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Experimental investigation of turbulent transport of material particles

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Abstract :

We report measurements of Lagrangian velocity and acceleration statistics of particles transported in a turbulent flow obtained with an acoustic Doppler velocimetry technique. We consider a homogeneous isotropic grid turbulence generated in a wind tunnel. As a first step we study isolated particles dynamics with a particular focus on the influence of particles finite size on their response to the turbulence forcing. As particles we use neutrally buoyant soap bubbles inflated with helium. The size of the particles can be adjusted from 1.5 mm to 6 mm, corresponding to inertial range scales. We show that the response time of the particles to the turbulence forcing increases with their size. We analyze our data in the frame of two times stochastic models, and show that the cut-off time scale in the Lagrangian energy spectrum of the particles dynamics has a dependence on their diameter consistent with a low-pass filtering of the turbulent cascade by the particles finite size.

Résumé :

Nous présentons des statistiques Lagrangiennes de vitesse et accélération de particules transportées par un écoulement turbulent. Ces mesures sont obtenues par vélocimétrie Doppler dans une turbulence de grille, homogène et isotrope. Dans une première étape, nous nous intéressons au cas de particules isolées et nous étudions plus particulièrement les effets de taille finie des particules sur leur réponse à la turbulence. Les particules utilisées sont des bulles de savons gonflées à l'hélium de sorte à être rendues iso-densité dans l'air. Leur taille, ajustable entre 1.5 mm et 6 mm, correspond à des échelles inertielles de la turbulence. Nous montrons que le temps de réponse des particules augmente avec leur taille et analysons ces résultats à la lumière de modèles stochastiques à deux temps. Nous montrons ainsi que le spectre Lagrangien d'énergie des particules présente bien une coupure à petite échelle liée à leur taille.

Key-words : Lagrangian velocity, homogeneous isotropic grid turbulence.

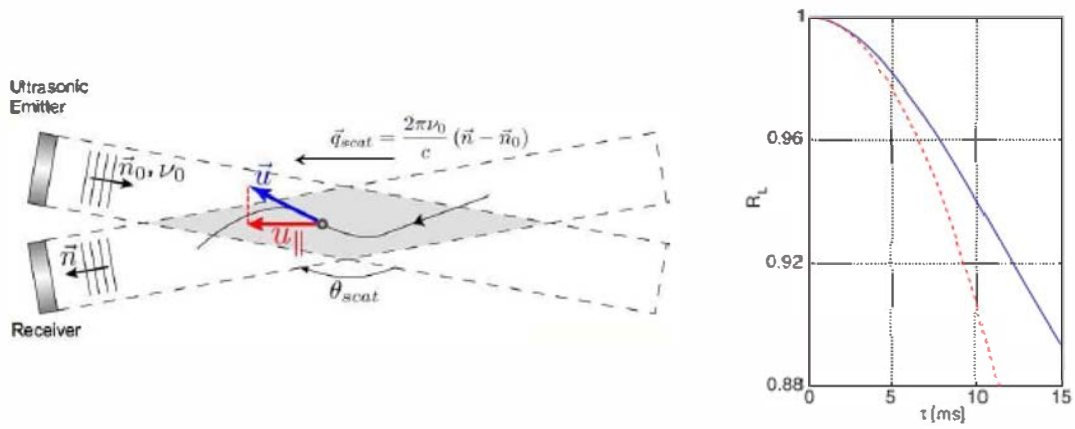
1. Introduction

Particle laden turbulent flows play an important role in various situations such as industrial processes or atmospheric dispersion of pollutants for instance. When the particles are neutrally buoyant and small (typically comparable in size with the dissipation scale of the surrounding turbulence) they behave as tracers for fluid particles. However, in many practical situations, the particles are heavier and/or larger, their dynamics is then affected by inertial effects and it deviates from fluid particles dynamics,(Maxey et al (1983), Aliseda et al. (2002), Ayyalasomayajula et al. (2006)). The precise role of size and density of the particles in the modification of their dynamics with respect to fluid tracers, remains largely an open question.

Here, we report measurements of Lagrangian velocity and acceleration statistics of material particles transported in a grid generated windtunnel turbulent flow, with a Reynolds number (based on Taylor microscale) of R_λ~200. The dissipation scale η is 200 µm and the energy injection scale L is 2.5 cm. As a first step, we only explore particles finite size effects. To decouple the role of size and density of the particles, we consider neutrally buoyant particles, which are soap bubbles inflated with helium and which diameter can be adjusted from 1.5 mm to 6 mm which corresponds to inertial range scales. The Lagrangian measurements are obtained with an acoustic Doppler velocimetry technique (figure 1a): from the instantaneous Doppler frequency shift of acoustic waves scattered by a particle in a turbulent flow, we measure the velocity of the particle (Poulain et al. (2004)). The instantaneous frequency is determined with a parametric maximum of likelyhood algorithm (Mordant et al. (2001)). The particles can be tracked over a period covering several dissipation time scales, corresponding to a significant fraction of the integral time scale of the flow.

2. Experimental Approach

The Lagrangian measurements are obtained with an acoustic Doppler velocimetry technique (figure 1a): from the instantaneous Doppler frequency shift of acoustic waves scattered by a particle in a turbulent flow, we measure the velocity of the particle (Poulain 2004). The instantaneous frequency is determined with a parametric maximum of likelyhood algorithm derived by Mordant et al. (2004). The particles can be tracked over a period covering several dissipation time scales, corresponding to a significant fraction of the integral time scale of the flow.



