How particle shape reshapes turbulence

APS DFD 2025, November 25, Houston, Texas

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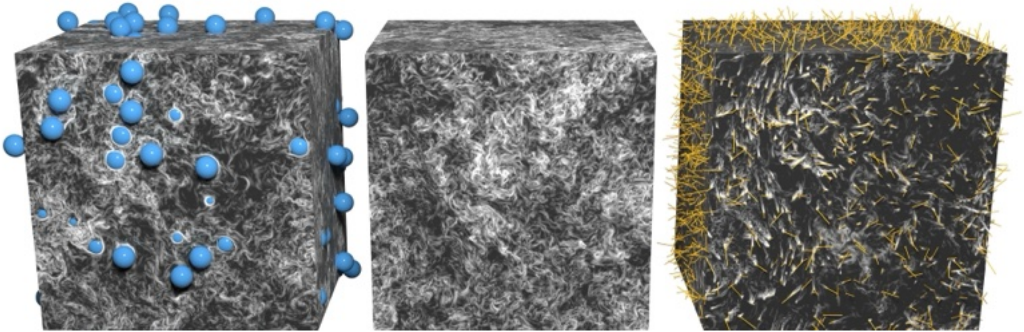

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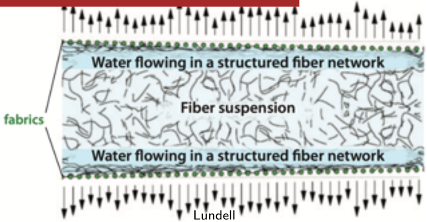
Motivation: Particle shapes in turbulent flows

Sandstorms

Ocean plastics

How does particle shape affect turbulent flows?

Robert J. Erwin



Lundell

Background

Previous studies (Voth & Soldati *AFM* 2017, Brandt & Coletti *AFM* 2021, Marchioli, Rosti & Verhille *AFM* 2025):

1. Small particles ($c \ll \eta$)
2. Spherical particles
3. Limited turbulence intensity

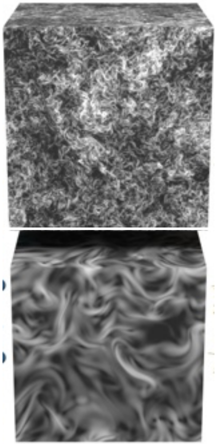
Our approach:

1. Finite size ($\eta < c < \mathcal{L}$)
2. Spheres *and* fibres
3. Wide range of turbulence intensities.

Homogeneous isotropic turbulence

- Direct numerical simulations on 1024^3 grid
- Domain size $(2\pi L)^3$
- ABC forcing (Libin & Sivashinsky *QAM* 1990)
- Five turbulence intensities

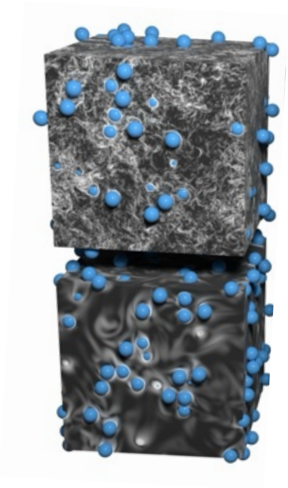
$$Re_{ABC} \equiv \frac{\sqrt{FL^3}}{\nu} = \{55.9, 112, 224, 447, 894\}.$$



Spheres

- Coupled to the flow using an immersed boundary method (Hori Rosti & Takagi *CAF* 2022)
- Number: 300
- Diameter: $c = 0.5L$
- Volume fraction: 8%
- Total surface area: $230L^2$
- Six mass fractions

$$M = \frac{M_{\text{particles}}}{M_{\text{particles}} + M_{\text{fluid}}} = \{0, 0.1, 0.3, 0.6, 0.9, 1\}.$$



$Re_{\mathrm{ABC}} = 894$

$Re_{\mathrm{ABC}} = 55.9$

Fibres

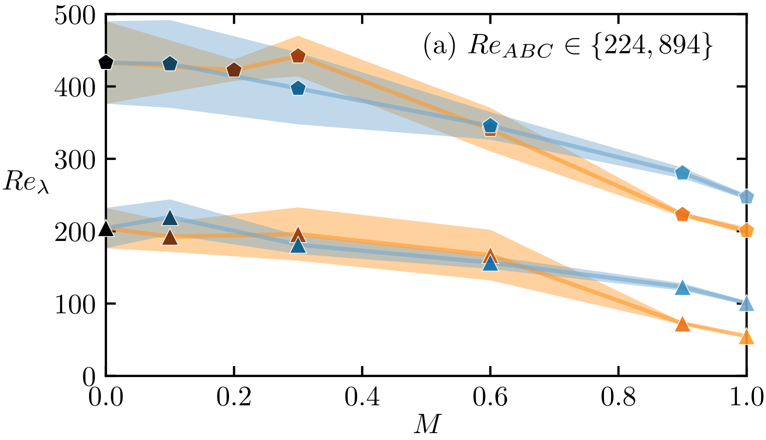
- Coupled to the flow using an immersed boundary method (Huang, Shin & Sung *JCP* 2007)
- Number: 10^4
- Length $c = 0.5L$
- Thickness $d = 0.018L$
- Volume fraction: 0.05%
- Total surface area $230L^2$
- Six mass fractions

$$M = \frac{M_{\text{particles}}}{M_{\text{particles}} + M_{\text{fluid}}} = \{0, 0.1, 0.3, 0.6, 0.9, 1\}.$$

