Chapter 1

Introduction

Turbulent motion has proved to be one of the most untractable problems of the physical sciences in the last century and has a wide range of applications in many fields of engineering and science. It is therefore important to understand the fundamental mechanisms at work in such complex flows. Turbulence flows are unsteady and contain fluctuations in space and time, which are the result of a subtle balance of terms involving many different length-scales and frequencies, and a detailed description of all possible states is not possible. This fact presents some of the most difficult problems in the fundamental understanding of the physics of turbulence, which is still unresolved.

In everyday life one may observe turbulence on a number of occasions: the smoke from a cigarette or over a fire exhibits a disordered behavior characteristic of the motion of the air which transports it. When we walk on the beach with wind in our face, when we watch the unsteady performance of our kite high up in the air we are experiencing turbulence. During air travel, one often hears the word turbulence generally associated with the fastening of seat-belts. The flow of water in rivers is turbulent. The wakes of cars, ships, submarines and aircraft are turbulent. The photosphere of the sun and the photospheres of similar stars are all in turbulent motion. All these turbulent motions show that large vortices in such motion are unstable and break up into smaller vortices. However, it is very difficult to give a precise definition of turbulence. Until now, there is still no universal description of turbulence, and most researchers try to describe it in one sentence:" *Turbulence is the disordered behavior of a fluid in space and time*".

Hinze (1959) in his book defines turbulence as follows:" *Turbulent fluid motion is an irregular condition of flow in which the various quantities show a random variation with time and space coordinates, so that statistically distinct average values can be discerned.*". According to Hinze, the turbulent motion of each part of the fluid is irregular in space and time. For a more detailed introduction to the subject the reader is referred to Bachelor (1953), Townsend (1956), Lin (1959), Lumley and Panofsky (1964), Monin and Yaglom (1975), Frisch (1995) and Lesieur (1997). Figure 1.1 shows the random velocity fluctuations of cylinder wake turbulence as a function of time, where the complexity of the velocity random fluctuations may be observed.

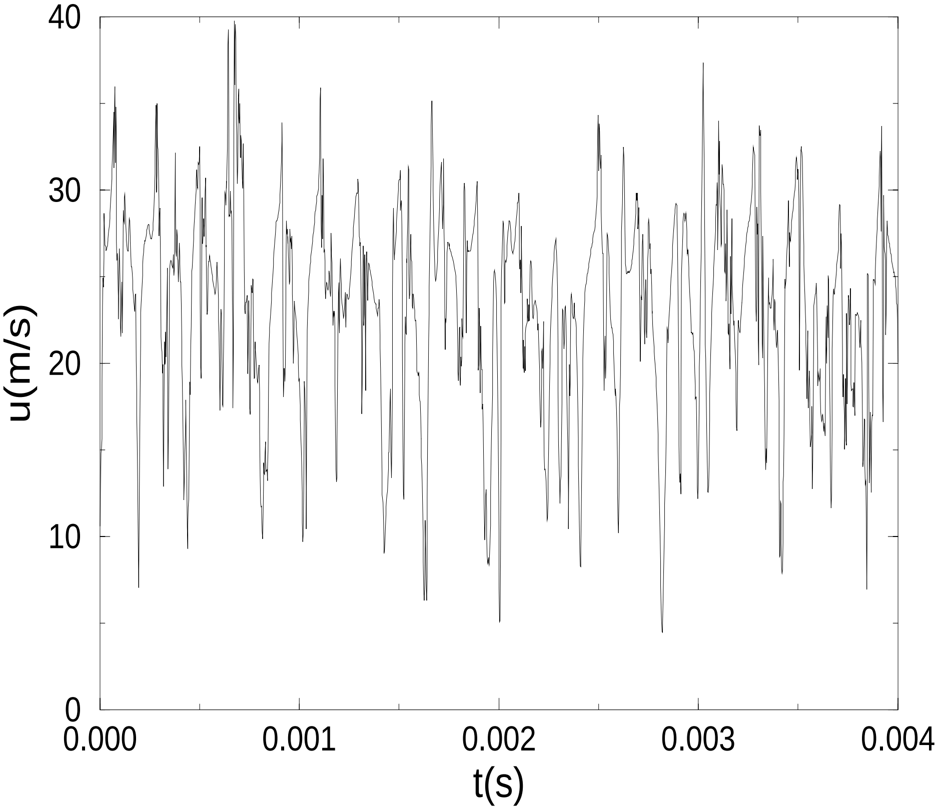

Figure 1.1: Velocity fluctuations as a function of time, measured in cylinder wake turbulence.

