ACCUMULATION OF MOTILE MICROORGANISMS IN TURBULENCE

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Abstract The effects of turbulence on marine ecology are studied by performing direct numerical simulations of motile microorganisms in isotropic homogeneous turbulence. We show that in a fully turbulent flow the patchiness and clustering is reduced respect to simple laminar and vortical flows. Micro-organisms in presence of gyrotaxis tend to accumulate if spherical in shape while elongated swimmers are more randomly distributed because of their sensitivity to the local shear. These results suggest that purely hydrodynamic phenomena can influence the marine life of microorganisms when the type of flow and their shape are changed.

INTRODUCTION

The macroscopic phenomena of marine landscape are influenced by the microscopic coupling between the flow structure and the motility of its inhabitants, such as bacteria and phytoplankton. An individual motile micro-organism's swimming trajectory is determined by the action of its cilia or flagella and by the advection by the bulk fluid. The orientation of its swimming direction is affected by a variety of external factors, purely hydrodynamic as vorticity and rate of strain of the fluid, or behavioral as a response to nutrient concentration and gravity. These external cues guide the swimmers and their interactions within the flow. Depending on the different external stimulus, the swimmers' reactions can be categorized for example as geotaxis, phototaxis, gyrotaxis and chemotaxis, etc. see [5] for a review. In particular, we focus our investigation on gyrotaxis that is a kind of microorganism locomotion resulting from a balance between the gravitational and viscous torques in a flow. The coupling of gyrotactic particles and a complex background flow has been drawn significant attention. The effect of turbulence on marine micro-organisms is a key research question that also has relevance on the understanding of the consequences of climate changes as marine life concentrates in the turbulent regions close to the surface and to the sea bed. We therefore perform numerical simulations of motile microorganisms, modeled as prolate spheroids, in isotropic homogeneous turbulence.

METHODOLOGY AND RESULTS

The numerical data set has been obtained by means of a Direct Numerical Simulation (DNS) in a triperiodic box with a standard pseudo-spectral code coupled with a Lagrangian solver for the swimming organisms. We consider the swimmers as prolate spheroids characterized by a swimming velocity u_s along a specific orientation vector $\mathbf{p}$ and advected by the local fluid velocity $\mathbf{u}$. The equations governing the dynamics of the position $\mathbf{x}$ and orientation $\mathbf{p}$ of the single microorganism are:

$$\frac{d\mathbf{x}}{dt} = \mathbf{u} + u_s\mathbf{p}. \tag{1}$$

$$\frac{d\mathbf{p}}{dt} = \frac{1}{2B}\left[k - (k \cdot \mathbf{p})\right]\mathbf{u} + \frac{1}{2}\omega \times \mathbf{p} + \alpha \cdot \mathbf{E} \cdot \left[I - \mathbf{pp}\right]. \tag{2}$$

where $\mathbf{E}$ is the deformation tensor and ω is the vorticity vector. Here, $\alpha = \left(\mathcal{AR}^2 - 1\right)/\left(\mathcal{AR}^2 + 1\right)$ is the eccentricity of the spheroids and $\mathcal{AR}$ is the aspect ratio (the ratio of the major axis to the minor axis). B is the characteristic time a perturbed cell takes to return to orientation k, which is the preferred direction for the swimmers. When there is no preferred direction (no gyro taxis), B goes to infinity.

We will consider the behavior of gyrotactic and non-gyrotactic swimmers in a three-dimensional turbulent flow at $Re_\lambda = 150$, as turbulence characterizes the life of microbes in water supply systems, ocean and bioreactors. We demonstrate how clustering and trapping phenomena observed in simple cellular or vortical flows [6, 4] are significantly decreased in a three-dimensional time periodic flow. We expand some recent studies of small-scale patchiness in the distribution of gyrotactic micro-organisms in vortical or turbulent flows [1, 2]. In particular, we investigate how the gyrotactic clustering in turbulence is modified by the elongation of the ellipsoidal swimmers. The parameters used in this study are in a realistic range and can also be replicated in the laboratory: for typical marine micro-organisms $B = 1-6s$, $u_s = 100-200\mu m/s$, thus $u_s/u_\eta \in [0.02 : 0.4]$, $B\omega_{rms} \in [0.1, 50]$, where u_η is the small-scale Kolmogorov velocity and ω_{rms} is the root mean square of the vorticity fluctuations. The shapes of the marine organisms however is varying and many phytoplankton species are not spherical, thus the clustering of such organisms in turbulent flows is affected by their individual geometry.