$Re_{\text{ABC}} = 894$

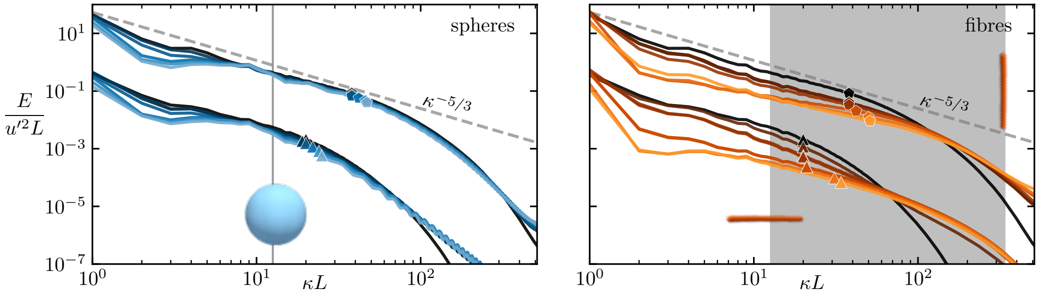
$Re_{\text{ABC}} = 55.9$

Effect on turbulence intensity



- Spheres and fibres both attenuate turbulence
- Denser particles have more effect
- Occurs at all Reynolds numbers Re_{ABC}.

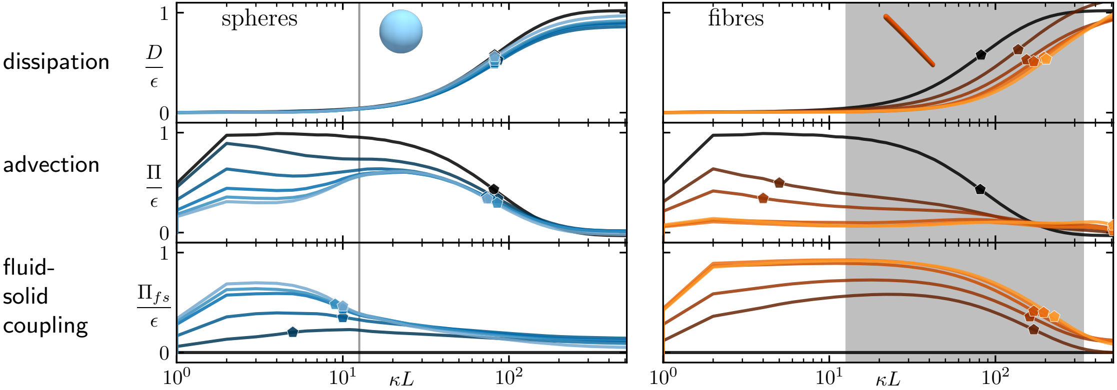
Energy spectra



- The inertial range increases with the Reynolds number
- Spheres: energy reduction at $\kappa < \kappa_c$ (large scales)
- Fibres: broadband energy modulation across all scales
- Both: enhanced dissipation in viscous range.

Spectral energy transfer

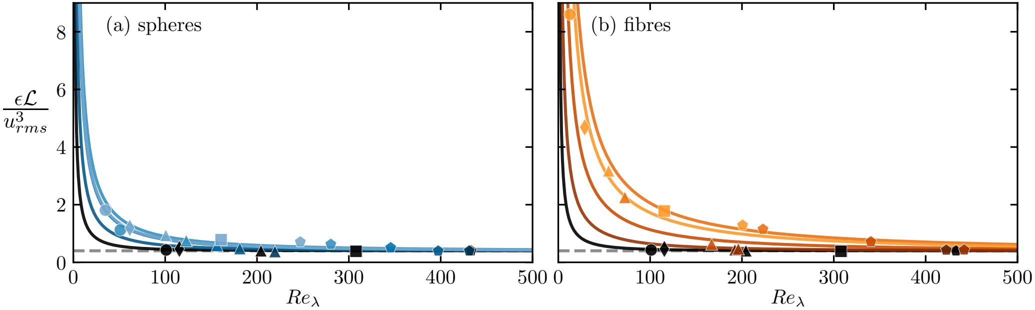
Energy balance: $\mathcal{F}_{inj}(\kappa) + \Pi(\kappa) + \Pi_{fs}(\kappa) + D(\kappa) = \epsilon$



- Fluid-solid coupling Π_{fs} bypasses the classical cascade Π (Lucci, Ferrante & Elghobashi *JFM* 2010).
- Spheres inject at κ_c (diameter)
- Fibres inject at $\kappa \sim \kappa_d$ (thickness).

