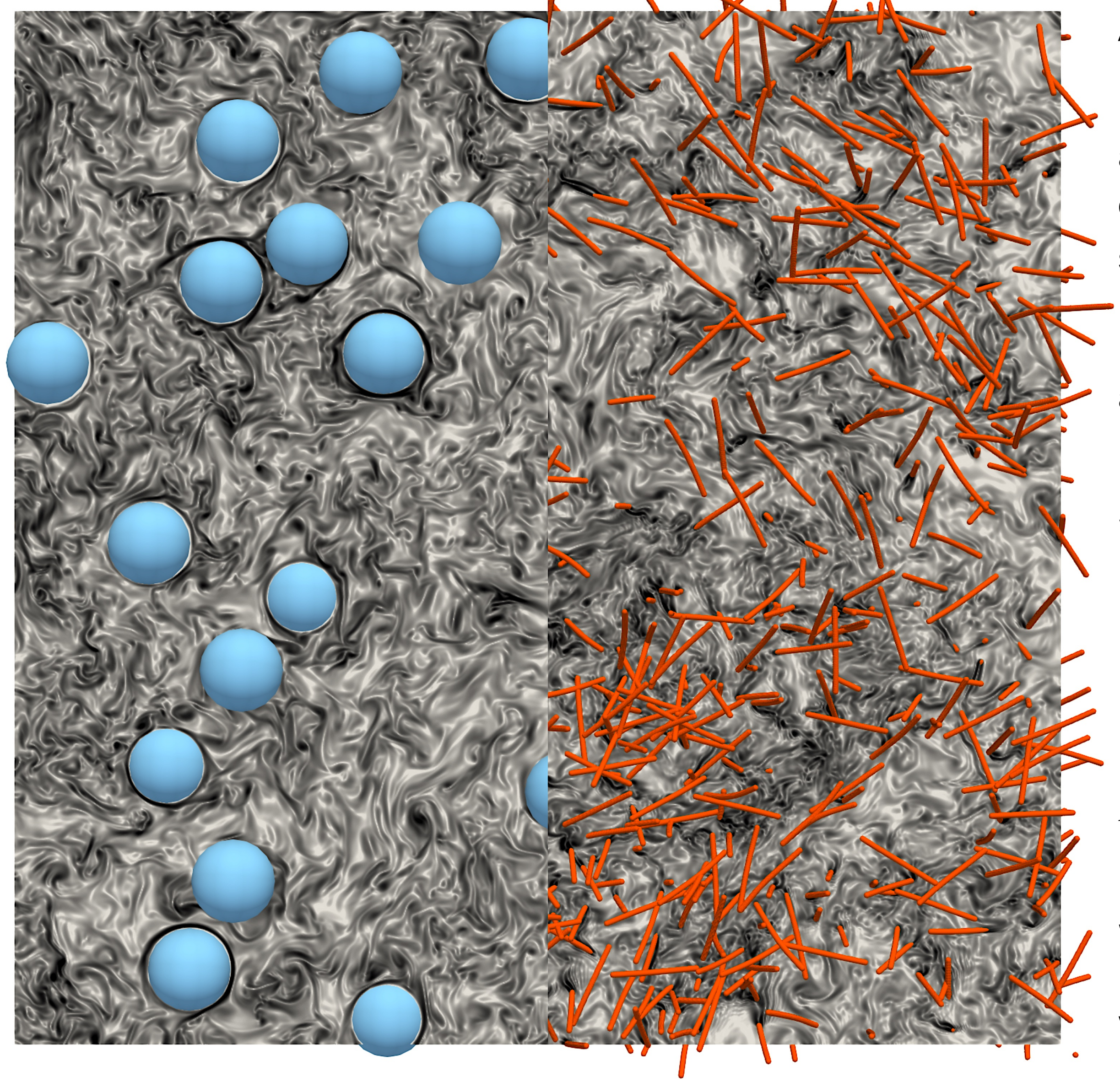
Turbulence modulation in multiphase flows at high Reynolds number

