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Particle Motion in Fluid: Analytical and Numerical Study

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Abstract:
Particle motion in fluid is discussed for one-particle systems as well as for dense suspensions, such as cementitious materials. The difference in large particle motion between larger particles and behaviour of fines (< 125 μm) is explained, motion of one particle is shown by numerical simulation. It is concluded and highlighted that it is the particular motion of the fines that to a large extent contribute to the rheological properties of a suspension. It is also shown why larger ellipsoidal particles do not necessarily contribute to the increase of viscosity.

Key words:
Bingham model, suspensional flow, cementitious material

1 INTRODUCTION

The study of particles in fluid has been conducted for over a century. One single sphere suspended in fluid is subjected to a downward gravitational force G as well as an upward buoyant force B. Once the particle density ρ_p differs from the density of the fluid ρ_f, a force is exerted on the suspended sphere: $G - B = \pi d^3 g(\rho_p - \rho_f)/6$. The particle diameter is denoted d and gravity is denoted g. As early as 1851, Stokes derived an expression for the frictional force acting on a perfect sphere when moving in a Newtonian fluid. This frictional force, called drag force F_d, is defined as $F_d = 3\pi\eta dv$ with sphere velocity v and Newtonian fluid viscosity η. This equation holds true for laminar flow of very small Reynold numbers (<< 1). Later Einstein studied the sphere addition effect on fluid viscosity published 1906 and 1911 [1]. His theory on the viscosity η of an incompressible Newtonian liquid subjected to creeping flow when adding density neutral spheres still holds: $\eta = \eta_f(1 + 2.5\phi)$ with subscript f referring to the fluid without the addition of spheres ϕ and denoting the particle concentration. The theory holds true for a sufficiently small particle volume of less than 5 percent with no interaction between the particles. This paper focuses on the motion of differently sized particles in fluid, from the microscale to the macroscale with no more than one particle in the fluid up to dense particle systems such as cementitious suspensions. It is a well known fact, that for the aggregates used, mostly the shape of small particles, i.e. the fillers influence the rheology of concrete. Also, a large non-spherical particle flowing in a non-Newtonian suspension is simulated numerically and evaluated. It is logically investigated how small particles move and in what way this can be linked to the viscosity of a suspensional fluid. The different types of behaviour between large and small particles and their effect on concrete workability is highlighted in this paper. The origin of plastic viscosity is explained.

2 PARTICLES IN FLUID

A particle subjected to Stokes' drag force is moving at an increasing velocity, until the drag force and the difference between gravity and buoyancy reach equality $F_d = G - B$ and a so called terminal velocity v_t is reached [2]. For a plastic non-Newtonian fluid modelled as a Bingham material with apparent viscosity $\eta = \tau_o/\dot{\gamma} + \mu_{pl}$ (with yield stress τ_o and plastic viscosity μ_{pl}) and shear rate $\dot{\gamma} = v_t/d$, the steady state terminal velocity is easily deduced, as $v \to v_t$:

$$v_t = \frac{d}{\mu_{pl}}\left(\frac{dg\left|\rho_p - \rho_f\right|}{18} - \tau_o\right) \tag{1}$$

No movement of the particle occurs at yield stress $\tau_o \geq (d_g|\rho_p - \rho_f|)/18$. Similarly, the maximum particle diameter, which can be held by the yield stress is [2, 3]:

