PARTICLES IN HOMOGENEOUS SHEAR TURBULENCE

Michel van Hinsberg[1], Herman Clercx[1], Prasad Perlekar[1], and Federico Toschi[1,2]
[1] *Department of Physics, Eindhoven University of Technology, Eindhoven 5600MB, The Netherlands.*
[1] *Department of Mathematics and Computer Science, Eindhoven University of Technology, Eindhoven 5600MB, The Netherlands.*

Abstract We study the dynamics and collisions of (inertial) particles in homogenous shear turbulence. Using statistical measures such as particle dispersion, relative dispersion, and particle collision rates we investigate the collision kernel. We use this collision kernel to make predictions on how a set of particles with a certain size distribution evolves in time.

INTRODUCTION

Turbulent flows occurs in various industrial and natural phenomena. In many of these cases, turbulent fluctuations are coupled to a large scale flow. Homogeneous shear turbulence is the first step in understanding how the mean flow influences turbulent fluctuations. The flow is homogeneous but non isotropic. Previous studies, e.g. [3, 1], have shown that streak like patterns reminiscent of turbulent channel flows are observed in numerical simulations of homogeneous, shear turbulence. In recent years, Lagrangian investigations have shed new light on various fundamental aspects of homogeneous and isotropic turbulence [5]. These studies allowed to quantify important phenomena like the clustering of inertial particles. Lagrangian investigations of homogeneous shear turbulence are relatively few. To highlight the difference between homogeneous-isotropic and homogeneous-shear turbulence, in Figure 1 we show the dispersion of particles from a point source. It is clear that the presence of shear introduces an additional dispersion mechanism in the system. More strikingly, a recent study [1] has shown that for inertial particles anisotropic behavior occurs even at scales where the carrier flow is already isotropic. Thus to understand collision kernels, both small and the large scales of turbulence must be investigated.

Pseudo-spectral codes in combination with particle tracking are commonly used in many applications [5]. The spectral code solves the flow field by means of direct numerical simulations in an Eulerian approach, while the particle trajectories are obtained by a Lagrangian approach. For homogenous and isotropic turbulence the particle collision kernel has been investigated and in particular it was shown that gravity changes the collision kernel [2]. In this study we want to investigate if this is the case also for homogeneous shear turbulence.

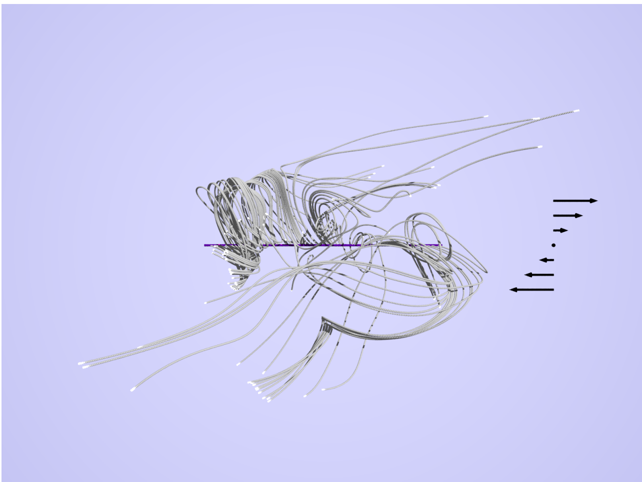

Figure 1. Trajectories of tracers in a homogeneous shear flow. All tracers started from the purple line and the mean flow is shown on the right hand side.

NUMERICAL SIMULATION AND RESULTS

We employ the classic Rogallo scheme to numerically integrate homogeneous shear turbulence [4]. Here the frame of reference moves with the main flow, thus the frame of reference is straining over time. In order to keep the frame of reference from deforming too much, a remesh step of the flow field must be performed after every $S\Delta t$ simulation time steps. Here S indicates the dimensionless shear rate and Δt the length of the simulation time step. In a later stage also gravity will be added in order to get more realistic collision conditions like the ones in clouds.

