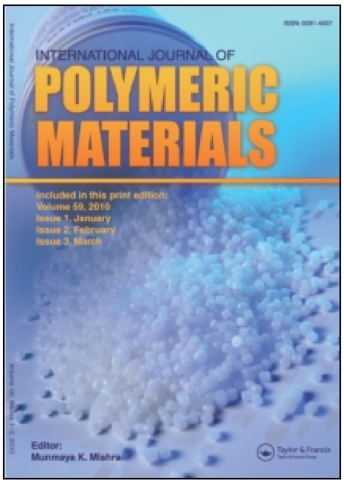

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Motion of Spherical Particles along the Wall in the Shear Flow of Newtonian and Non-Newtonian Fluid

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The motion of particles in the flow of Newtonian and non-Newtonian fluid is investigated. Both laminar and turbulent flows are considered.

KEY WORDS Shear flow, spherical particles, Newtonian fluid, non-Newtonian fluid.

RESULTS AND DISCUSSION

Particle motion in uniform flows and the slow motion of a particle along the wall with a lubrication layer have been studied extensively.

In the last case the influence of a fluid is only due to the particle-wall interaction via the thin lubrication layer.

Here we consider the case of a particle motion influenced by the gravitational force and the particle-fluid interaction force when both forces can be of the same order.

The experimental apparatus is shown in Figure 1. Fluid was pumped through the glass tube[1] at a measured flow rate.

The angle of tube inclination varied from 0° (vertical position) to 90° (horizontal position). The spherical particles[2] were made from lead, steel or glass. Newtonian fluids (water and glycerol solutions) and the non-Newtonian "Milling yellow" were used. The rheological properties of the last mentioned fluid are well described by a power-law model.

The basic experimental results will be considered for Newtonian fluids. In conclusion we will demonstrate how the results obtained can be generalized for the case of non-Newtonian fluids.

To analyze the experimental data we use the following definition of the drag coefficient:

$$C = F(\tfrac{1}{2}\rho u^2 S)^{-1} \tag{1}$$

where u is the particle velocity relative to the fluid flow, F is the force acting on

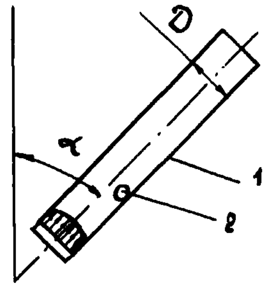

FIGURE 1 Experimental set up: 1 = glass tube, 2 = spherical particle, D = tube diameter, α = angle of tube.

the particle, ρ is fluid density, $S = \pi d^2/4$, d is particle diameter. Thus in the case of uniform fluid flow the drag coefficient is the function of Reynolds number

$$Re_p = \rho du/\eta \tag{2}$$

where η is the fluid viscosity.

For steady state particle motion the force acting on the particle is as follows:

$$F = P(\cos\alpha \pm k\sin\alpha), \qquad k = F_{fr}/P\sin\alpha \tag{3}$$

where k is the traditional friction coefficient. Friction force F_{fr} depends upon the weight of the particle P in the fluid and the hydrodynamic force, which tends to press it towards the wall. The plus or minus sign depends on whether the particle moves up or down the tube (with or against the fluid flow). From Equations (1) and (3), for the spherical particle we have

$$C = \tfrac{4}{3}gd(\rho_s/\rho - 1)u^{-2}(\cos\alpha \pm k\sin\alpha) \tag{4}$$

where g is the acceleration of the gravitational field, ρ is the particle density.

For the case of particle motion along the wall in the horizontal or inclined tube we substitute in Equation (4):

$$u = \langle v\rangle_d \mp w \tag{5}$$

where $\langle v\rangle_d$ is the mean (averaged over the distance equal to a particle diameter) local undisturbed flow-rate, w is the particle velocity along the tube wall.

