TURBULENT EMULSIONS

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How can turbulence transform a viscous multi-component fluid into an elastic solid? How do jammed emulsions flow? What is the relation between the stirring protocol and the final emulsion (jammed) state?

Turbulence, the chaotic state of fluid motion, is ubiquitous and responsible for the development of intermittent velocity fluctuations with non-trivial correlations spanning a broad range of length- and time-scales. This complex flow behavior is present even in simple Newtonian fluids, such as water, which are characterized by a linear relation between the viscous stresses, arising from the flow, and an applied shear.

However, many ordinary fluids such as toothpaste, ketchup and mayonnaise, are non-Newtonian. These fluids are characterized by an internal microscopic composition responsible for the emergence of a non-linear relationship between viscous stresses and the locally applied shear.

Figure 1: How does a complex fluid flow under turbulence? Current computing capabilities allow to study the dynamics of complex fluids in complex flows. This requires accurately modeling and resolving both the small-scale physics (e.g. surface tension, disjoining pressure) as well as the large-scale turbulence. The dynamics of the formation of a jammed state in a stabilized emulsion, such as oil in water systems, can be investigated e.g. via multicomponent Lattice Boltzmann methods capable of modeling fluid-fluid interfaces with surface tension and disjoining pressure. (Left panel) Under the influence of a turbulent stirring, oil droplets constantly undergo coalescence and breakup: droplets shapes are visibly non-spherical. (Right panel) After that the turbulent stirring is switched off the emulsion achieves a metastable equilibrium: in this case spherical droplets corresponding to a non-jammed state (volume fraction of dispersed phase \textasciitilde 40\%).
Despite the weakness of microscopic forces, these can interplay with turbulent stresses in a non-trivial way and, as a consequence, (turbulent) non-Newtonian fluids can display a remarkably rich phenomenology. One well known example is the turbulent drag reduction due to the addition of a small amount of polymers: even few parts per million in weight of polymer can reduce turbulent drag by up to 80% [1].

One of the most fascinating and complex aspects of turbulence in complex fluids is the tight interplay between macroscopic turbulent fluctuations and small-scale internal structure. Indeed, while the presence of small-scale forces can considerably alter the large-scale flow, this same large-scale flow does, in turn, modify the microscopic structure of the complex fluid. For example, polymeric stresses influence turbulent drag while turbulent stresses stretch polymers. Similarly, turbulent stresses break-up droplets, while the presence of a dispersed droplet phase influences the macroscopic (turbulent) flow itself.

As a concrete example of turbulence in complex flow we focus on turbulent emulsions, i.e. turbulence in fluids made of two (or possibly more) immiscible fluid components. When subject to turbulence such fluids will form droplets, giving rise to turbulent emulsions. The physical properties controlling the dynamics of such emulsions include the densities and the viscosities of the two fluids, the surface tensions and the Reynolds number of the flow. Another key ingredient is the volume fraction of the two fluid components. Think of a layer of oil on top of water: when stirring the fluids sufficiently strong the (flat) interface between oil and water will be broken and droplets will be formed. In a turbulent flow, the droplets size is controlled by inertial effects, droplets deform and break under the influence of turbulent velocity fluctuations. The relative importance of turbulent velocity fluctuations with respect to surface tension forces is measured by the dimensionless Weber number. Combining Kolmogorov K41 theory of turbulence with surface tension energy estimate one can readily compute a critical droplet diameter (usually named after Kolmogorov and Hinze): droplets larger than this critical diameter will break up due to turbulent stresses, while smaller droplets are stable, except for eventual coalescence events. This idealized picture is actually just a small part of the story. In fact, due to the strong intermittency of turbulent fluctuations the distribution of droplet radii is rather polydisperse around the critical Hinze diameter (Perlekar et al. [2]). When the two fluids have the same physical properties, it is energetically favorable to form droplets of the minority phase dispersed into the majority phase and not vice-versa, in this way the energy associated to surface tension is minimized. It is interesting to notice that the physical arguments leading to the Kolmogorov-Hinze critical droplet diameter apply also in the case of dense emulsions (e.g. 50%-50%) where no droplets are present but rather a bi-continuous (turbulent) morphology occurs. Turbulence can arrest spinodal decompositions maintaining the system in a statistically stationary conditions with turbulence constantly breaking structures larger than the Hinze length-scale (Perlekar et al. [3]). However, all these emulsions are unstable and, when the turbulent stirring is switched off, the two fluid components invariably separate via spinodal decomposition or via droplets coalescence, according to the volume fractions.

The physical picture is however very different for stabilized emulsions, e.g. via the addition of agents capable of inducing a disjoining pressure between droplets (e.g. surfactants). In this case switching off turbulence will lead to a metastable state characterized by a dispersed droplet phase that will, eventually and extremely slowly, destabilize the emulsion due to diffusion (Ostwald ripening).

Many common food products, such as mayonnaise, fall in this category and display a remarkable phenomenology ranging from that of a viscous fluid to that of an elastic solid. Stabilized emulsions, additionally, can display much of the rich phenomenology typically associated with soft glassy systems, including aging, metastability, yield stress, thixotropy, etc.

The presence of a disjoining pressure between droplets induces an elasticity in the system. In order to be able to break up droplets one needs to overcome the energy barrier associated to surface tensions, while, in order to let two droplets coalesce, one need to push them strongly enough against each other in order to win the disjoining pressure. Today’s computer and numerical models allow to incorporate the physics associated to these small-scale forces, as well as to resolve systems large enough to allow capturing the macroscopic rheology and turbulent dynamics.
As much as in the kitchen, in order to achieve large volume fraction of the dispersed droplet phase (i.e. larger than 50%) it is necessary to adiabatically increase its volume fraction. This allows to maintain the system in a local minimum of the free energy, escaping more (stable) minima corresponding to the inverted emulsion (where the minority phase is dispersed). Strong forcing, too rapid increase or too large values of the dispersed phase volume fraction will however invariably lead to the so-called catastrophic phase inversion (a sudden non-equilibrium process through which the emulsion rapidly destabilize and phases invert).

How does phase inversion occur? How do dense stabilized emulsions flow? What is the nature of turbulence in such complex fluids? These fascinating questions are still in search for complete answers. High performance computers, new theoretical insights and innovative experimental techniques will be key in this endeavor.

Figure 2: In this case a jammed state was produced by adiabatically increasing the volume fraction of the dispersed phase. Droplets are now clearly non spherical and, despite pushing against each other, they do not coalesce thanks to the action of a sufficiently strong disjoining pressure (volume fraction of the dispersed phase ~75%).

REFERENCES