Thermodynamics of Rotors driven by 3D turbulence

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Motivations and context

The transfer of kinetic energy from a flow to useful work constitutes a central problem in energy harvesting for wind farms or wave energy converters. These systems often rely on a steady flow component dominating the fluid dynamics, yet the velocity fields of natural flows fluctuate over a broad range of time and length scales. Moreover, energy extraction becomes difficult when turbulent fluctuations are comparable to the response time of the energy harvesters. The goal of the internship is to experimentally investigate how a rotor extracts power from a strong 3D turbulent flow and to describe its dynamics using tools of stochastic thermodynamics.

Experimental approach

We recently developed an experimental system in which the fluid is energized by centimetric magnetic stirrers subjected to an oscillating magnetic field, as detailed in references [1, 2] and in Fig. 1. In this system, the energy injected at a given scale is constantly transferred to smaller scales until it is dissipated by viscosity. Meanwhile, the scales larger than the energy injection scale are in statistical equilibrium, similar to a system at thermodynamic equilibrium. The framework of stochastic thermodynamics thus offers non-invasive tools to characterize the work generated by an out-of-equilibrium system and the power transferred to the rotor [3].

Research focus

We will first focus on measuring the rotor dynamics, notably the probability density functions of the angular velocity and the torque exerted by the flow. The goal is to test whether a fluctuation theorem can be used to describe the work injected into the rotor via its coupling with the turbulent flow structure. We will also tune the intensity of the turbulence by increasing the energy injection to assess the range of validity of this fluctuation theorem.

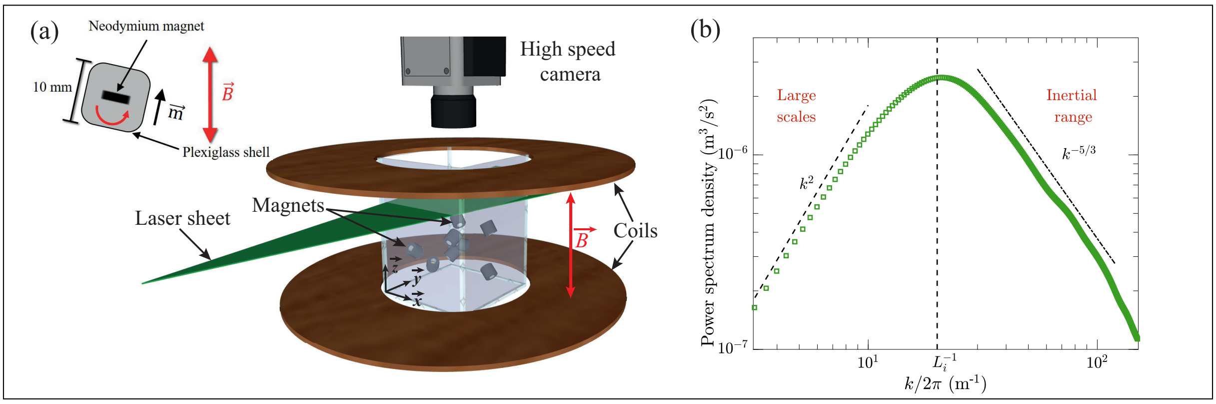

Figure 1: (a) Experimental setup showing the liquid reservoir and the encapsulated magnets together with a schematic representation of a magnetic stirrer rotation induced by an externally vertical oscillating magnetic field $B(t)$. The AC magnetic field imparts a torque $\vec{\Gamma}$ over the stirrer's magnetic moment $\vec{m}$. (b) Power spectrum density, $E(k)$ of the measured fluid velocity showing a k^2 power-law spectrum at large scales, characteristic of equipartition, and a $k^{-5/3}$ power law of the turbulent energy cascade towards small scales.

References

[1] A. Cazaubiel et al., Three-dimensional turbulence generated homogeneously by magnetic particles, Phys. Rev. Fluids **6**, L112601 (2021).

[2] J.-B. Gorce and E. Falcon, Statistical Equilibrium of Large Scales in Three-Dimensional Hydrodynamic Turbulence, Phys. Rev. Lett. **129**, 054501 (2022).

[3] N. Francois et al. Nonequilibrium thermodynamics of turbulence-driven rotors, Phys. Rev. Lett. **124**, 254501 (2020).