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Shear thickening in dense suspensions: an experimental study

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ABSTRACT

Shear thickening is an intriguing rheological behaviour which consists in a brutal increase in the viscosity above a critical shear rate. It is famously encountered in suspensions of corn starch in water. Despite having been discovered in the early 1930's, its underlying mechanisms remained a mystery for a long time. In 2013–14, numerical and theoretical works [1–3] put forward a frictional transition scenario to explain this phenomenon.
In this talk, I will present experimental work investigating this frictional transition scenario. In order to test the ideas of this model, one has to go further than standard rheological techniques, since they do not provide access to the frictional state of the measured suspension. I will thus focus on the techniques that we developed in order to evidence the frictional transition and link it to the presence of a shear-thickening behaviour.

Videos to this article can be found online at https://doi.org/10.1016/j.sctalk.2022.100038.

Figures and tables

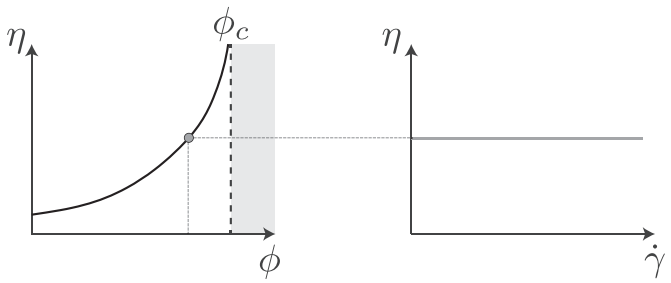

Fig. 1. Viscosity η of a classical suspension (modeled as hard spheres in a Newtonian fluid) as a function of the imposed packing fraction ϕ (left) or the imposed the shear rate $\dot{\gamma}$ (right). Above the critical packing fraction ϕ_c, the suspension is jammed and can no longer flow. Below this critical packing fraction, the viscosity of the flowing suspension is independent of the shear rate. From [4].

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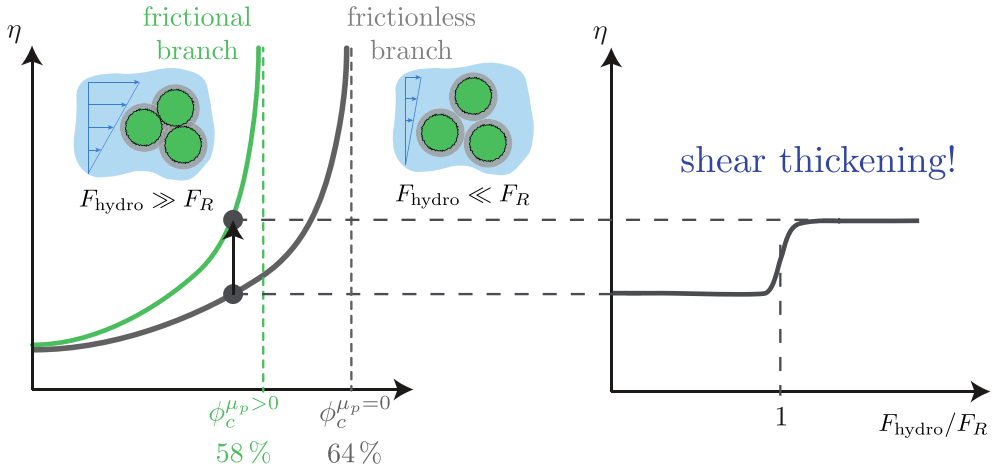

Fig. 2. Shear thickening as a result of a frictional transition in the suspension. The suspension can evolve on either the frictionless (grey) or the frictional (green) rheological curve (viscosity as a function of the packing fraction, on the left) depending on the nature of the contacts between the particles. This frictional or effectively frictionless nature of the contacts depends on the ratio between the hydrodynamic forces and the short range repulsive force that exists between the grains. At a given packing fraction, increasing the shear rate changes the frictional behavior of the suspension and makes it go from one curve to the other. Adapted from [4].

