Particle transport in turbulent flows

L. Biferale, [1] M. Cencini, [2] A. S. Lanotte, [3] A. Seminara, [4] F.Toschi, [5]

[1]University of Tor Vergata and INFN, Via della Ricerca Scientifica 1, 00133 Rome, Italy

[2]INFM-CNR, SMC Dipartimento di Fisica, Università di Roma “La Sapienza”, Piazzale A. Moro, 2 I-00185 Rome, Italy

[3]CNR-ISAC Istituto di Scienze dell’Atmosfera e del Clima, 00133 Roma, and INFN, Sez. di Lecce, Italy

[4]Harvard University, School of Engineering and Applied Sciences, 29 Oxford Street, 02138, Cambridge - MA, USA

[5]Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands and CNR-IAC, 00161 Roma, and INFN, Sezione di Ferrara, 44100 Ferrara, Italy

Fluid turbulence is part of our every day life, being ubiquitous in both natural and cosmic environments, in engineering and medical applications. Quite commonly, such flows are seeded by dust, soot, droplets, bubbles, and other particulate matter whose transport and mixing properties are governed by the chaotic nature of the flow. The dynamics and growth of particles in a fully-developed turbulent flow is fundamental to science as well as to technology- examples of open scientific issues include rain formation in clouds, pollution dispersion in the atmosphere, scavenging phenomena, optimization and emission reduction in combustion, plankton population dynamics, and constitute a major scientific challenge for fundamental research and for practical implications.

The recent research activity has focused on the study the dynamical and statistical features of particle suspensions in fully developed turbulent flows. Turbulence means the presence of non linear interactions of many degrees of freedom, with huge fluctuations taking place from the scale where energy is injected - from meters to kilometers- to the scale where energy is dissipated by viscosity, ranging from microns to millimeters [1]. The adimensional parameter controlling the status of turbulence is the Reynolds number, whose values can significantly change from laboratory or numerically simulated flows ($Re_\lambda \sim 400 - 600$) to natural flows ($Re_\lambda \sim 10^4$). Particulate matter seeding the flow are small, finite-size objects, whose density can be much smaller or much higher than that of the advecting fluid. Because of the density mismatch, such particles do not simply follow flow streamlines as tracers do (neutrally buoyant small particles): the description of their motion must account for inertia whence the name *inertial particles.* A distinctive feature of inertial particles is that they do not distribute homogeneously in the flow as fluid tracers do. More precisely, at long times after the injection, particles concentrate on fractal sets evolving with the fluid motion, leading to the apparition of a strong spatial inhomogeneity dubbed *preferential concentration.* These inhomogeneities are due to correlations among particle positions and the local properties of the flow: light particles, such as air bubbles in water, concentrate in vortical regions of the flow forming filament clusters within turbulent eddies. On the opposite heavy particles, such as water drops in air, avoid regions of the flow with intense vorticity (see e.g. in Figure 1, an example of the instantaneous spatial distribution of heavy particles in a numerically simulated turbulet flow).

During the last year, we have focused our attention of the behaviour of *heavy* inertial particles, dispersed in statistically homogeneous and isotropic incompressible turbulent flows. By means of high resolution direct numerical simulations (DNS) of three dimensional flows at different Reynolds number $Re_\lambda \in [100; 400]$ (i.e. numerical resolution of 512^3, 1024^3 and 2048^3 grid points), we have followed the motion of millions of particles, with different degree of inertia. This is expressed in terms of the adimensional Stokes number $St = \tau_p/\tau_\eta$, where τ_p is the particle response time to fluid fluctuation, while τ_η is the fluid time scale associated to the viscous scale (or Kolmogorov time).

