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Relative dispersion of particle pairs in turbulent channel flow

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ABSTRACT

Lagrangian tracking of particle pairs is of fundamental interest in a large number of environmental applications dealing with contaminant dispersion and passive scalar mixing. The aim of the present study is to extend the observations available in the literature on relative dispersion of fluid particle pairs to wall-bounded turbulent flows, by means of particle pair tracking in direct numerical simulations (DNS) of a turbulent channel flow. The mean-square change of separation between particle pairs follows a clear ballistic regime at short times for all wall distances. The Eulerian structure functions governing this short-time separation are characterised in the channel, and allow to define a characteristic time scale for the ballistic regime, as well as a suitable normalisation of the mean-square separation leading to an overall collapse for different wall distances. Through fluid particle pair tracking backwards and forwards in time, the temporal asymmetry of relative dispersion is illustrated. At short times, this asymmetry is linked to the irreversibility of turbulence, as in previous studies on homogeneous isotropic flows. The influence of the initial separation (distance and orientation) as well as the influence of mean shear are addressed. By decomposing the mean-square separation into the dispersion by the fluctuating velocity field and by the average velocity, it is shown that the influence of mean shear becomes important at early stages of dispersion close to the wall but also near the channel centre. The relative dispersion tensor Δ_{ij} is also presented and particularly the sign and time evolution of the cross-term Δ_{xy} are discussed. Finally, a ballistic cascade model previously proposed for homogeneous isotropic turbulence is adapted here to turbulent channel flows. Preliminary results are given and compared to the DNS. Future developments and assumptions in two particle stochastic models can be gauged against the issues and results discussed in the present study.

1. Introduction

The transport and mixing of passive components by turbulent flows are commonly encountered in a large number of environmental and industrial applications. Many atmospheric pollution studies have investigated contaminant dispersion in the context of Lagrangian tracking of single particles (Hoffmann et al., 2016; Fung et al., 2005; Angevine et al., 2013). In these studies, mesoscale meteorological models are often coupled with a Lagrangian particle dispersion model providing a numerical method for simulating the dispersion of passive pollutants in the atmosphere by means of a large ensemble of Lagrangian particles moving with the modelled flow velocity field (Fung et al., 2005). Recently, relative displacement measurements from balloons and drifters have been conducted both in the atmosphere and the ocean (Lumpkin and Elipot, 2010; LaCasce, 2010; Koszalka et al., 2009).

Relative pair dispersion is of theoretical interest because particle pairs simultaneously sample the velocity field at different positions. In fluid flows, the short-term mean-square difference between tracer particle velocities is equivalent to the second-order Eulerian velocity structure function, which is related to the turbulent kinetic energy spectrum. The turbulent kinetic energy at a particular scale determines how a tracer cloud is stirred relative to its centre of mass.

In the last few decades, advances in experimental techniques and computational power have enabled the characterisation of particle trajectories and relative pair dispersion in canonical turbulent flows. Most of these studies have dealt with fluid tracers in homogeneous isotropic turbulence (HIT) and have led to a greatly increased understanding of the Lagrangian properties of turbulent flows (Toschi and Bodenschatz, 2009), and in particular, of the mechanisms of transport and diffusion of tracer particles in isotropic flows. A review on recent advances in experiments, direct numerical simulations (DNS) and theoretical studies on particle pair dispersion has been provided by

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Salazar and Collins (2009), additionally to the review of Sawford (2001) on two-particle Lagrangian stochastic models. As described by Sawford (2001), particle pair Lagrangian stochastic models are a suitable tool for predicting dispersion of contaminant plumes in turbulence, since separation statistics of particle pairs can be directly related to the concentration covariance and to the dissipation of scalar fluctuations.

Fewer studies have dealt with particle pair dispersion in anisotropic and inhomogeneous turbulence, which is however ubiquitous in atmospheric flows. In particular, most real flows are characterised by the presence of mean shear or solid boundaries, which effectively suppress the movement of the fluid in the wall normal direction. This results in turbulent flows that are anisotropic due to the presence of a mean shear, and inhomogeneous because of confinement by the walls. Near the walls, turbulent fluctuations are mainly described by the formation of large-scale organised structures that are elongated in the mean flow direction (Smits et al., 2011; Stanislas, 2017).

As first described by Richardson (1926), turbulence can greatly enhance the pair separation process. In his seminal paper, Richardson proposed that the separation of two tracers in a turbulent flow can be described (in a statistical sense) by a diffusive process, with a non-constant diffusion coefficient $K(D)$ which depends on the separation D between the two particles. When D is within the inertial subrange of a turbulent flow (that is, much larger than the dissipative scale η and much smaller than the scale of the largest turbulent eddies L), Richardson found from measurements that the diffusion coefficient $K(D)$ is proportional to $D^{4/3}$, which is since known as Richardson's 4/3 law. As later shown by Obukhov (1941), the same relation can be derived from dimensional arguments in the framework of K41 local isotropy theory (Kolmogorov, 1941). This requires the additional hypothesis that there is a loss of memory of the initial condition, such that the initial pair separation D_0 no longer plays a role in the separation process (Batchelor, 1950). As a consequence, the mean-square separation between two particles is expected to grow as $\langle D^2(t)\rangle = g\varepsilon t^3$ when D is in the inertial subrange, where ε is the mean turbulent energy dissipation rate, and the non-dimensional coefficient g, known as Richardson's constant, is expected to have an universal value.

