > \sigma_{cr}$ and does not break within the time window considered in this figure. Critical stress isosurface is taken at the time of ductile rupture. Aggregate trajectories are tracked several time steps backward from this time.

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