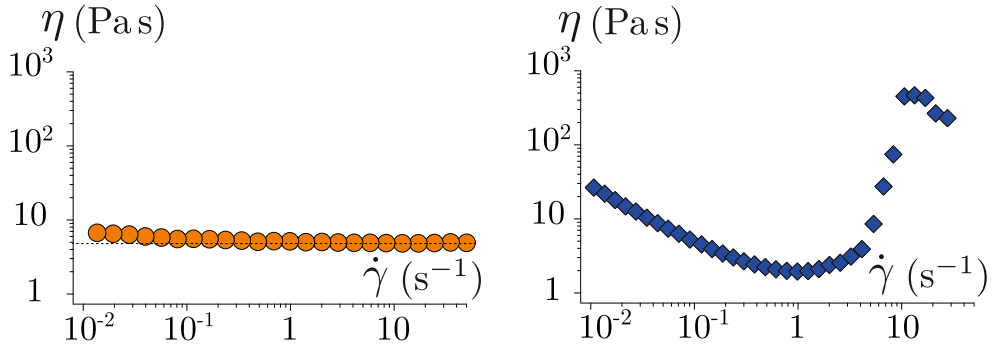

Fig. 3. Left: shear rate independent rheology of a suspension of large glass beads in a density-matched fluid. This suspension will serve as a non shear-thickening, "standard suspension" benchmark. Right: shear-thickening rheology of a suspension of potato starch in a density-matched fluid. From [4,5].

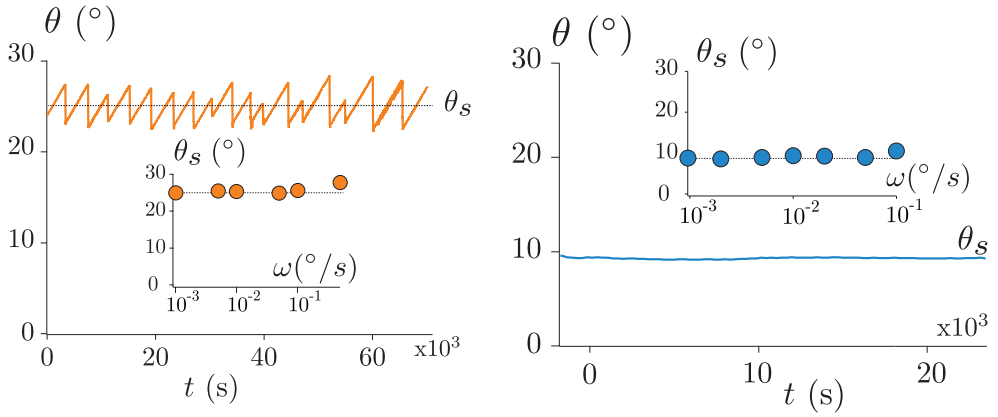

Fig. 4. Results of steady avalanche experiments in rotating drums. Angle of avalanche θ versus time t for (left) the non shear-thickening glass beads suspension and (right) the shear-thickening potato starch suspension. Insets: Steady-state avalanche angle θ_s versus drum rotation speed ω. The non shear-thickening suspension shows a typical frictional behavior while the shear-thickening suspension behaves like a suspension of frictionless grains. Adapted from [4,5].