Tennekes (1972) proposed a list of some basic characteristics of turbulent flows. So, a turbulent flow is or exhibits:

- *Irregularity or randomness*: the turbulent flow is unpredictable.
- *Diffusivity*: which causes rapid mixing and increased rates of momentum, heat

and mass transfer.

- *High Reynolds number*: turbulent flows always occur at high Reynolds numbers.
- *Three-dimensional vorticity fluctuations*: Turbulence is rotational and three dimensional.
- *Dissipation*: turbulent flows are always dissipative.
- *Continuum*: turbulence is a continuum phenomenon, governed by equations of fluid mechanics.
- *Flows*: turbulence is a feature of fluid flows and not of fluids.

One of the principal parameters controlling the turbulence is the Reynolds number, which is a dimensionless characteristic parameter of the flow,

$$Re = \frac{LV}{\nu}, \tag{1.1}$$

where V is the mean velocity of the flow, ν is the kinematic viscosity of the fluid and L is the integral scale of the large eddy can be generated in the flow. If the Reynolds number is not too large, the flow will be laminar. At higher Reynolds number, the flow becomes chaotic in both space and time. It is this spatiotemporal chaos that is called fluid turbulence.

In fact it is not easy to solve the turbulence problem, because it is not a totally random process, and it has not been possible to find a theory that describes the phenomenon completely. We do not yet have a set of equations that could be used to efficiently compute turbulent flows. The complexity of turbulence is also related to the fact that it is not a perfect random process, with a large number of scales of the flow playing an important role. The fundamental dynamical equations that govern turbulent flow are the Navier-Stokes equations, their computational complexity becomes intractable for large Reynolds numbers. This is a system of coupled non-linear partial differential equations and must be supplemented by initial and boundary conditions. The development of a statistical theory for turbulent fluctuations from the Navier-Stokes equations is always faced with the closure-problem. This means that one has a set of $n-1$ equations with at least n unknown variables in it. Many attempts have been made to realize plausible closures, as in Computational Fluid Dynamics the *one-equation models*, the *two-equation models* (e.g. the mixing length model and the $k-\epsilon$ model) and the *second-order closure* models. Moreover, since computers have recently become powerful enough to simulate some flows of (engineering) interest, there exist some models for some specific flows. However, these models are not *universal*.

Hence, turbulence is often referred to as the unsolved problem of classical physics and is often an important item of discussion at conferences. Most studies of turbulent flow were only devoted to homogeneous and isotropic turbulence. However, homogeneity and isotropy can even be questionable in the small scales. Figure 1.2 shows three different flows configurations: cylinder wake turbulence, jet turbulence and grid turbulence respectively. These pictures of the experimental facets of turbulence, taken from the book of Van Dyke (1982) "An Album of Fluid Motion" and from Lesieur (1997) Book "Turbulence", are visualized by the laser induced fluorescence illumination technique, and show clearly the important role of the large scale coherent structures and the induced non-homogeneity.

Richardson (1922) proposed fully developed turbulence as a hierarchy of eddies of different size. In his scenario, he assumed a cascade process of eddies breaking down. At eddies of size L energy is injected, then energy is transmitted to smaller and smaller eddies, and finally it is dissipated in small eddies of scale η where viscosity plays a dominant role. The mean rate of energy transfer per unit mass plays a central role in this scheme. The Navier-Stokes equation, which describes the evolution of the velocity field v of the fluid is:

$$\frac{\partial \vec{v}}{\partial t} + \vec{v}.\nabla\vec{v} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\vec{v} + \vec{f} \tag{1.2}$$

where ρ is the mass density, p the pressure and ν the dynamic viscosity. The term $\vec{v}.\nabla\vec{v}$ is called the nonlinear term and implies a breaking of bigger eddies into smaller eddies, the term $\nu\nabla^2\vec{v}$ is called the viscous term and represents a dissipation of kinetic energy as internal energy of fluid, while the term $\vec{f}$ represents the external forcing acting on the fluid. However, though the main ideas of energy supply, energy transfer and energy dissipation are common to both schemes, it is very difficult to produce a definitive quantitative relation between the two descriptions.

