Shape tilting in viscoelastic fluids

Shape tilting refers to the fact that falling long bodies tend to line up along the longest line in the body. A cube will fall in such a way that the line between vertices is along gravity.

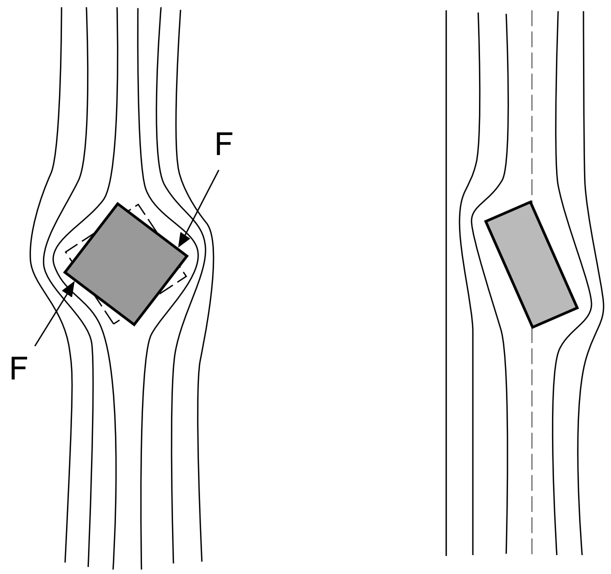

Figure 1. Particles tend to line up vertex to vertex.

The experiments of Lui and Joseph 1993 and Joseph and Liu 1993 give evidence to shape tilting, but not in such an ideal form as in the diagram. Joseph and Lui 1993 studied the sedimentation of cylinders in the viscoelastic fluid SI, which is only modestly shear thinning. They say that, "None of the cylinders turned broadside-on and all the round nose and cone end cylinders would turn to put their long side straightly parallel to gravity. The sharp end cylinders tilt as they fall with short cylinders tilting more than long ones (see figure 10). Liu and Joseph 1993 called this 'shape tilting,' and they discussed some mechanisms associated with extensional stresses at sharp corners which could induce this tilting." [15]