Consider a flow with a mean velocity $\boldsymbol{U} = (Sy, 0, 0)$ and fluctuations $\boldsymbol{u} \equiv (u, v, w)$. The Navier-Stokes equations for the fluctuations $\boldsymbol{u}$ are

$$D_t\boldsymbol{u} + Sy\partial_x\boldsymbol{u} + Sv\hat{e}_x = -\nabla p + \nu\nabla^2\boldsymbol{u}, \text{ and} \tag{1}$$

$$\nabla \cdot \boldsymbol{u} = 0, \tag{2}$$

where $D_t = \partial_t + \boldsymbol{u} \cdot \nabla$ is the material derivative, S is the shear rate, $\hat{e}_x$ is the unit vector along x-direction, p is the pressure, and ν is the kinematic viscosity of the fluid. The second and the third term on the left hand side correspond to the advection of the fluctuations by the mean flow and the modification of the strength of the fluctuations by the shear. The boundary conditions are assumed to be shear periodic i.e., $\boldsymbol{u}(x + 2\pi St, y + 2\pi, z + 2\pi) = \boldsymbol{u}(x, y, z)$.

Using Rogallo's transformation

$$\begin{aligned} x' &= x - Sty, \\ y' &= y, \text{ and} \\ z' &= z. \end{aligned}$$

and working in the frame of reference that deforms with the mean flow, the Navier-Stokes equations are modified to:

$$D_t\mathbf{u} + Sv\hat{e}_x = -\nabla p + \nu\nabla^2\mathbf{u}, \text{ and} \tag{3}$$

$$\nabla \cdot \mathbf{u} = 0. \tag{4}$$

where the derivatives are now with respect to the primed variables. The prime symbol is not shown explicitly for convenience. Note that since we are working in the frame that deforms with the mean shear the advection of the mean flow is removed and the solutions in this frame are periodic. Therefore we can now work with standard Fourier transforms.

We validate our numerical simulations against earlier studies of [3, 1]. We choose $S = 0.5$, $\nu = 5 \cdot 10^{-3}$, and a cubic box with each side of length 2π. The plot in Fig. 2(left) shows the time evolution of energy for the homogeneous, shear flow. Similar to the earlier studies of [3, 1] we find sharp jumps in the evolution of energy. Furthermore, the probability distribution function of the horizontal component of velocity is Gaussian, whereas the vertical component is non-Gaussian 2 (middle-right).

We will discuss this algorithm, the first results on particle trajectories in homogeneous shear turbulence, and the implications for the collision kernel.

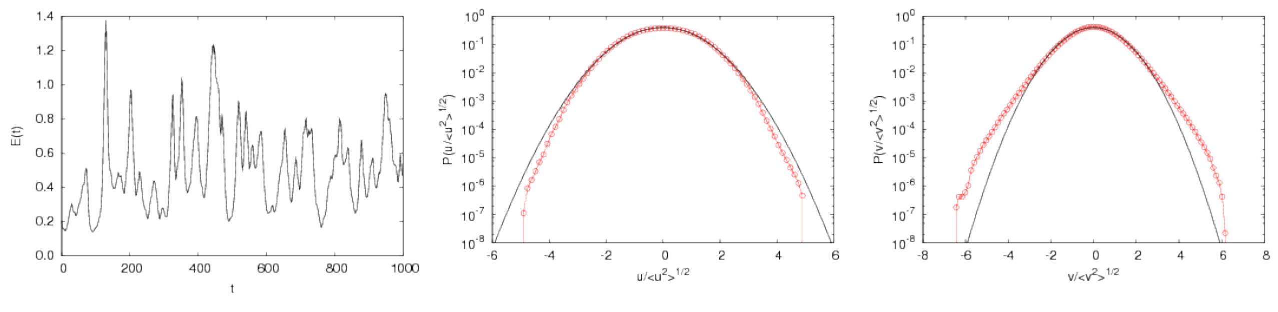

Figure 2. (left) Time evolution of turbulent kinetic energy $E(t) = \frac{1}{L^2}\sum |u^2|$. Notice the sharp jumps in the time-evolution of the energy. Pdf of the horizontal (center) and vertical (right) component of the velocity. Unlike homogeneous, isotropic turbulence the vertical component pdf is non-Gaussian.

References

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