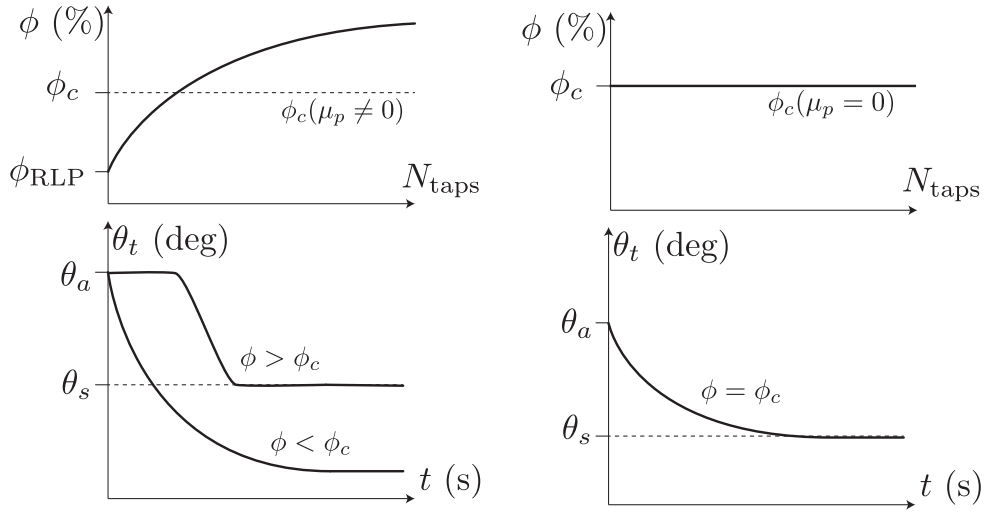

Fig. 5. Compaction: expected evolution of the packing fraction phi with the energy given to the system (here applied through taps and thus quantified by the number of taps). Dilatancy: expected time evolution of the transient avalanche angle θ_t depending on the compaction state of the suspension. The avalanches are started by imposing an angle θ_a higher than the steady avalanche angle θ_s of the system. Based on [6] for frictional grains and on [7] for frictionless ones.

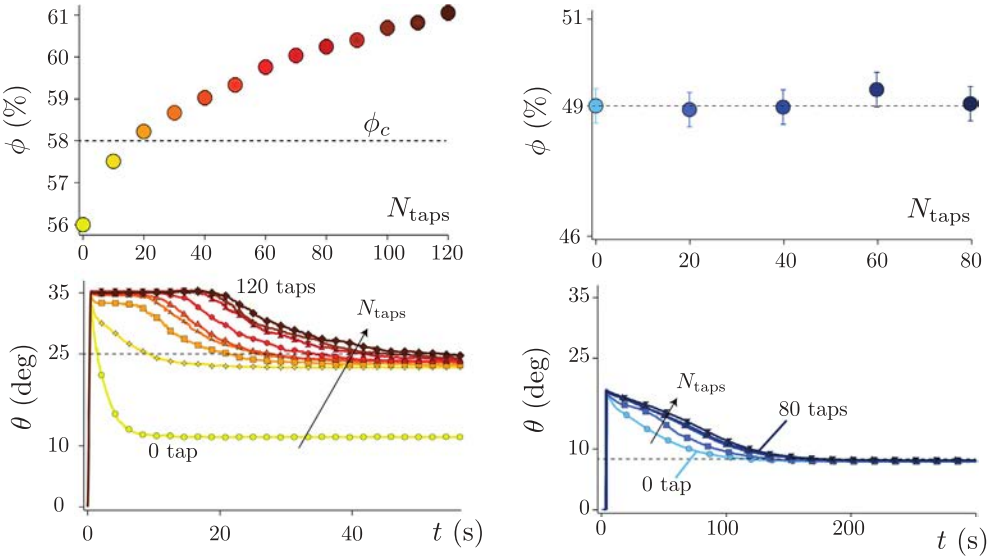

Fig. 6. Evolution of the packing fraction and transient avalanche angle for (left) the non shear-thickening glass beads suspension and (right) the shear-thickening potato starch suspension. Once again the non shear-thickening suspension (on the left) shows a typical frictional behavior while the shear-thickening suspension (on the right) behaves like a suspension of frictionless grains. From [4,5].