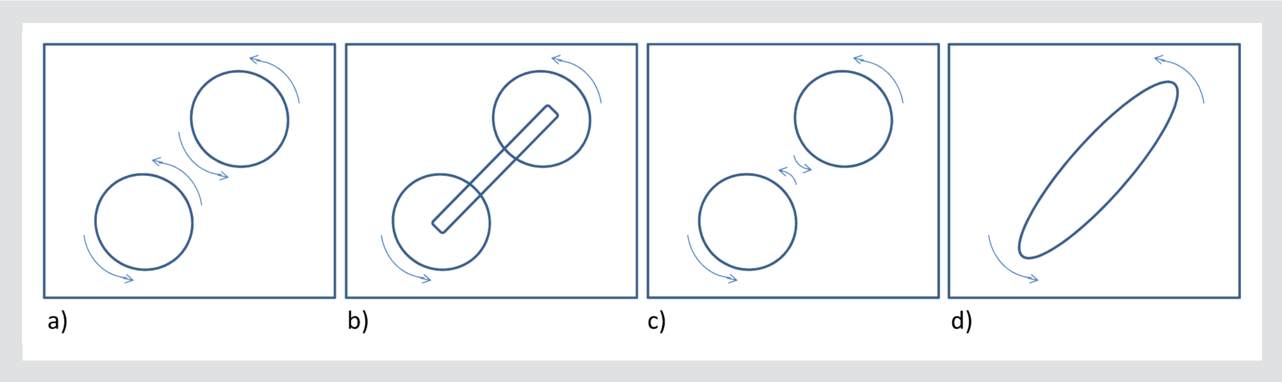

Figure 6: Rotation of particles in fluid – principle behavior (figure a to c redrawn from [13]).

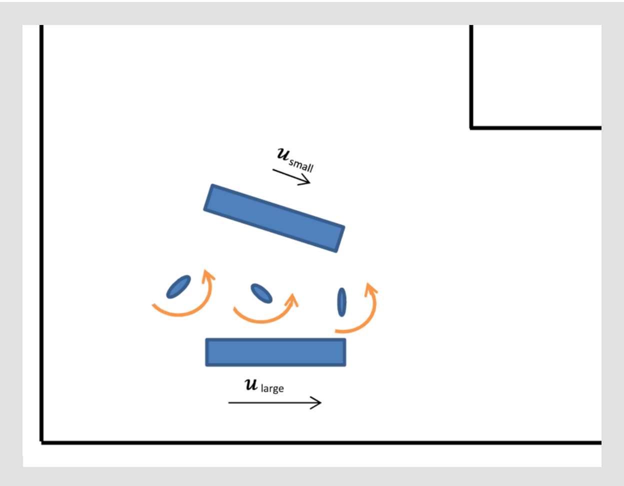

Figure 7: Interaction between large and small particles in flow around a corner.

6 CONCLUDING REMARKS

It was shown by numerical simulation that an elongated particle will align its major axis with the flow direction. The centre of the particle follows the fluid flow along the streamlines. Finer particles may rotate between the larger particles moving at different velocities or once the stream-lined flow is not linear, as in corners and bends. The rotation of crushed, non-spherical finer particles as well as particles of a few microns that agglomerate leads to an increased viscosity of the fluid. Another factor of non-spherical fines increasing the viscosity of a suspension is the larger particle surface area to be wetted by fluid compared to the surface area of a sphere. This effect densifies the particle system and increases flocculation. Flocs may be broken by superplasticisers, however the particular rotation of non-spherical particles will still increase viscosity. In addition to this, the amount of fine particles by far exceed the amount of larger particles in a normal or self-compacting concrete. This makes the fine particle shape even more important determining the rheological properties of a suspension. In practicality,for fresh concrete, this implies that very elongated or flaky filler materials need to be removed from the concrete of mixed with more rounded, favourable filler material in order to obtain workable concrete. Larger, ellipsoidal particles on the other hand do not affect workability to the same extent, their resistance to flow is actually lower than for spherical particles. Since large slender particles align themselves with the flow direction, this can be an advantage when casting e.g. fibre reinforced beams. When fluid travels from one end to another, the fibres can be oriented in a favourable way [9]. In case of radial flow, when e.g. filling a large slab by feeding the concrete at one spot in the middle and letting it flow radially, slender particles tend to orient themselves with the direction of the velocity vector. This results in an almost tangential particle orientation in circles around the feeding position [24], since the tangential velocity u_θ is more than six times larger than the radial velocity u_r ($2\pi u_r = u_\theta$).

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