hp210269 - Ianto Cannon, Stefano Olivieri and Marco Edoardo Rosti



Abstract

Nature has many examples of particle-laden turbulent flows, for example, sandstorms, volcanic ash clouds, pollen dispersal, and microplastics in the ocean. To this end, we perform simulations of turbulent flows with a range of Taylor-Reynolds numbers $12.8 < Re_\lambda < 442$, containing finite-size fibres and spheres with solid mass fractions $0 < M < 1$. We show that spheres and fibres increase dissipation in the fluid, but the anomalous ($Re_\lambda \to \infty$) value of dissipation is unchanged. Spheres reduce the turbulent kinetic energy at large scales, while fibres reduce it across a range of scales. Both particle shapes produce shearing flows in their locality.

Numerical method

We make direct numerical simulations using the in-house code *Fujin*. This solves the incompressible Navier-Stokes equations on a 1024^3 grid. We use an Eulerian immersed boundary method [1] to model the spheres. In the case of fibres, we use a Lagrangian immersed boundary method [2]. The flow is sustained using Arnold-Beltrami-Childress forcing [3] with amplitude F. We investigate the effect of varying the forcing Reynolds number $Re_{ABC} \equiv F^{1/2}L^{3/2}/\nu$, which takes values from the table to the right.

marker	Re_{ABC}
⬟	**894**
■	447
▲	224
◆	112
●	**55.9**

Figure 1. Setup

We use an L^3 cubic domain with triperiodic boundary conditions. This figure shows vorticity magnitude in a slice through the domain. A case with spheres is shown on the left and a case with fibres on the right.