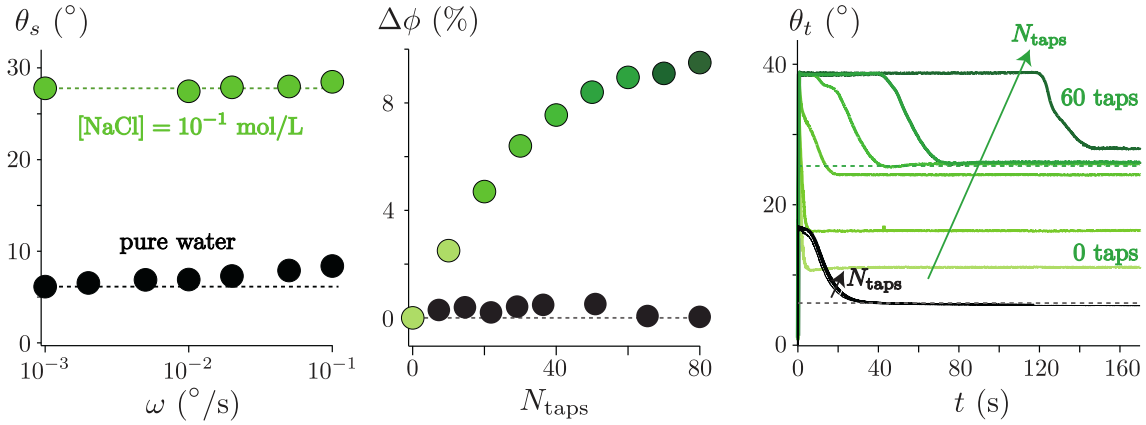

Fig. 7. Steady avalanche angle, compaction and dilatancy results for a suspension of silica particles immersed in pure water or in an ionic solution. In pure water, there is an electrostatic repulsive force between the grains, which then behave as frictionless ones. In the ionic solution, the added ions screen this repulsive force, and the suspension thus retrieves a typical frictional behavior. Adapted from [4,5].

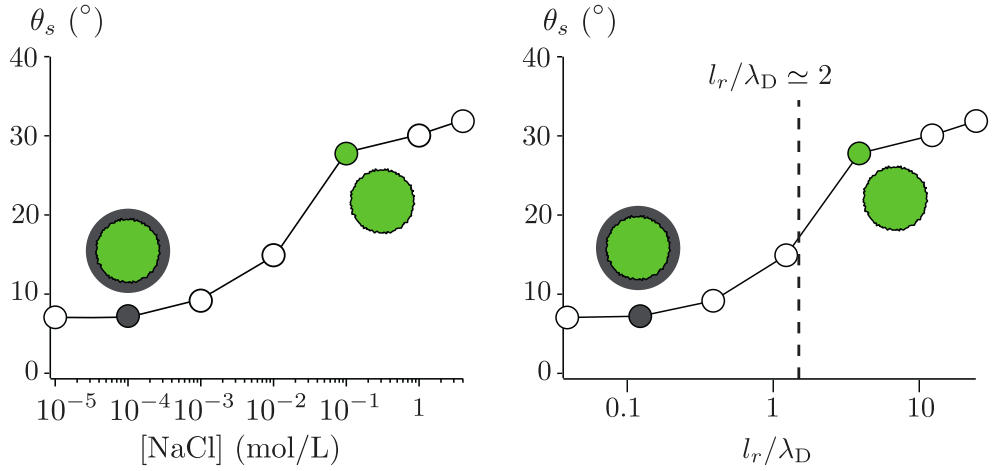

Fig. 8. Left: evolution of the steady avalanche angle θ_s (an indirect measurement of the macroscopic friction coefficient of the suspension) with respect to the ionic concentration (an indirect measurement of the range of the repulsive force), for suspensions of silica particles in ionic aqueous solutions. We observe that there is, indeed, a frictional transition when the repulsive force is screened by ions. Right: same data plotted as a function of the ratio between the typical roughness of the particles l_r and the range λ_D of the repulsive force. The frictional transition theory predicts a transition around $l_r/\lambda_D \simeq 2$. Adapted from [4,5] .