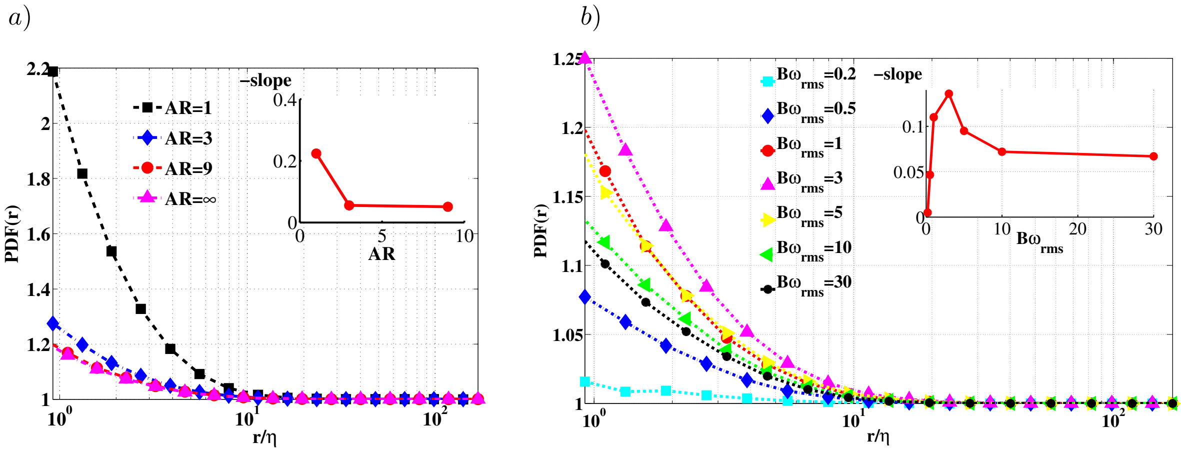

Figure 1. Radial distribution function for gyrotactic swimmers. a) Same values of $B\omega_{rms}$ and different aspect ratio. b) Aspect ratio $\mathcal{AR} = 9$ for the same swimming speed. The inset displays the scaling exponent at small separations.

The main finding of this work are reported in figure 1 where the radial distribution function $g(r)$ that represent the probability to find a microorganism pair at distance r is plotted. The slope of the radial distribution function at small distance quantifies the clustering level of the swimmers configuration. For gyrotactic swimmers of different shape clustering decreases when the aspect ratio of swimmers is increasing as plotted in figure $1a)$. In other words, spherical particles having a preferential swimming direction exhibit the most significant aggregation. Results are obtained with fixed value of the parameter $B\omega_{rms}$ that governs the gyrotaxis in turbulent flows. We show in figure $1b)$ that the maximum clustering of prolate swimmers, yet significantly weaker than that observed for spherical microorganisms, is for $B\omega_{rms} = 3$ whereas it is about 1 for spherical swimmers. Low values of $B\omega_{rms}$ indicate short re-orientation times and strong torques. As a consequence the swimmers tend to align to the vertical direction and swim upwards: in this case an initial uniform distribution will tend to remain. For weak gyrotaxis, large values of $B\omega_{rms}$, particles tend to behave as pure swimmers and the accumulation is not relevant. Small-scale clustering is therefore occurring for intermediate values of $B\omega_{rms}$ and these optimal values shifts towards longer time scales for prolate swimmers.

FINAL COMMENTS

We observe that clustering of prolate swimmers without taxis, observed in simple flows, is destroyed by turbulence while concerning gyrotactic microorganisms of different shapes the clustering is most evident for spherical shapes and decreases with the aspect ratio of the swimmers. The orientation of the latter is affected more by the gravity and local shear. Our finding confirmed that microorganisms that can actively change their shape, such as *Ceratocorys horrida* [3], have an active control mechanism to alter their distribution to favor encounters or uptake.

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