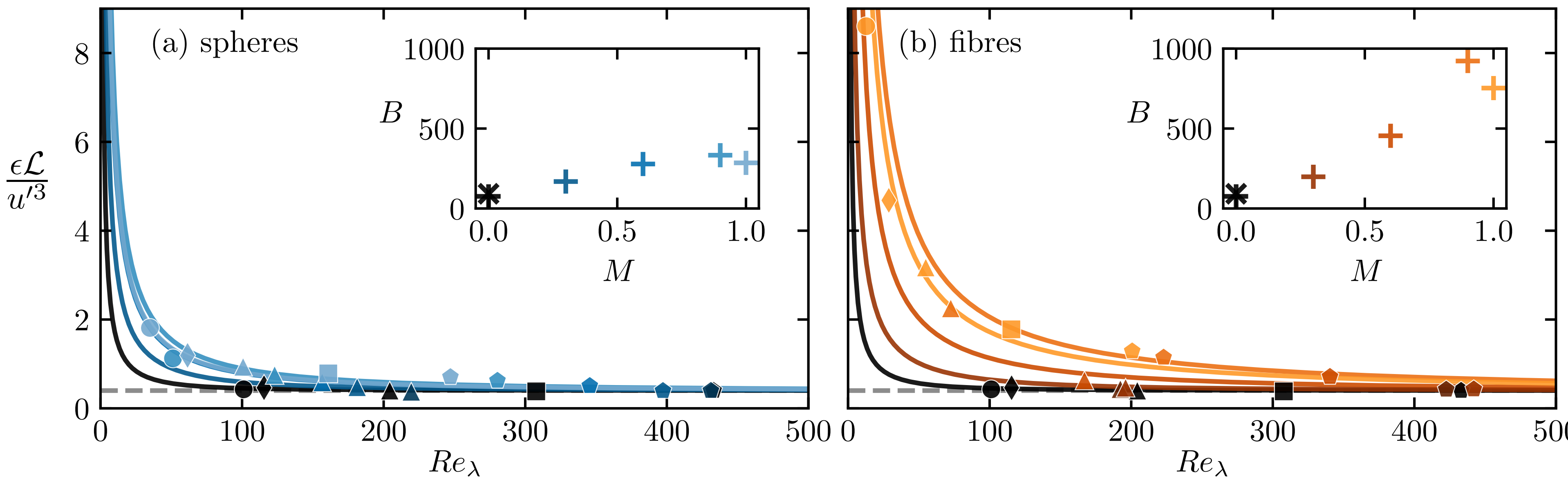


Figure 2. Anomalous dissipation

Dependence of the normalised dissipation $\epsilon\mathcal{L}/u'^3$ on the Taylor-Reynolds number Re_λ, where ϵ is the dissipation rate, $\mathcal{L}$ is the integral length scale, and u' is the RMS velocity. Horizontal dashed lines show the anomalous value of dissipation $\epsilon\mathcal{L}/u'^3 = 0.4$ measured by [4] for single-phase turbulent flows. Solid lines show fits of $\epsilon\mathcal{L}/u'^3 = 0.2 + 0.2\sqrt{1 + B^2/Re_\lambda^2}$. The fitted values of B are given in the inset plots. Donzis' result ($B = 92$) [4] is marked with an 'X'.

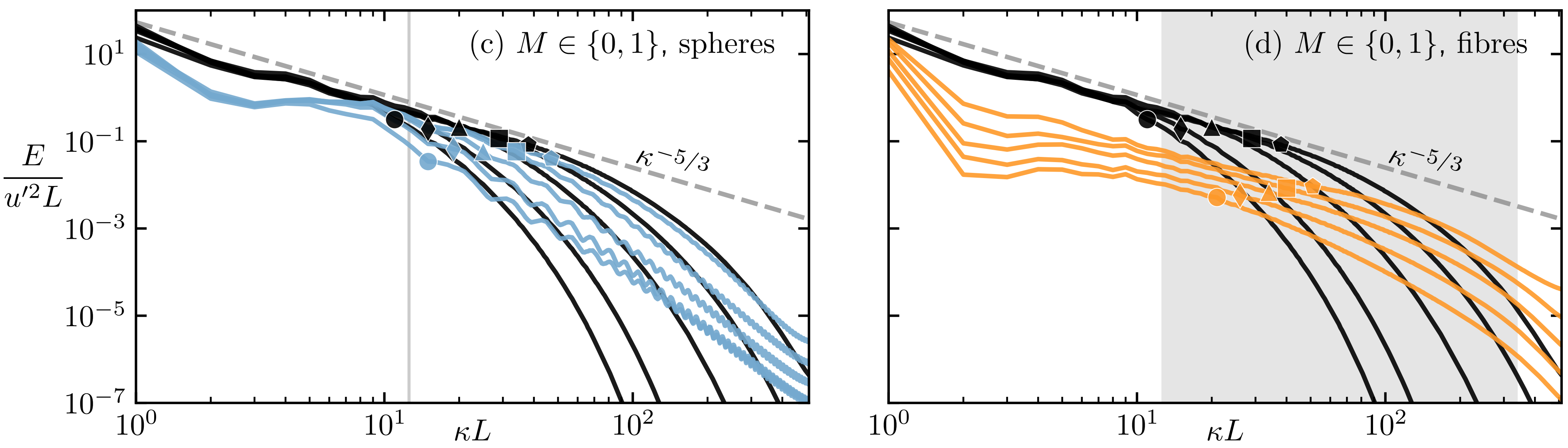


Figure 3. Kinetic energy spectra

On the left, we show flows with spheres, and the vertical grey lines show the wavenumber of the sphere diameter. On the right, we show flows with fibres, and we shade the region between the wavenumber of the fibre length and the wavenumber of the fibre diameter. Single phase ($M = 0$) cases are in black, and cases with fixed ($M = 1$) particles are in colour. Markers are at the wavenumber of the Taylor length-scale. We see that spheres reduce the energy at large scales, and fibres reduce energy across a range of scales, down to their diameter.