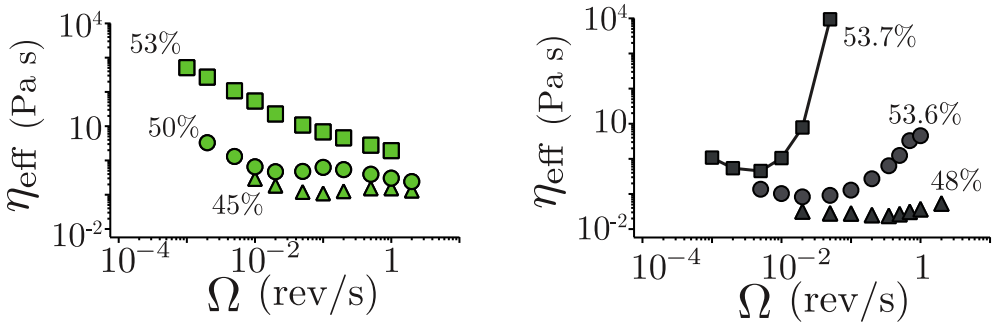

Fig. 9. Rheograms of suspensions of silica beads in ionic solutions (left: [NaCl] = 10^{-1} mol/L, right: [NaCl] = 10^{-4}mol/L). The percentages are the different packing fractions. The solid black line is simply a guide for the eye. Adapted from [4,5].

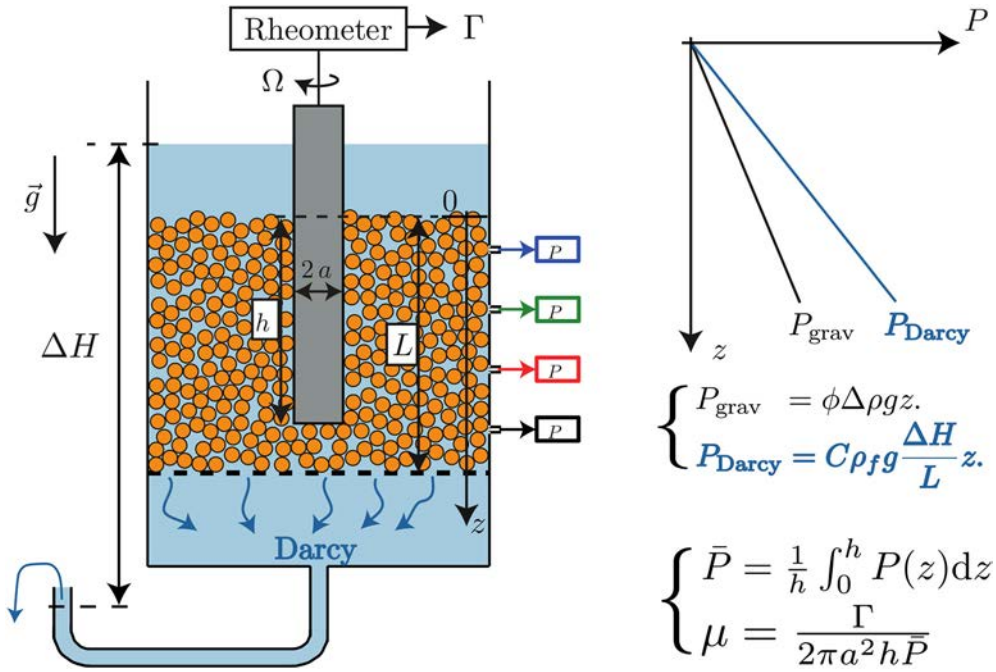

Fig. 10. The Darcytron: a new, pressure-imposed rheometer adapted to non buyoant shear-thickening suspensions. A vertical pressure gradient is imposed by a Darcy flow through the suspension, settled on a fixed grid. This Darcy gradient is added to the gravity gradient. With a tool connected to a rheometer head, we can measure the macroscopic friction coefficient μ of the suspension at a given average imposed pressure $\bar{P}$.