Now consider the motion of a spherical particle in the upward fluid flow in horizontal and inclined tubes. In this case it was found that

$$\langle v\rangle_d - w = u \approx \text{const} \tag{6}$$

for any Reynolds number Re based on the tube diameter. The constant in (6) depends upon the tube inclination α, particle size and density, viscosity and density

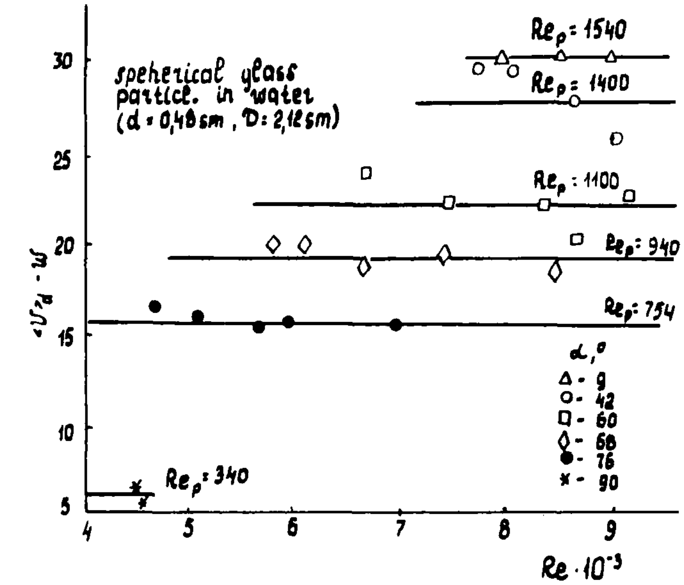

FIGURE 2 Spherical glass particles in water. Plots of $\langle v \rangle_d - w$ vs. Re for various angles of tube α: d = 0.48 cm, D = 2.12 cm.

of a fluid, and properties of the particle and tube material. The constant value might change during the transition from laminar to tubulent flow.

In the analysis of experimental data (Figure 2) the motion of a particle rolling up along the tube wall was considered (Figure 3a), with rotation rate increasing with flow rate.

When the particle transport in tubes with slight inclination (i.e. almost vertical) was studied, the other types of particle motion appeared. For instance, rather light particles (glass ballotini) demonstrated saltation when fluid viscosity was increased (see Figure 3b).

The drag coefficient for the sphere rolling up along the tube wall was calculated from Equation (4) (using the values of u given in Figure 2) for small inclinations (small values of α), when the friction is of minor importance. These results are given by curve II in Figure 4, which corresponds to the classical case (I) if the drag coefficient is multiplied by 1,5.

After the friction coefficient k was determined from curve II (as in the case of dry friction, it appeared to be almost constant), the validity of the assumption of small friction effect at small α was checked.

Curve II represents the experimental data for various particle and fluid parameters and various tube diameters (for the case $d/D \ll 1$).

Concerning the motion of two or more particles, it can be shown that the persistent motion of a chain of more than two contacting particles is impossible due to the instability. In the case of horizontal or almost horizontal tubes two particles move one after another (Figure 3c), but when the angle from horizontal is increased, particles start to jump over one another (see Figure 3d). An intermediate behavior was also observed (see Figure 3e), with the trailing particle slightly vibrating without jumping over the leading one.

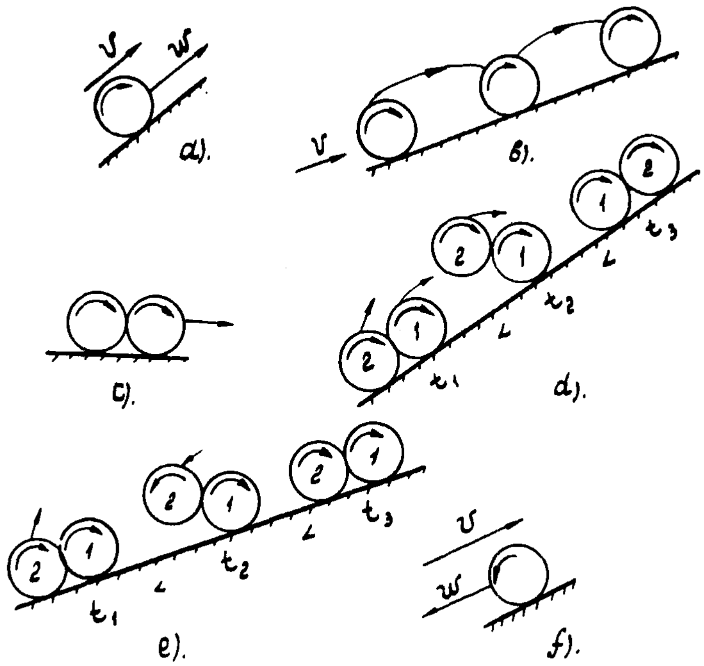

FIGURE 3 Alternate types of particle motions resulting from changes in flow rate, tube angle and fluid viscosity.