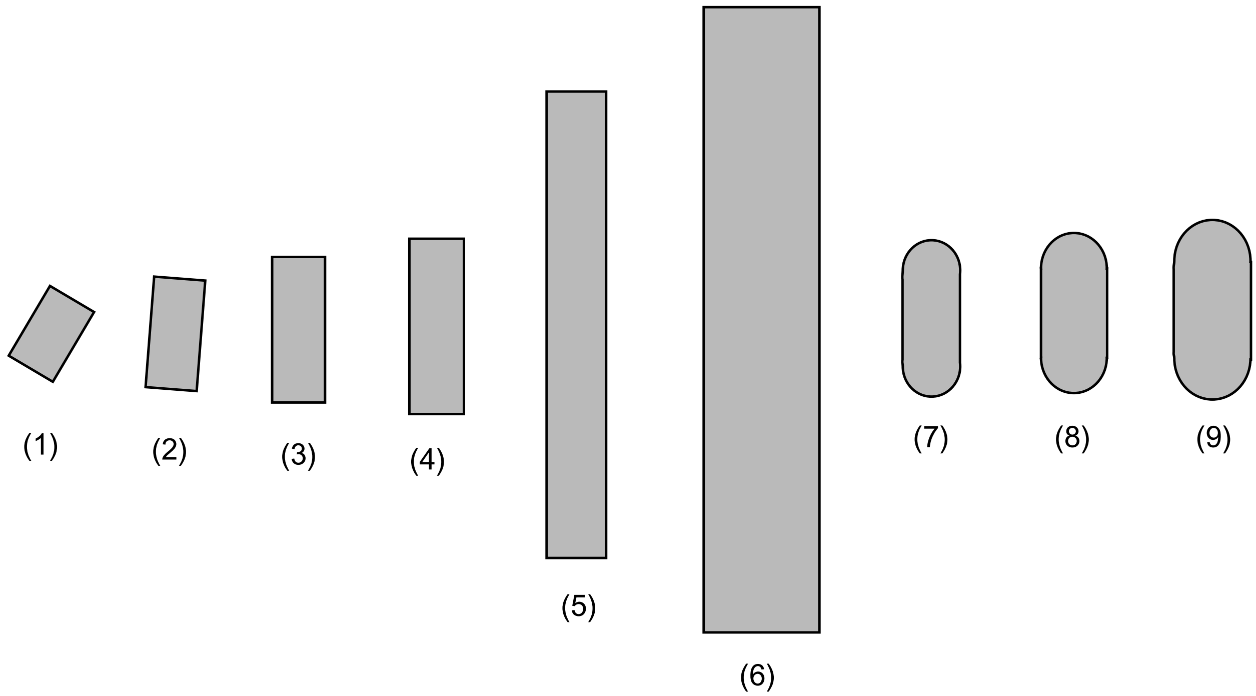

Figure 2. Sketch of the orientation of cylinders falling in S1 in the channel of 0.5 × 6.7 × 25.5 inches except particle (6) in the channel of 1 × 1.63 × 28 inches. The particles (1) to (6) are tungsten carbide and (7) to (9) are brass.

Effects of shear thinning

The tilting of falling long bodies is not restricted to shape tilting. The tilting of symmetric bodies falling in viscoelastic fluid is not yet well understood. It is possibly associated with wall effects and the effects of shear thinning. Many experimenters look to study the effects of normal stresses with shear thinning. The preferred experimental method for eliminating the effects of shear thinning is to use a fairly dilute solution of a high molecular weight polymers into a highly viscous Newtonian solvent. These solutions are called Boger fluids. They have nearly constant viscosities and to exhibit normal stress effects. However, the ratio of the normal stresses to shear stresses is rather small so that the fluids that are viscous dominate and falling particles tend to behave as they do in a Newtonian fluid.

It would be desirable to understand the effects of shear thinning from theory so that experiments with natural viscoelastic fluids, which nearly always shear thin, could be interpreted.

Joseph gave a heuristic argument which indicates that one important effect of shear thinning is to augment the effects of the normal stresses (the viscoelastic pressure) which tend to turn the body into the stream.

The heuristic argument showing how shear thinning amplifies normal stresses is as follows: consider the normal stress at a plane wall and then imagine that a similar situation applies at the boundary of a long falling body. If the fluid shear thins then the wall shear stress is given by

$\tau_w = \eta\left(\overset{\circ}{\gamma}_w\right)\overset{\circ}{\gamma}_w$ and the viscosity $\eta\left(\overset{\circ}{\gamma}_w\right)$ goes down when the shear rate $\overset{\circ}{\gamma}_w$ goes up (shear thins). But the normal stress

$$-\psi_1 \overset{\circ}{\gamma}_w^2 = \frac{\tau_w}{\eta\left(\overset{\circ}{\gamma}_w\right)} \overset{\circ}{\gamma}_w \tag{2}$$

must strongly increase if τ_w is constant as it would be, say in the Poiseuille flow in a pipe. Huang, Hu and Joseph 1998 showed that ellipses falling in a viscoelastic fluid were stable in a tilted orientation when the fluid shear thins and were unstable when shear thinning was suppressed.

It would be of great interest to have mathematically rigorous results for the effects of shear thinning.

Experiments

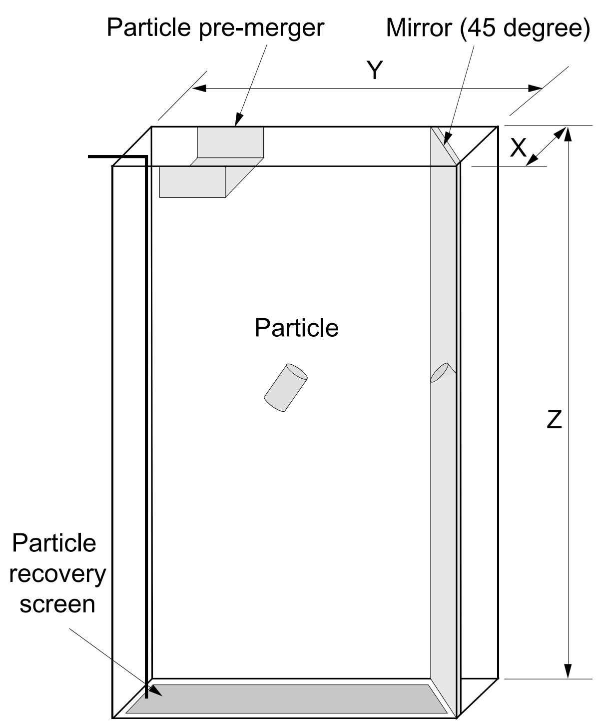

Figure 3. The sketch of the sedimentation channel.