As mentioned above, the initial separation D_0 must be taken into account at short separation times (Batchelor, 1950). This dependency can be expressed as a short-term ballistic growth of the mean-square separation:

$$\langle \mathbf{R}(t)^2\rangle = \langle (\mathbf{D}(t) - \mathbf{D}_0)^2\rangle = \langle \delta \mathbf{v}_0^2\rangle t^2 \quad \text{for } t \ll t_B, \tag{1}$$

where $\mathbf{D}(t)$ is the instantaneous particle separation vector and $\mathbf{D}_0 = \mathbf{D}(0)$, $\delta\mathbf{v}_0$ is the initial relative velocity between the particles, and t_B is a characteristic time scale of the ballistic regime, that may be related to the characteristic time scales of the turbulent flow. Eq. (1) can be obtained from the Taylor expansion of $\mathbf{D}(t)$ about $t = 0$. The average $\langle\cdot\rangle$ is taken over an ensemble of particle pairs initially separated by $\mathbf{D}_0$. In HIT, if $D_0 = |\mathbf{D}_0|$ is within the inertial subrange, the ballistic time t_B may be taken as proportional to the eddy-turnover time at the scale D_0 (also referred to as the Batchelor time scale), i.e. $t_E = D_0^{2/3}\varepsilon^{-1/3}$ (Batchelor, 1950).

By following two million passive tracers in a direct numerical simulation, Biferale et al. (2005) found high levels of intermittency for travel times up to ten Kolmogorov time scales in pair dispersion statistics in HIT at $Re_\lambda = 260$. The authors proposed an alternative method for calculating Richardson's constant by computing statistics at fixed separations. Also in HIT, Rast and Pinton (2011) studied pair dispersion by analysing the time scale t_B during which particle pairs remain together before the separation increases significantly in a simplified point-vortex flow model. The authors suggested that pair separation may be understood as an average over separations which follow Richardson's scaling but each over a fluctuating time delay t_B.

Relative dispersion in HIT is known to be a time-asymmetric process. That is, when fluid particles are tracked backwards in time (starting from an imposed *final* separation), they tend to separate faster than in the forward case (Sawford et al., 2005; Berg et al., 2006; Buaria et al., 2015). Recently, Jucha et al. (2014) and Bragg et al. (2016) linked this temporal asymmetry at short times to the irreversibility of turbulence, which can be understood as the directionality of the turbulent energy cascade (from large to small scales in 3D turbulence). Moreover, Bragg et al. (2016) compared backward and forward in time dispersion statistics for inertial particle pairs. They found that the ratio of backwards to forwards in time mean-square separation may be up to an order of magnitude larger for inertial particles than for fluid particles in isotropic turbulence. Inertial particles were found to experience an additional source of irreversibility arising from the non-local contribution of their velocity dynamics.

Richardson's super-diffusive regime described above requires the existence of an intermediate time range in which the following two conditions are simultaneously satisfied: (1) the initial separation has been forgotten ($t \gg t_B$), and (2) particle separation remains small enough such that their trajectories are still correlated ($D(t) \ll L$). The second condition is equivalent to $t \ll T_L$, where T_L is the Lagrangian integral time scale (Salazar and Collins, 2009). This implies large scale separation which occurs for turbulent flows at very high Reynolds numbers.

In inhomogeneous and anisotropic turbulent flows, the relative dispersion problem is more complex, since the statistics depend not only on the magnitude, but also on the direction of the initial particle separation vector $\mathbf{D}_0$ and on the initial particle position. Moreover, particles do not separate equally in each direction. Therefore, the mean-square separation $\langle\mathbf{R}(t)^2\rangle$ can be generalised into a dispersion tensor $\Delta_{ij}(t) = \langle R_i(t)R_j(t)\rangle$ (Batchelor, 1952) containing more than a single independent component (as opposed to the isotropic case).

The case of a homogeneous shear flow was studied by direct numerical simulations (DNS) by Shen and Yeung (1997). The authors observed that particles separate faster when they are initially oriented in the cross-stream direction, that is, when they are in regions of different streamwise mean velocities. Moreover, regardless of their initial separation vector, over time their mean-square separation becomes larger in the streamwise direction than in the spanwise and cross-stream directions. Celani et al. (2005) studied the competition between the effects of turbulence fluctuations and a linear mean shear on particle separation using a simple analytical model. They proposed the existence of a temporal transition between a first stage of separation, where turbulent fluctuations dominate and Richardson's law can be expected to hold, and a second stage where mean shear becomes dominant. The transition is expected to happen at a crossover time which is proportional to the characteristic time scale of the mean shear.

More recently, Pitton et al. (2012) studied the separation of inertial particle pairs in a turbulent channel flow using DNS at a friction Reynolds number $Re_\tau = 150$. Results for inertial particles were compared to fluid tracers. The authors observed that mean shear induces a super-diffusive regime at large times, when particle separation becomes of the order of the largest scales of the flow. Arguably due to an insufficient separation of scales, Richardson's regime was not clearly identified. Pitton et al. (2012) removed the effect of mean shear by tracking particles which follow the fluctuating velocity field. They found that, although pair separation is importantly reduced at long times compared to the case with mean shear, separation in the streamwise direction remains dominant over the wall-normal and spanwise separations.

The DNS of Pitton et al. (2012) revealed the fundamental role played by inertial particle-turbulence interactions at small scales in the initial stages of pair separation. The authors found a super-diffusive pair dispersion of inertial particles in channel flow. This super-diffusion at short times exhibited strong dependency on particle inertia, and persisted even when the influence of mean shear was removed by the procedure described in the previous paragraph. Using DNS and Lagrangian tracking of inertial particles, Sardina et al. (2012) studied turbulence-induced wall accumulation of inertial particles