Scientific problems in turbulence

R. Benzi, L. Biferale, G. Boffetta, C.M. Casciola, M. Cencini, A. Mazzino, P. Gualtieri, R. Piva, S. Succi,F. Toschi

This short note is the result of meeting in Roma on the 16th march 2007. The participants to the meeting were: R. Benzi, L. Biferale, G. Boffetta, C.M. Casciola, M. Cencini,A. Mazzino, P. Gualtieri, R. Piva, S. Succi, F. Toschi. During the meeting, we discuss several questions concerning turbulence and in particular our possible support to the forthcoming CERN initiative on laboratory experiments with cryogenic system.

The Italian research groups represented in the meeting are all extremely interested in the CERN initiative. Although none of us is working in laboratory experiments, we can provide our skill and competence to work on the scientific questions the experiments in CERN may be able to answer. If it is needed, we can provide the appropriate skills to perform high resolution numerical simulations based on a number of different numerical schemes and physical situations.

Concerning the scientific questions, although there is not such a thing like a "turbulence problem", we all feel that there are well defined scientific problems whose answer can eventually define a theoretical framework to understand turbulent flows and their statistical properties. Here we list some of the most relevant ones.

1) **Universal properties of small scale intermittent fluctuations.** In the last twenty years there has been an extraordinary effort to understand the scaling properties, if any, of fully developed turbulence. In particular, the question of intermittency or anomalous scaling have been the focus of a number of experiments and numerical simulations. Also, theoretical ideas, in the framework of the multifractal model by Parisi and Frisch, have been tested against experimental results. Recently an important breakthrough have been achieved in the study of passive scalar turbulence. New concepts and ideas have been introduced in the study of turbulence. For the case of passive scalar, and related problems, we can now provide theoretical arguments to prove that the statistical properties of passive scalar fluctuations shows anomalous scaling independent, for large enough Reynolds number, to the large scale forcing as well as to the way energy is dissipated at small scales, i.e. anomalous scaling is universal with respect to infrared and ultraviolet boundary conditions. Most of the scientific community believes that universality is a feature of the Navier-Stokes equations, but we still need to provide theoretical arguments to show that this is indeed the case. Laboratory experiments at large Reynolds number can provide us with the experimental data to check whether or not universality is observed. Also, many theoretical predictions based on the multifractal theory are still to be checked for large Reynolds number flows.

2) **The dissipative structures of turbulent flows** So far most of the laboratory experiments as well as numerical simulations have been focused on the statistical properties of small scale turbulence. One important point concerning turbulence is the behavior of the dissipation range, i.e. the set of scales where non linear effects are balanced by the dissipation effect. There are different theories which have been proposed to study the dissipation range. Also, a clear definition of the dissipation range is still missing. At the dissipation scale, numerical simulations show that the dynamics can be described in terms of coherent structures, i.e. vortex filaments. Are these structure compatible with the anomalous scaling? Can one predict the statistical properties of the dissipation range regardless the vortex filaments? How is intermittency and anomalous scaling related to dynamics of vortex filaments in the dissipation range? Is the nature of vortex filaments related to similar structures observed in wall bounded turbulence? These are just small sample of questions related to the dissipation range that the scientific community is trying to address and to investigate. We consider these questions of primary importance in understanding the physics of turbulence and we look forward to any experiments in this direction.

3) **Rayleigh Benard convection** Despite the major effort in understanding the dynamics of Rayleigh Benard convection, there are a number of different questions one is looking forward to solve. The CERN initiative provide an unique opportunity to investigate RB turbulence at large Rayleigh number. We want to add on this particular point a related subject which we consider important to address, namely the Rayleigh Taylor turbulence. In an appendix, we provide a short introduction to the problem, its scientific relevance and a list of open questions.

4) **Turbulent in non isotropic flows and in channel flows**. One of the basic idea underlying the Kolmogorov theory on turbulence, is that for large enough Reynolds number and small enough scale, turbulence can be considered to be homogenous and isotropic. On the other hand there important physical situations, like wall bounded turbulence, where most of the turbulence dynamics, for instance drag effects, happens to concentrate in regions where turbulence can never be considered isotropic. Are we able to provide a general theory of non isotropic turbulence? Are any feature of universality preserved in non isotropic turbulence? There are many questions which need to be investigated starting from our knowledge on isotropic and homogenous turbulence. There exist many different theoretical ideas which need to be tested against accurate experimental results at large Reynolds number. Again, the CERN initiative may provide an unique opportunity to solve some of the above questions.

5)**Turbulence and roughness** There are a number of fascinating and important physical problems in turbulence which deserve attention from the scientific community. Turbulent channel flows on rough surfaces provide a nice example of a fundamental question which is still need to be investigate accurately. Scaling properties of bulk quantities (energy dissipation, drag, mean velocity profile)