Further, Kolomogorov (1941) based on Richardson's cascade idea, studied fully developed turbulence, i.e. turbulence which is free to develop without imposed constraints, from an especially illuminating perspective, which is reviewed in any standard textbook on turbulence or fluid mechanics (Landau and Lifshitz (1987), Monin and Yaglom (1975), Frisch (1995)). Kolmogorov (1941) made the bold assumption that turbulence should exhibit universal and isotropic statistics for scales smaller than the integral scale L. Moreover, for scales larger than the Kolmogorov's scale η, the viscosity should play no dynamical role. There is then a range of length scales called the *inertial range*, in which the flow statistics are expected to be universal, isotropic and independent of the viscosity. Since then extensive experimental and numerical studies have attempted to describe the statistical behavior of fully developed turbulence. Landau (see Frisch (1995)) was the first to point out that the Kolmogorov's theory of 1941 could not be true because he did not take into account intermittency. Landau stated that the energy dissipation displays important fluctuations about its mean value. A consequence is that Kolmogorov's (1941) theory, which does not take into account the fluctuations of the energy dissipation must certainly be corrected in order to contemplate this intermittent character. By taking note of Landau's suggestion, Kolmogorov and Oboukhov (1962) introduced a refined similarity hypothesis called *log-normal* model. In this version, they assumed that the energy dissipation is log-normally distributed.

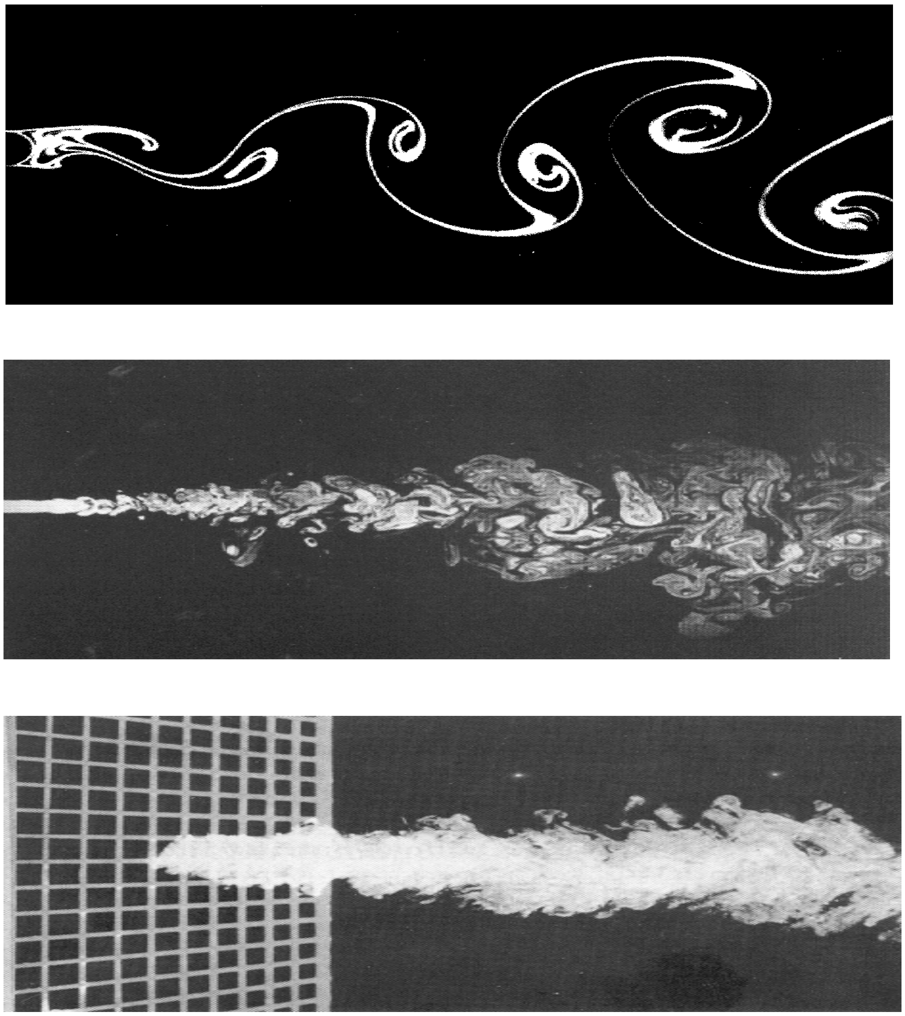

Figure 1.2: Turbulent flows in three different configurations, from the top down: cylinder wake turbulence (Van Dyke 1982), jet turbulence (Van Dyke 1982) and grid turbulence (Lesieur 1997).