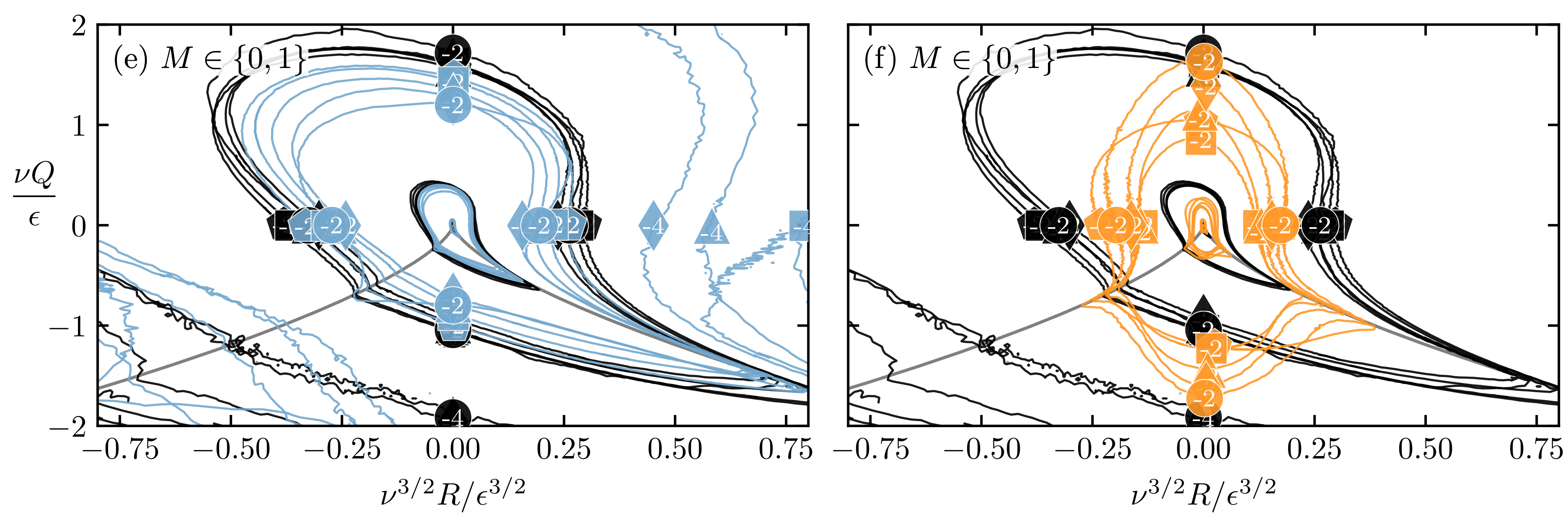


Figure 5. Invariants Q and R of the fluid velocity gradient tensor

Single phase ($M = 0$) cases are in black, and cases with fixed ($M = 1$) particles are in colour. Numbered markers show the value of $\log P$ at each contour, where P is the probability density. The grey curve is where the discriminant $27Q^3/4 + R^2$ is zero, above this curve the flow is vorticity-dominated, and below this curve the flow is strain-dominated. Spheres reduce the vorticity and shear in the flow, whereas fibres produce a new flow which is shear dominated.

