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FOCUS ON FLUIDS

It takes three to tangle

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The clustering of debris floating on liquid interfaces such as water surfaces is a complex phenomenon that finds its applications in numerous examples from industrial processing and environmental systems. The recent paper by Shin & Coletti (*J. Fluid Mech.*, vol. 984, 2024, R7) presents an experimental campaign investigating the three effects of turbulence, particle interactions and interfacial effects, to elucidate how the three force scales drag, capillary forces and lubrication give rise to three distinct regimes of clustering in dense suspensions. The study, hence, provides a useful systematic to categorize the clustering mechanisms. As an important finding, it is shown that, depending on volume fraction and non-dimensional turbulent shear, particles either tend to cluster into aggregate sizes larger than the Kolmogorov scale or can break into pieces that are as small as the primary particle size.

Key words: suspensions, cohesive sediments, particle/fluid flow

1. *De nihilo nihil* – clustering needs contact

Particle suspensions are ubiquitous and they yield fascinating dynamics including non-Newtonian rheological behaviour and particle clustering. These are two very important examples of processes occurring in many applications in engineering (e.g. froth flotation, pneumatic conveying) and in the environment (e.g. flocculation of fine-grained sediments, debris flows). For dilute suspensions, particles may interact with each other upon contact, which can be driven by three different mechanisms: (i) Brownian motion, (ii) differential settling and (iii) fluid shear. While Brownian motion may be neglected in most large-scale, practical engineering systems, differential settling is relevant in environments where the root-mean-square velocity of the turbulent fluctuations u_{rms} is lower than the settling velocity of the sediment grains. Consequently, for most environments, fluid shear is the dominant mechanism that brings particles into contact (Partheniades 2009). For a dense suspension, however, a regime change can be identified.

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As the mean free path between particles decreases, collisions and contact become more and more frequent, so that eventually frictional contacts and short-range hydrodynamic interactions dominate over long-range hydrodynamic effects. This behaviour has been observed, e.g. for the rheology of dense suspensions, where the transition happens at around 30 % volume fraction (Vowinckel *et al.* 2021).

As particles decrease in size, the inertial effects diminish, allowing any attractive force to cause the particles to bond together and form larger aggregates with hydrodynamic properties that are very different from those of their original primary particles. The flocculation and clustering of cohesive particles is therefore an intriguing phenomenon in flows laden with fine-grained sediments (Vowinckel *et al.* 2023). Flocs, aggregates and clusters are stable assemblies of particles that are held together by their cohesiveness. As an example that addresses differential settling, Sutherland, Barrett & Gingras (2015) investigated the settling of fine-grained clay particles in salt water for various sediment concentrations. Such particles are cohesive so that they form aggregates upon contact. It was observed in these experiments that distinct settling fronts emerge as a clear indication for flocculation at sediment concentrations larger than 20 grams per litre, whereas the front remained more fuzzy at lower clay concentrations.

Experiments considering fluid shear find that flocculation is governed by a delicate balance between cohesiveness and shear forces. While cohesive properties always promote flocculation, shear can act either to enhance or retard flocculation. On the one hand, shear promotes flocculation as particles are brought into more frequent contact. On the other hand, aggregate growth is disturbed, if a certain critical threshold value for the shear rate is exceeded. Consequently, there is an optimal shear rate for maximum aggregate growth at various sediment concentrations. This was observed in the experiments by Dyer (1989), where dilute concentrations up to 10 grams per litre were considered. As an important finding, this study has shown that aggregates cannot exceed the Kolmogorov eddy size as the smallest scale of the turbulent motion. As the aggregate size becomes larger than this critical length scale, the shear forces will very soon thereafter break the aggregate apart (cf. Fettweis *et al.* 2006).