After the refined similarity hypothesis, different types of intermittency models were proposed to describe the turbulence cascade and particularly the behavior of scaling exponents (Novikov & Stewart (1964), Frisch *et al*. (1978), Meneveau & Sreenivasan (1987), Frisch & Vergassola (1991) and She & Leveque (1994)). Most of these models have been formulated in terms of either the moments of absolute values of velocity differences or the moments of dissipation. The success of these models can be evaluated chiefly on the basis of how well they agree with experiments. However, there are no models that agree with all experiments, although each model works quite well within a limited domain of available data. Therefore, it is not possible to generally recommend one model over the others. Some of the most popular models for fully developed turbulence are: She-Leveque model (She and Leveque (1994)), p-model (Meneveau and Sreenivasan (1987)), β-model (Frisch *et al*. (1978)) and random β-model (Benzi *et al*. (1984)).

Unfortunately, real turbulent flows, such as geophysical flows, are neither homogeneous nor isotropic. It is difficult to study their dynamics because of the increase of the flow complexity. Most of these flows show the presence of coherent structures, which affect the statistical properties of the structure functions and increase the inhomogeneity of turbulent flows. These coherent structures can be defined as a region of space which at a given time has some kind of organization regarding any quantity related to the flow (velocity, vorticity, pressure, density, temperature, etc.).

The central topic of this research is the understanding of the dynamics of non-homogeneous turbulent motions. Measurements of the absolute scaling exponents of the velocity structure functions for the three different flow configurations at different locations on the turbulent flows, show them to be scale-dependent. The Extended Self Similarity proposed recently by Benzi *et al*. (1993) gives a new scaling based on relative scaling exponents that seems to be a scale-independent but not uniform. It would be different in various flows or various locations of the same flow. So, the basic question is the following: is the intermittency a general tool able to determine the most important dynamical properties of non-homogeneous turbulence? Recently, Babiano *et al*. (1997) proposed a model to analyze non-homogeneous turbulence. This model is based on the statistical properties of the absolute energy transfer at scale ℓ, which is related to the non-linear term of the Navier-stokes equation and is estimated from the third-order structure function. In this model the nonlocal dynamics on the velocity structure functions is separated from the intermittency phenomenon, and I will apply this new tool to different complex and realistic flows.

1.1 Outline

In this thesis the second chapter on *Homogeneous turbulence* reviews the most important models for fully developed turbulence, starting with Kolmogorov's theory K41, the log-normal model K62 and She-Leveque model. In these models the importance of structure function and their scaling exponents are stressed. Furthermore the search for more general homogeneous models, which lead the way to more realistic theories, is contained in this chapter.

Chapter 3 describes the theory of *Non-homogeneous turbulence*. We start with a non-uniform energy dissipation random field, then we describe the method of Extended Self Similarity (ESS), Benzi *et al*. (1993). Finally, we describe the Dubrulle (1994) and Babiano *et al*. (1997) models. The last one will be used as the key model of non-homogeneous turbulence throughout this thesis.

In chapter 4 we describe the *Experimental set-ups* used to generate the non-homogeneous flows and to measure longitudinal velocity fluctuations. Different techniques were used such as: hot-wire with constant temperature anemometry (CTA) and sonic velocimeter Sontek 3D. We also describe the wind tunnel, the water channel and the three different basic flow configurations contained in this thesis: cylinder wake turbulence, jet turbulence and grid turbulence.

In chapter 5 we present the *Experimental results* of the three types of experiments. For the cylinder wake turbulence, which was measured at the highest frequency and accuracy, we present the experimental results of energy spectrum, third order structure function, absolute scaling exponents, relative scaling exponents up to the sixth order, hierarchy transfer, intermittency and probability distribution function at different downstream distances and for three lateral distances from the cylinder symmetry plane. Due to the lower resolution and lower statistical accuracy of jet and grid data, only the third order structure function, absolute scaling exponents, relative scaling exponents and intermittency are presented at different downstream distances in the axisymmetric axis of the flows.

In chapter 6 we give some applications in real life *Geophysical flows*. The data were collected in the Ebro Delta (Spain) and in Knebel Vig Bay (Denmark). In the first experiment, the velocity fluctuations were collected by means of 2D Electromagnetic sensors (EMS) that will described in the same chapter and in the second, the velocity fluctuations were collected by means of sonic velocimeter SONTEK-3D described in chapter 4. We report similar data to those presented for the laboratory experiments stressing how to evaluate the intermittency caused by the non-homogeneous structure of the wave generated turbulence.

In chapter 7 we give some general conclusions concerning laboratory and geophysical data.