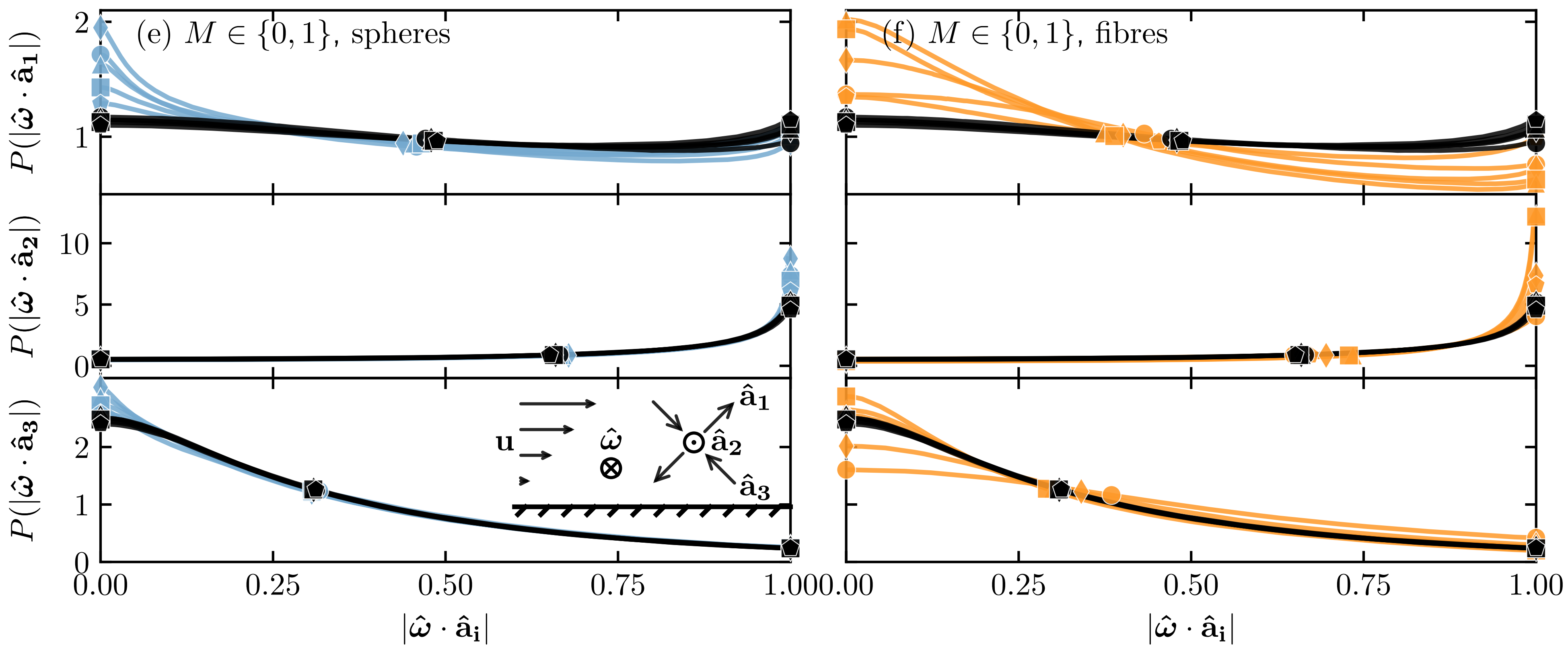


Figure 4. Alignment of the vorticity $\hat{\omega}$ with the strain-rate eigenvectors $\hat{\mathbf{a}}_1, \hat{\mathbf{a}}_2, \hat{\mathbf{a}}_3$

Markers denote the mean alignment $\langle|\hat{\omega}\cdot\hat{\mathbf{a}}_i|\rangle$. The inset shows directions of vorticity and the strain-rate eigenvectors in a laminar shear flow above a flat non-slip surface, $\hat{\mathbf{a}}_1$ and $\hat{\mathbf{a}}_3$ are confined to the shear plane, while $\hat{\mathbf{a}}_2$ and $\hat{\omega}$ are perpendicular to it. When particles are added, $\hat{\mathbf{a}}_1$ and $\hat{\mathbf{a}}_3$ become more perpendicular to the vorticity, and $\hat{\mathbf{a}}_2$ becomes more aligned. This is consistent with the existence of a shear layer at the particle surfaces.

References

[1] Hori, Rosti, Takagi, *Comput. Fluids,* 2022
[2] Huang, Shin, Sung, *J. Comp. Phys,* 2007
[3] Libin, Sivashinsky, *Quart. Appl. Math,* 1990
[4] Donzis, Sreenivasan, Yeung, *J. Fluid Mech,* 2005

OIST OKINAWA INSTITUTE OF SCIENCE AND TECHNOLOGY
沖縄科学技術大学院大学