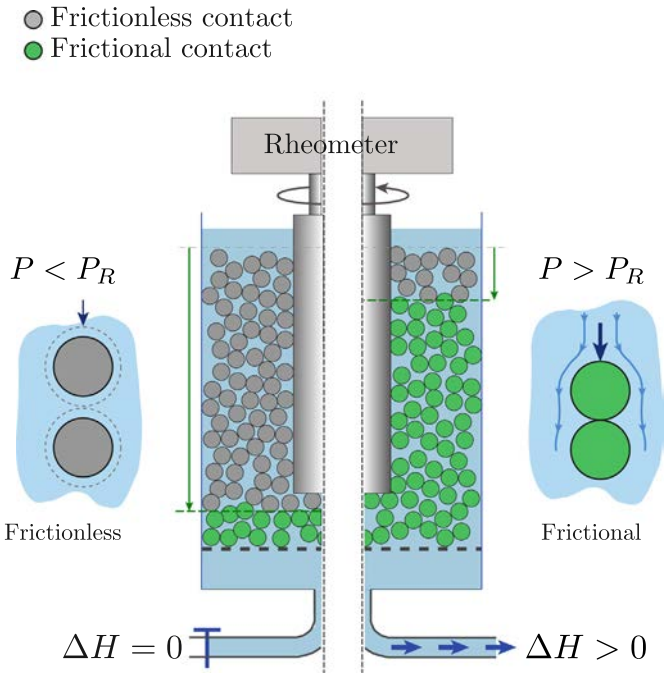

Fig. 11. The Darcytron used with a shear-thickening suspension. The critical height at which most contacts will change from being effectively frictionless to being frictional is a function of the imposed Darcy pressure gradient.

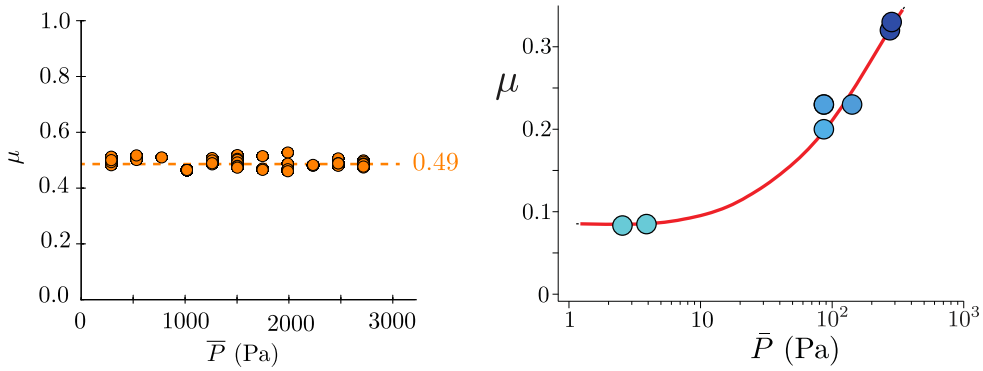

Fig. 12. Evolution of the macroscopic coefficient μ with the average applied granular pressure $\overline{P}$. Left: classical suspension of large frictional glass beads in a viscous Newtonian fluid. The friction coefficient is independent of the applied pressure. Right: shear-thickening suspension of silica beads in pure water. The friction coefficient increases with the applied pressure. Adapted from [4,8].

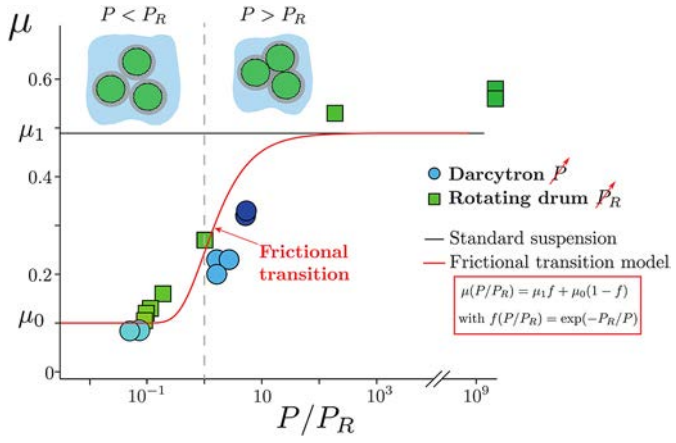

Fig. 13. Master curve showing the frictional transition when changing the repulsive pressure (with the rotating drums) or the applied pressure (with the Darcytron). These results show that the relevant parameter that controls this transition is indeed the ratio between the applied stress and the repulsive stress between the grains. Adapted from [8].

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Further reading

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