On the sedimentation of spherical particle, while the spherical particle is settling in an inclined tube, it is rolling down along the tube wall and rotating as shown in Figure 3f ($v = 0$).

The drag coefficient for a settling sphere was calculated in a way similar to that for a sphere moving up the tube: by means of Equation (4) for small α when the friction effect was negligible. The result is shown in Figure 4 by curve III, corresponding to values given by curve I if multiplied by the factor 2,5.

If flow rates are small enough to maintain the downward motion of a particle along the tube wall, then

$$\langle v \rangle_d + w = u \approx \text{const} \tag{7}$$

It is worth noting that the constant value of u was equal to the sedimentation velocity (within the $\pm 10\%$ error).

In Figure 5 some experimental data for steel particles are shown. In the case of transition from laminar to turbulent flow the value of u remained constant. For lighter particles, however, the values of u for laminar and turbulent flows were different.

It is worth mentioning that in the case of turbulent flow the particle could become detached from the tube wall. This effect was pronounced in particular for light particles moving in tubes with slight inclinations ($v = 0$, sedimentation).

Considering experimental data for Newtonian fluids from Figure 4, it follows

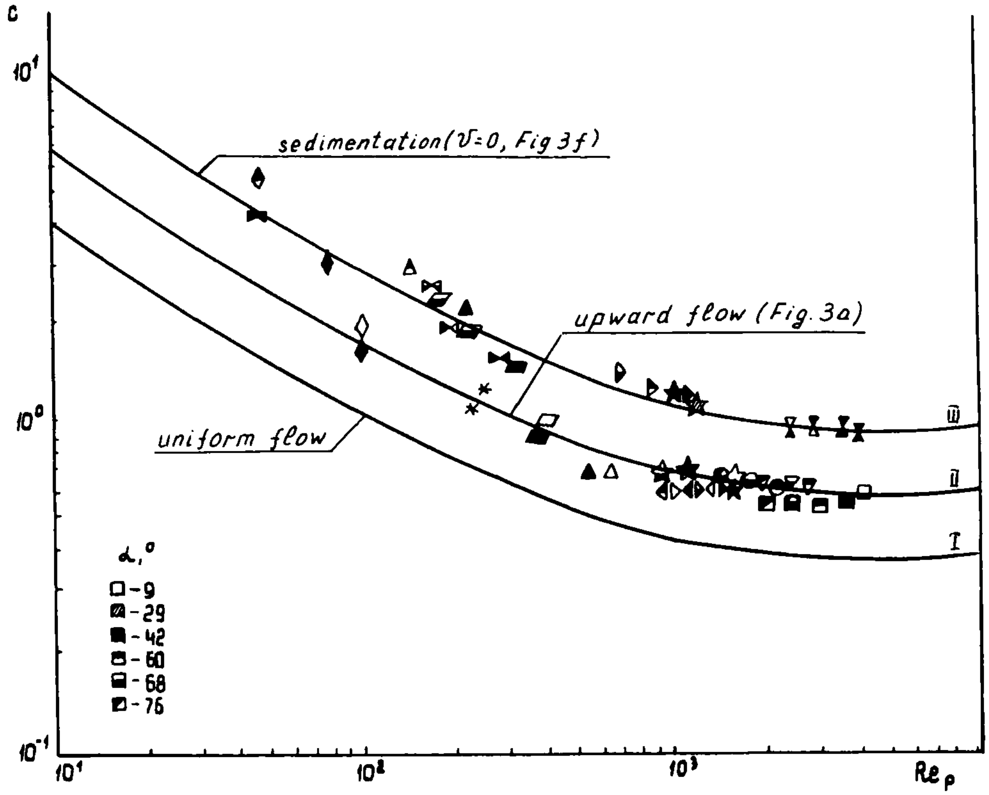

FIGURE 4 The drag coefficient (Equation 4) versus Re_p for various angles of tube α. I = uniform flow, II = upward flow (Figure 3a), III = sedimentation flow (ν = 0, Figure 3f).

that the drag coefficient for a particle rolling up the tube wall (curve II) is smaller than a particle rolling down (curve III). It seems that this effect is due to the different directions of particle rotation when it moves up or down the tube, as well as to the asymmetric nature of the flow pattern near the particle.