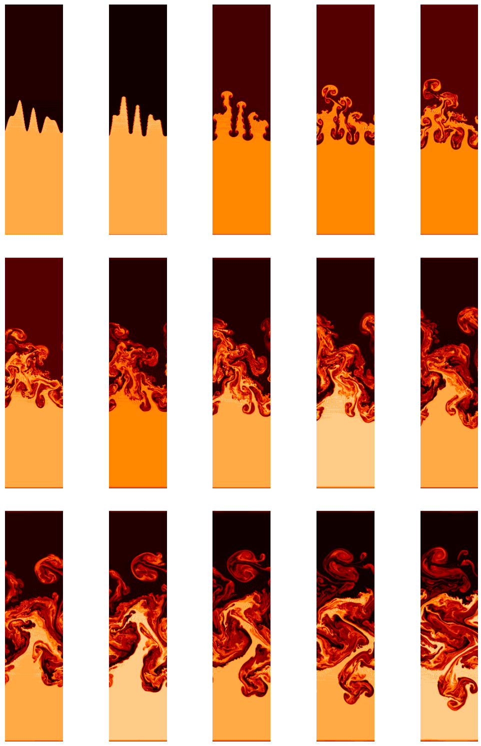

Figure 1: Time evolution of a perturbation imposed to the interface separating two fluids of different densities. From the numerical simulations of Ref. [8]

are poorly investigated in literature both experimentally and theoretically. High Reynolds number are needed in order to assess scaling properties, if any. We argue that this problems, as well as similar problems related to basic turbulent flows (jets, rotating turbulence,..) are extremely worthwhile to be investigated in future laboratory experiments.

Rayleigh Taylor turbulence

The Rayleigh–Taylor (RT) instability is a well-known fluid-mixing mechanism occuring when a light fluid is accelerated into a heavy fluid (see Fig. 1). For a fluid in a gravitational field, such a mechanism was first discovered by Lord Rayleigh in the 1880s [1] and later applied to all accelerated fluids by Sir Geoffrey Taylor in 1950 [2].
RT instability plays a crucial role in many field of science and technology. Its deep understanding is thus important to a wide variety of applications, including inertial

confinement fusion, nuclear weapons explosions and stockpile management, and supernova explosions.
Avoiding RT instability in inertial confinement fusion applications requires both very high precision in the target manufacture, and very high uniformity in the heating of the outside of the capsule–that is, very high symmetry.
RT instabilities emerge in the implosion of both a fission primary device and a fusion secondary device. In the case of the fission primary, the instability arises when the shock wave from the lighter high explosive detonation reaches the much denser tamper. In the case of a fusion secondary, the instability arises when the lighter radiation implosion plasma in the hohlraum reaches the metalic core of the secondary. Hydrodynamic instabilities play a major role in determining the efficiency and performance of inertial confinement fusion implosions. In laser-driven implosions, high-performance capsules require high aspect ratios (the ratio of the radius to the shell thickness). These capsules are susceptible to hydrodynamic instabilities of the Rayleigh-Taylor, Richtmyer-Meshkov, and Kelvin-Helmholtz varieties, which can in principle severely degrade capsule performance.

Rayleigh-Taylor instabilities develop behind the supernova blast wave on a time scale of a few hours. The importance of the RT instability and turbulence in accelerating a thermonuclear flame in Type Ia supernovae (SNe Ia) is well recognized. Flame instabilities play a dominant role in accelerating the burning front to a large fraction of the speed of sound in a Type Ia supernova. The Kelvin-Helmholtz instabilities accompanying the RT in-stability in SNe Ia drives most of the turbulence in the star, and, as the flame wrinkles, it will interact with the turbulence generated on larger scales.

A deeper understanding of the mechanism of flows driven by RT instability would shed light on the many processes that underpin fully developed turbulence.

The difficulty inherent in sustaining an unstable density stratification has challenged experimentalists for over half a century. Several innovative approaches have been recently developed (see e.g. [3]).

With the advent of supercomputers, high-resolution 3D numerical simulations of RT at high Reynolds numbers have become a reality. However, simulations using many different benchmark codes and experiments disagree already on apparently innocent observables like, for instance, the value of the growth constant α associated with the spread of the turbulent mixing zone (see e.g. [4]). The differences are higher by 100 %.

Despite the long history of RT turbulence, a consistent phenomenological theory has been presented only very recently by Chertkov [5]. For the statistics inside the mixing zone, different behaviors are expected for the 3D and the 2D case. About the former, the “5/3”-Kolmogorov scenario [6] is predicted, while the Bolgiano picture [7] is expected for the 2D case. The latter scenario has recently been verified in [8] by means of direct numerical simulations.

Up to now, neither experimental results nor high resolution direct numerical simulations had been able to verify the theoretical prediction by Chertkov in 3D. In our opinion this is a crucial limitation of the current investigations which need to be rapidly overcame. In this respect, the opportunity to carry on accurate experiments exploiting the facilities at CERN gives an exciting possibility to improve our knowledges on RT turbulence.

To be more specific, here is a list of physically relevant points to be addressed:

1. Give the first experimental verification of the mean field theory by Chertkov for RT turbulence.
2. Investigate the relationships between Rayleigh–Taylor turbulence and Rayleigh–Bènard turbulence. The adiabatic scenario proposed by Chertkov suggests close statistical relations between the two systems.
3. Provide the first evidence of the so-called "ultimate state of thermal convection", still elusive for the classical Rayleigh–Bènard turbulence.
4. Identify universality classes for RT turbulence. As an example, an important question to address is on whether the statistics of the temperature field in RT turbulence is equivalent (i.e. in the sense of having the same scaling exponents and, eventually, the same prefactors) to that of a passive scalar evolving in the same velocity field as the one sees by the temperature.
5. Investigate whether RT flows retain memory of their initial conditions. Such memory effect has recently been postulated to explain the discrepancy between experiments and simulations in relation to the growth constant associated with the spread of the turbulent mixing zone.

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