(a) (b)

Fig. 1. (a) Principle of acoustical Doppler velocimetry: an ultrasonic plane wave is generated by an emitter and scattered by the particle. The Doppler shift of the scattered wave is directly related to the longitudinal component $u_{//}$ of the particle's velocity. (b) Lagrangian velocity autocorrelation function for 6 mm bubbles. The dashed line represents the parabolic fit $1-\tau^2/\tau_\lambda^2$ around τ=0 used to determine the Lagrangian microscale τ_λ.

3. Experiemental Results

In order to investigate the influence of particle size on its Lagrangian dynamics, we first consider how the Lagrangian velocity autocorrelation function is affected when we change the bubbles diameter.

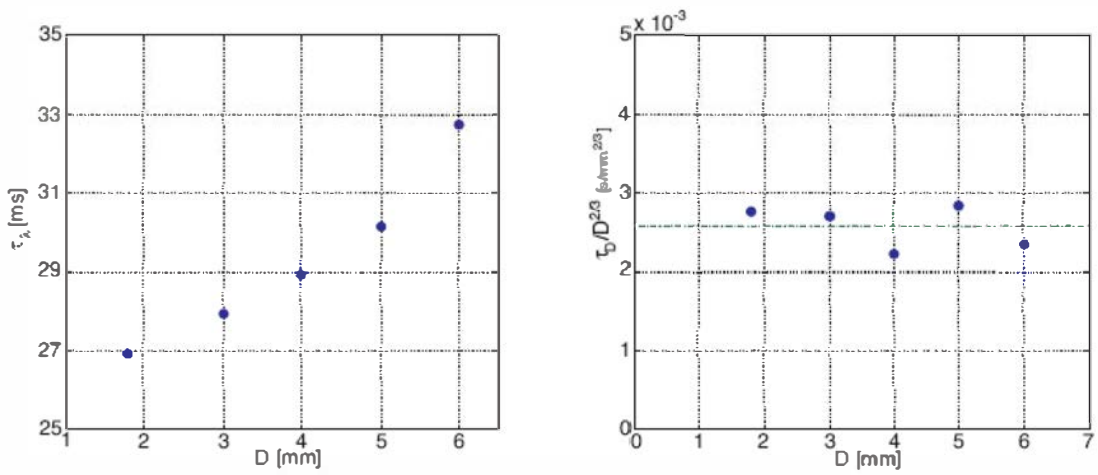
Figure 1b represents for instance the Lagrangian velocity autocorrelation function R_L for 6 mm particles. Note that we only show a relatively short time lags range, for which we have enough Lagrangian trajectories to ensure a good statistical convergence.

From the curvature at τ=0 we can estimate an equivalent Lagrangian Taylor time scale $\tau_\lambda(D)$ associated to the Lagrangian dynamics of a particle of diameter D. Figure 2a shows a clear dependence of τ_λ on particle size. We note that as the particle size decreases, τ_λ appears to approach an asymptotic value (which we can estimate here around 25 ms) which corresponds to the intrinsic Lagrangian microscale of the turbulent flow, as smaller particles approach fluid tracers. The increase of the microscale of the Lagrangian dynamics of the particles as their size increases suggests a longer response time of larger particles to the turbulence forcing. This is consistent with the intuitive phenomenology, that large particles do not feel velocity gradients at scales smaller than their size, and therefore, they must filter in some way the turbulent energy cascade at some small scale related to their size. To test further this scenario, we analyse the Lagrangian velocity correlation function in the frame of two times stochastic model given by Sawford et al. (1991).

In this description, the autocorrelation function is given by a double exponential law :

$$R_L(\tau) = \frac{\tau_\lambda^2 e^{-2t\tau_D/\tau_\lambda^2} - 2\tau_D^2 e^{-t/\tau_D}}{\tau_\lambda^2 - 2\tau_D^2} \qquad (1)$$

where τ_D is a small time scale characterizing the cut-off of the particles Lagrangian energy spectrum. For fluid particle tracers, for instance, τ_D is directly related to the viscous dissipation time τ_η. For particles with finite diameter D in the inertial range, in the scenario described above where the fluid turbulent energy is low-pass filtered by the particle at a scale corresponding to its diameter D, the corresponding cut-off time scale can be estimated in the framework of K41 phenomenology as $\tau_D \sim \varepsilon^{-1/3} D^{2/3}$, where ε is the energy dissipation rate.



(a) (b)

Fig. 2. (a) Time microscale τ_λ as a function of the particles diameter D. (b) Compensated cut-off time scale $\tau_D / D^{2/3}$ as function of D.

From our measurements, we determined the cut-off time scale τ_D as a function of the particle diameter by fitting the autocorrelation function with expression (1). We haven't represented the fit on figure 1b because it is almost undistinguishable from the measured correlation function. Figure 2b shows the compensated cut-off timescale $\tau_D / D^{2/3}$ measured for different particle's diameter. In spite of some scattering, the agreement with the $D^{2/3}$ prediction is good and consistent with the small scales cut-off scenario.

4. Conclusion

In the work presented above, the finite size effects of the particles, in a homogeneous isotropic turbulent flow have been studied. We have found that the Lagrangian response time of the material particles increases as their diameter increases, which is due to the fact that particles are insensible to the velocity gradients at scales smaller than their diameter. As a result of this phenomenon we have observed filtering in the Lagrangian energy spectrum. Lagrangian microscale time, τ_λ have been determined by fitting parabolas to Lagrangian velocity autocorrelation. It has been found that τ_λ decreases as the diameter of the particle decreases and it tends to reach an asymptotic value. Later on, a two times stochastic model is used to determine small time scale, τ_D. The realation derived from K41 phenomenology, $\tau_D \sim D^{2/3}$ appears to work in a good agreement when we plot $\tau_D / D^{2/3}$ as a function of particle's diameter. Other diagnosis not discussed here, based for instance on measurements of the acceleration variance of the particles as a function of their diameter also confirm this idea. Further investigation will explore the role of particles density.

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