Consider now the effect of friction for a particle moving along the tube wall. As for the case of a dry friction, the first approximation, the value of the coefficient, can be put constant, at $h = kd/2$, for a given particle and tube materials and fluid properties. For a given particle and tube materials, the value of h is greater for more viscous fluids. This effect is sharply pronounced for light glass ballotini, when the friction coefficient h could change by a factor of 25 if the fluid viscosity increased or decreased by only a factor of 3.

When the particle moves up the tube the friction is higher than in the case of downward movement, in particular for light particles and high fluid viscosity. This seems to be due to the additional hydrodynamic forces acting on the particle and directed to the wall for upward motion or from the wall for downward motion. The latter effect causes the "floating" of a particle when it moves down a tube with small inclination.

Consider now the influence of turbulence on the friction force acting on the particle. If rather light particles move up the tube the turbulence tends to increase

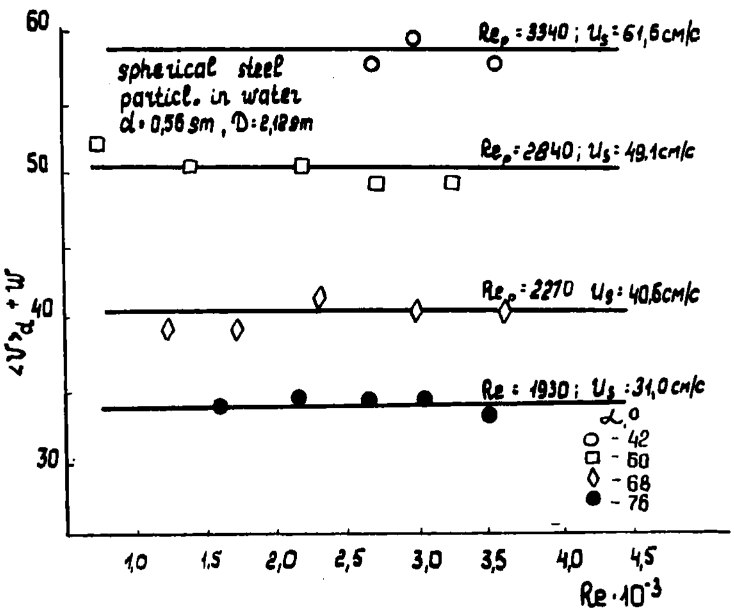

FIGURE 5 Spherical steel particles in water. Plots of $\langle v \rangle + w$ vs. Re for various angles of tube α.

the friction coefficient h, i.e. to increase the hydrodynamic force, which presses the particle against the wall. The opposite effect takes place if the particle moves down the tube.

The greater friction force for more viscous fluids can become almost equal to the gravitation force (for light particles). Such conditions can produce the maximum in flow velocity (versus α diagram), corresponding to the stopping or starting of the particle motion, a phenomenon confirmed in experiments.

It is worth noting that at $\alpha > \alpha_{max}$ the particle usually rolls along the tube wall, while at $\alpha < \alpha_{max}$ some small saltations could be observed (see Figure 3).

The motion of spherical particles in non-Newtonian power-law fluid is governed by the equation

$$\sigma = \tilde{K}\dot{\gamma}^n \tag{8}$$

where σ is the stress, $\dot{\gamma}$ is the deformation rate, $\tilde{K}$ and n are the rheological constants.

We use the generalized Reynolds number introduced by Metzner[1]:

$$Re_P = 8^{1-n}\left(\frac{4n}{3n+1}\right)^n \frac{u^{2-n}d^n\rho}{\tilde{K}} \tag{9}$$

It is well known that by using this definition of Re_P, many formulas for Newtonian fluids can be applied to describe the non-Newtonian behavior.

Our experiments have demonstrated that most of the above-described properties of particle motions in the flow in tubes are restrained. For instance, the drag coefficient in the form of Re_P for a rolling particle is the same as in the case of Newtonian fluid (see curve II in Figure 4). On the other hand, for a power-law fluid the curve III (drag coefficient for the case of sedimentation) coincides with curve II. The latter effect is possibly due to a change in viscosity of a power-law fluid under the deformation process.

Reference

1. A. B. Metzner and I. C. Reed, *AIChE Journal*, 1, 434 (1955).