Cohesiveness can be induced by different particle properties. Three prominent examples are (i) electrostatic van-der-Waals forces, (ii) biofilms and (iii) capillary forces. Most of the studies in the recent literature investigating flocculation have focused on three-dimensional flows with only two phases (solid and liquid), where capillary forces do not play a role. In addition, these studies are mostly limited to dilute systems with mass fractions below 20 grams per litre (e.g. Dyer 1989; Sutherland *et al.* 2015). However, it can be expected that, at liquid interfaces, where buoyant particles tend to accumulate, capillary forces are going to play a key role and this process also deserves further consideration. The study by Shin & Coletti (2024) addresses this research question in a rigorous manner by investigating sediment suspensions at a liquid interface subjected to quasi-two-dimensional turbulence (Shin, Coletti & Conlin 2023). Such a scenario is useful to investigate the clustering of debris floating in the ocean such as the Great Pacific Garbage Padge (GPGP) or the deposition of ash on lakes in the aftermath of a wildfire or even the selective separation of various milled rock materials in froth flotation, to name only three prominent examples. What is more, it was recently shown by Zhao *et al.* (2023) that such a quasi-two-dimensional set-up can be utilized to make predictions for particle clustering in fully developed three-dimensional isotropic turbulence as well. Zhao *et al.* (2023) were able to show this by numerical simulations, where the flow field was further simplified by the initial condition of two-dimensional Taylor–Green vortices. With this computational approach, particles were driven by the analytically defined flow field, but no feedback by the particles was imposed on the fluid.

2. *In medias res* – a regime map for clustering at liquid interfaces

In the study by Shin & Coletti (2024), shallow layers of a conductive fluid were placed on a tray with a chequerboard array of magnets arranged at distance L_f of alternating polarity underneath to generate the two-dimensional turbulent field. Full details of this procedure are given in Shin *et al.* (2023). Particles were nearly neutrally buoyant, non-Brownian and possessed little inertia, that is, they had low Stokes numbers. The authors conducted a set of experiments varying the particle size from diameters of 1.09 to 1.84 mm, the volume fraction ϕ from 0.01 to 0.71 and the turbulence intensity, where turbulent intensity is defined by the Reynolds number, $Re = u_{rms}L_f/\nu$, and was varied from 192 to 1747. Here, ν is the kinematic viscosity of the fluid. As a main consequence of these choices for the physical parameters, the ratio of particle diameter to Kolmogorov length scale was in the range of 0.57–3.54.

Having established the physical setting, Shin & Coletti (2024) provide a scaling analysis to identify the three most important forces governing the system behaviour. Those are forces due to capillary attraction ($F_{capillary}$), long-range hydrodynamic forces due to fluid drag on the particle (F_{drag}) and short-range hydrodynamic forces due to lubrication ($F_{lubrication}$). The forces due to capillary attraction are especially hard to assess. Shin & Coletti (2024) therefore developed an elegant argument to measure the power-law relation for the difference of the initial interparticle distance to the distance evolving in time. This was done for two particles in creeping flow conditions and serves as a surrogate for capillary attraction. Similar to the classical picture of Dyer (1989) for dilute suspensions, Shin & Coletti (2024) derive a non-dimensional capillary number $Ca = F_{drag}/F_{capillary}$ that describes the competition of fluid shear and capillary forces, i.e. the higher the Ca the stronger the impact of fluid shear. Lubrication forces are important to the system only for small interparticle distances. Those forces are dissipative and represent the work needed to squeeze fluid out of the gaps of approaching particles. Hence, it becomes the dominant force for denser systems.

For every experimental run, Shin & Coletti (2024) measured the fraction of clustered particles, the cluster diameter and the particle kinetic energy. The data show clear trends. As the capillary number increases, the fraction of clustered particles decreases in a power-law behaviour. Furthermore, as the volume fraction is increased beyond 40 %, the cluster diameter increases sharply while the particle kinetic energy decreases (figure 1*a*). This observation shows that shear serves to break up particle clusters, but this can be counteracted by a high enough volume fraction which does not allow for cluster dispersal. In fact, at volume fractions larger than 40 %, shear generates very few very large clusters that are able to decouple their kinematics from the fluid flow despite the Stokes number of individual particles being low. This observation gives rise to a comprehensive regime map that distinguishes three limits, in which one of the three force scales prevails (figure 1*b*). For low capillary numbers, the attractive forces promote the formation of large clusters regardless of the volume fraction. For $Ca > 1$, shear breaks up the clusters as long as the volume fraction is below 40 %, while for more dense systems dissipative lubrication forces promote the formation of clusters that become as large as 10 L_f even for the highest Ca-values investigated ($Ca = 3.0$).

