Euromech Colloquium 513, Dynamics of non-spherical particles in fluid turbulence
6-8 April 2011, Udine, Italy.

Orientation, distribution and deposition of elongated, inertial fibers in turbulent channel flow

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Suspensions of elongated rigid fibers in turbulent flows are commonly encountered in applications of engineering interest. Examples include pulp production and paper making, where controlling the rheological behavior and the orientation distribution of fibers is crucial to optimize production operations. In addition, recent experiments [1] demonstrated that elongated fibers may represent a feasible alternative to flexible polymers for reducing pressure drops in fluid transport systems. Despite this practical importance, very few phenomenological studies aimed at a deeper understanding of the physics of turbulent fiber transport are available [2, 3]: as a result, current knowledge of the mechanisms govering fibers-turbulence interaction is not satisfactory and requires extensive investigation. Our study is intended to complete the abovementioned studies adding new data in the parameter space (λ, τ_p and Re_τ), where λ is fiber elongation, τ_p is fiber response time, and Re_τ is the shear Reynolds number. New statistics will be presented to fully characterize fiber behavior, and highlighting the circumstances in which fibers behavior significantly deviates from that of spherical particles. To this aim, fiber dispersion in a turbulent channel flow at $Re_\tau = 150$ is first investigated using Direct Numerical Simulation and Lagrangian tracking under the one-way coupling approach. Fibers are treated as prolate ellipsoidal particles which move according to inertia and to hydrodynamic drag and rotate according to hydrodynamic torques. Results are presented for $\lambda = 1, 3, 10, 50$, and $\tau_p^+ = 1, 5, 30, 100$. Superscript + is used here to represent dimensionless variables expressed in wall units.
The orientational behavior of fibers is examined together with their preferential distribution, near-wall accumulation, and wall deposition: all these phenomena are interpreted in connection with turbulence dynamics near the wall. Results confirm that, in the vicinity of the wall, fibers tend to align with the mean streamwise flow direction. However, this aligned configuration is unstable, particularly for higher inertia of the fiber, and can be maintained for rather short times before fibers are set into rotation in the vertical plane. The situation complicates in the spanwise and wall-normal flow directions, where fiber inertia and elongation destabilize near-wall alignment in a non-trivial fashion. Fiber orientational behavior and fiber translational behavior are also observed to influence the process of fiber accumulation at the wall: compared to the case of spherical particles, the elongation has little or no effect on segregation; yet it does affect the wallward drift velocity of the fibers in such a way that longer fibers tend to deposit at higher rates. No preferential orientation and no significant segregation is observed in the channel centerline.
In the final paper, one-way coupling results will be complemented by and compared to new results coming from simulations that include two-way coupling effects. This step of the work aims at exploring from a physical viewpoint the mechanism of fiber-induced turbulent drag reduction and will assist in highlighting differences between coupled and uncoupled predictions of fiber preferential orientation and distribution.

References

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