Channels

In the sedimentation experiments particles will be dropped in a liquid-filled channel. Two channels will be made, one called a two-dimension channel (0.5” x 8” x 40”) and another called a three-dimensional channel (4” x 4” x 36”). The two-dimensional channel is basically three-dimensional though one dimension of the cross section is much smaller than the other. In the two-dimensional channel, there is a thin and long mirror places in 45 degree in one side, so that both the front and side tilting can be observed in front view. Also paper scales graduated to one millimeter are fixed to the backside of the channel. In the two-dimensional channel, the distance between the dropping particles and the front and back wall is very small. The effects of the sidewalls will be very important. The three-dimensional channel is set up to minimize the side wall effects. Particles are collected on a screen that may be withdrawn without changing the fluid. In order to avoid air bubbles on the particles, a pre-wetting device will be used.

Particles

Various particles, such as cylindrical particles, cubic particles and plate particles with different weights will be used in the sedimenting test. In order to get systematic results for same-diameter cylindrical particles, flat ends, round ends and flat angle cut ends with the same weight will be made. We will make the same particle of different material to vary the weight for a fixed shape.

Measurement and visualization

Velocities and tilt angles will be measured with a high-speed digital camera which can take pictures at 1000 frames per second. The images can be replayed forward and backward at different play rates, and also can be stored in computers. Movable reticles allow spatial measurement, and the elapsed time is observed while the recording is being made and replayed. Those functions allow one to measure the falling speed and tilt angle of sedimenting particles. To visualize particle paths, orientation and fluid streamlines, color dye will be injected to the channel to form horizontal strip lines. These lines form a grid which deforms under motion and they give rise to an excellent record of the streamlines and wake structures created by falling particles.

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Numerical simulation

The goal of our numerical simulations is to simulate experiments and suggest hypotheses about migration and lift of spherical particles in shear flows and the orientation of long particles and shape tilting in sedimentation. For this purpose we plan to sue the distributed LaGrange-Multiplier (DLM) method.

The basic idea of this method is to imagine that fluid fills the space inside as well as outside the particle boundaries. The fluid-flow problem is then posed on a larger domain (the "fictitious domain"). This larger domain is simpler, allowing a simple regular mesh to be used. This in turn allows specialized fast solutions techniques. The larger domain is also time-dependent, so the same mesh can be used for the entire simulation, eliminating the need for repeated remeshing and projection this is a great advantage, since for three-dimensional particulate flow the automatic generation of unstructured body-fitted meshes in the region outside a large number of closely spaced particles is a difficult problem. In addition, the entire computation is performed matrix-free, resulting in significant savings.

The velocity on each particle boundary must be constrained to match the right-body motion of the particle. In fact, in order to obtain a combined weak formulation with the hydrodynamic forces and torques eliminated, the velocity inside the particle boundary must also be a rigid-body motion. This constraint is enforced using a distributed LaGrange multiplier, which represents the additional body force per unit volume needed to maintain the rigid-body motion inside the particle boundary, much like the pressure in incompressible fluid flow whose gradient is the force required to maintain the constraint of incompressibility. DLM has been implemented [refxx18] for viscoelastic fluids. A solution for the collisions has only recently been found (Singh et al 2001)

DLM works well for three-dimensional simulation (Pan, et al 2001) but is too expensive and has not been fully parallelized. All routines in our three-dimensional DLM codes are parallel except those that deal with solutions of the Poisson problem. On an eight-processor machine we are currently getting a speedup of around 4.5 and the bottleneck comes from the parts that are currently not parallelized. During the next few months, we plan to write parallelized Poisson solvers for our two and three DLM codes which is expected to increase the speedup factor to 6.5 or better. We also plan to test the fully parallelized code on more than eight processor machines to determine if the speedup remains satisfactory when the number of processors used ins much larger than eight. If we find that the speedup factor deteriorates significantly, we would use other approaches in addition to the OpenMP which we are currently using to obtain the desired speedup factor.

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