3. *Quo vadis?* – major outcomes and future perspectives

The study by Shin & Coletti (2024) provides several very important findings. As a first obvious outcome, the proposed regime map allows for rapid assessment and categorization of the cluster formation mechanisms as a function of only two non-dimensional

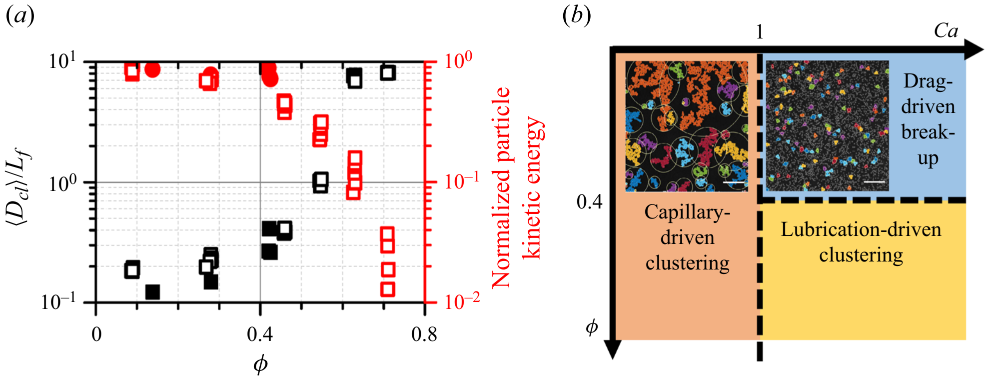

Figure 1. (*a*) Mean cluster diameter D_{cl} and normalized particle kinetic energy as a function of ϕ. The diameter is seen to increase for $\phi > 0.4$, whereas kinetic energy drops sharply. (*b*) Regime map for clustering in the (Ca, ϕ)-space. The snapshots are for $\phi = 0.28$ with different Ca. White circles and scale bar indicate D_{cl} and L_f, respectively. Images taken and modified from Shin & Coletti (2024).

parameters, i.e. the particle volume fraction and the capillary number. The regime map thereby confirms previous studies in the dilute regime, where an optimal shear rate was proposed for cluster formation. The parameter space investigated by Shin & Coletti (2024), however, goes beyond this finding by considering dense suspensions up to a volume fraction of 71 %. This choice opens up the perspective on two more interesting aspects. First, if systems are dense, clusters can grow beyond the Kolmogorov scale due to lubrication effects. Second, the clusters formed in denser suspension have the potential to decouple from the fluid motion. Consequently, the large clusters become stable entities that cannot be broken up by fluid shear as easily. This has important consequences for environmental systems in which debris floats on the water surface, such as the GPGP.

As an interesting aspect for future work, it will be worthwhile following up on the argument of Zhao *et al.* (2023) described above and testing if the results provided by Shin & Coletti (2024) would also apply for three-dimensional isotropic turbulence or even turbulent flow with mean shear. In such cases, capillary forces will no longer be the mechanism for clustering. Instead, cohesive forces due to van-der-Waals forces or biofilms become the driving factor. Such particles, however, have to be fine grained so that the ratio of particle diameter to Kolmogorov length scale should increase. A common value for this ratio is around 10 (Vowinckel *et al.* 2023), and this consideration would be a useful extension of the parameter range considered by Shin & Coletti (2024). The regime map by Shin & Coletti (2024), therefore provides a valuable tool for engineers to characterize cluster formation as well as their kinematics and has the potential to become an important tool for practitioners dealing with questions of particle-laden flows in environmental and process engineering.

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