Anomalous dissipation

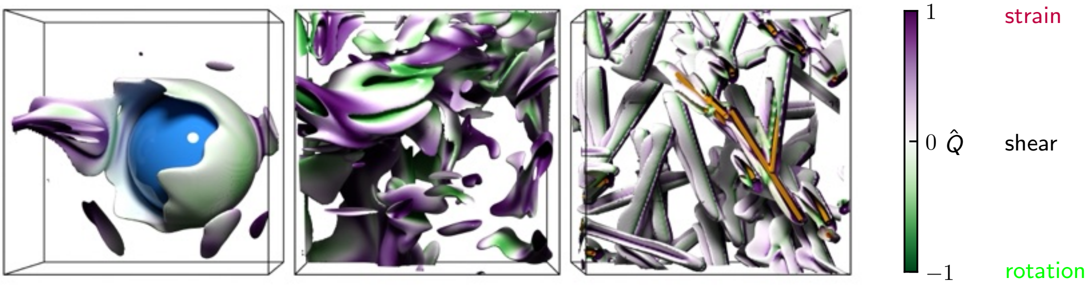
Dissipative anomaly: $\epsilon\mathcal{L}/u_{rms}^3 \to$ constant as $Re_\lambda \to \infty$ (Taylor *RSL* 1935)



- All flows converge to ≈ 0.4 (Donzis, Sreenivasan & Yeung *JFM* 2005)
- Higher mass of particles gives a slower rate of convergence
- Fibres halve the rate of convergence compared to spheres.

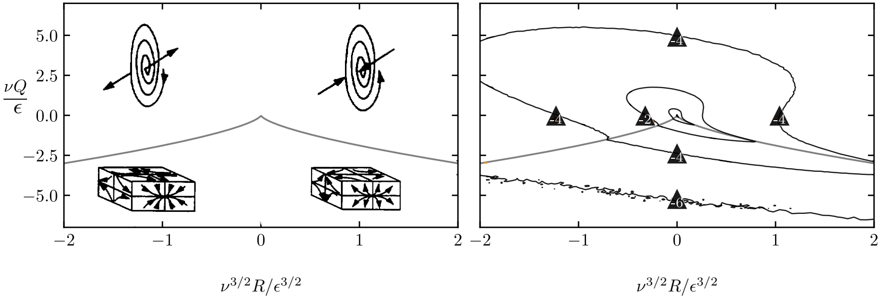
Particle wakes

Surfaces where dissipation is 6ϵ, coloured by flow topology parameter $\hat{Q} = \frac{2s_{ij}s_{ij} - \omega_i\omega_i}{2s_{ij}s_{ij} + \omega_i\omega_i}$



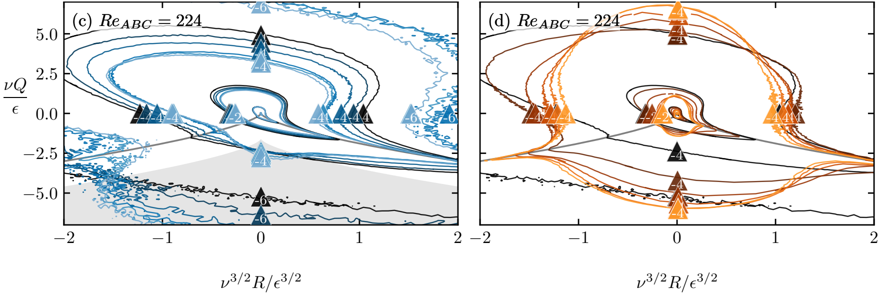
- Single phase: complex structures (Meneveau & Sreenivasan *JFM* 1991)
- Spheres: sheet-like (2D) with shear
- Fibres: tube-like (1D) structures with strain upstream, shear in wakes.
- The spatial intermittency of the dissipation is measured in Cannon, Olivieri & Rosti *PRF* 2024.

Flow topology: *Q*–*R* joint probability distribution



- Invariants of the velocity gradient tensor:
  - $Q = \frac{1}{4}\omega_i\omega_i - \frac{1}{2}s_{ij}s_{ij}$
  - $R = \frac{1}{4}\omega_i s_{ij}\omega_j - \frac{1}{3}s_{ij}s_{jk}s_{ki}$
- Single phase flow is dominated by **vortex streching** and **uniaxial strain** (Cheng & Cantwell *IAA* 1996).

Flow topology with particles



- Spheres dampen vortices
- Spheres enhance strain

- Fibres decorrelate Q and R
- Fibres greatly enhance strain.

Conclusion

Findings:

1. Particles reduce turbulence intensity at all *Re*
2. Anomalous dissipation: $\epsilon\mathcal{L}/u_{rms}^3 \to 0.4$ as $Re_\lambda \to \infty$
3. Particles bypass the classical turbulent energy cascade
   - Spheres inject at diameter scale
   - Fibres inject at thickness scale
4. Different dissipation structures:
   - Spheres: 2D sheets
   - Fibres: 1D tubes

Implication:

- For pollen dispersal, ocean plastics, sandstorms and papermaking, **particle shape matters, not just mass**

Cannon, Olivieri & Rosti 2024, *Physical Review Fluids*

Thank you!

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