We have compared numerical data to those obtained in laboratory experiments - realised at the Max Planck Institute in Gottingen-, at similar values of the order parameters of the system (Reynolds and Stokes numbers). By integrating information from experiments and numerics, a quantitative understanding of the velocity scaling properties over a wide range of time scales and Reynolds numbers was achieved. By a systematic study of the possible source of statistical errors and bias affecting experimental and numerical

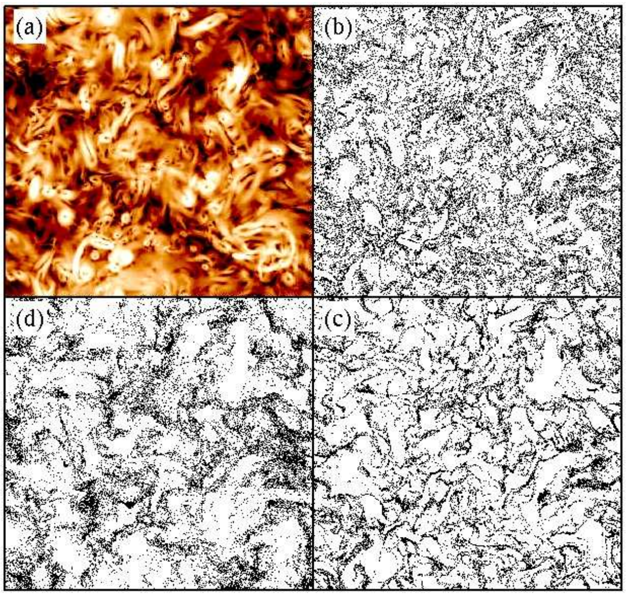

Figure 1. (a) The modulus of the pressure gradient, giving the main contribution to fluid acceleration, on a slice $512 \times 512 \times 4$. B/W code low and high intensity, respectively. Heavy particle positions in the same slice are shown for (b) $St = 0.16$, (c) 0.80 and (d) 3.30. Note that heavy particles positions correlate with regions of low acceleration (low vorticity). Note also the presence of voids with sizes much larger than the dissipative scale (i.e. about 1 in the grid unit).

measurements, we could resolve apparent disagreement between observed scaling properties of the Lagrangian particle velocity [2]. Also, in collaboration with different numerical and experimental groups, the universality properties of Lagrangian velocity statistics in statistically homogeneous and isotropic flows have been studied, and it has been shown that the Parisi-Frisch Multifractal theory, suitably extended to the Lagrangian domain, is able to capture intermittency of velocity statistics over the whole rage of time scales investigated [3].

Finally, the growth of cloud droplets by diffusion of water vapor in a three-dimensional homogeneous isotropic turbulent flow has been considered [4]. For this, we performed a series of high resolution DNS, describing the motion of liquid water droplets under the effect of the Stokes drag and of gravity. Particles were moreover immersed in a space-time varying supersaturated vapour field (Twomey model), passively advected by the flow. Even if in a much simplified situation, as compared to real cumulus clouds, we could show that droplet size spectrum broadening is observable and that it increases with the Reynolds number of turbulence. This is a key point towards a proper evaluation of the effects of turbulence for condensation in warm clouds, where the Reynolds number typically achieve extreme values. The obtained droplet spectral broadening as a function of the Reynolds number was shown to be consistent with dimensional arguments. A generalization of this expectation to Reynolds numbers not accessible by DNS was proposed, yielding upper and lower bounds to the actual size-spectra broadening.

Acknowledgment
Numerical simulations were performed at the supercomputing center CINECA (Italy). Raw data from our numerical simulations can be downloaded freely from the web site of the iCFD-database HTTP://CFD.CINECA.IT.

REFERENCES

1. Uriel Frisch, "Turbulence: the legacy of A.N. Kolmogorov", Cambridge University Press, Boston (1995).
2. L. Biferale, E. Bodenschatz, M. Cencini, A.S. Lanotte, N.T. Ouellette, F. Toschi, & H. Xu, *Lagrangian Structure Functions in Turbulence: A Quantitative Comparison between Experiment and Direct Numerical Simulation*, Phys. Fluids 20, 065103 (2008).
3. A. Arneodo et al., *Universal Intermittent Properties of Particle Trajectories in Highly Turbulent Flows*, Phys. Rev. Lett. 100 254504 (2008).
4. A.S. Lanotte, A. Seminara & F. Toschi, *Cloud droplet growth by condensation in homogeneous isotropic turbulence*, DOI: 10.1175/2008JAS2864.1 in press on J. Atmos. Sci. (2009).