FREE PRECIPITATION OF SPHERICAL PARTICLES IN ANOMALOUS-VISCOSITY LIQUIDS

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An experimental study is reported of the motion of solid spherical particles in four concentrated high-polymer solutions in a centrifugal force field. The results are compared with the theoretical dependences given by Tomita, Slattery, and Wasserman.

The anomalous properties of non-Newtonian liquids lead to deviations from the Stokes law during the precipitation of solid spherical particles in such media. There have been several attempts to theoretically predict the quantitative values of these deviations [1-6]. Most authors have used a power law to describe the viscosity properties of the liquids. When this approach is used, the solution of the problem of the motion of a sphere can be written

$$C_f = \frac{24\varkappa}{\mathrm{Re}_{ge}}, \tag{1}$$

where $\varkappa$ is the correction coefficient giving the deviation of the drag from the Stokes law for the case in which a power law is used as the rheological equation of state. The quantity $\varkappa$ was given in [1-3] graphically as a function of the rheological constant n.

We report here measurements of the velocity of spheres in centrifugal force fields by the procedure described in [7]. For these experiments we used 8% and 10% solutions of carboxymethylcellulose (CMC) in a 0.6% aqueous solution of NaOH, a 4.5% solution of natural rubber (NR) in toluene, and a 7% aqueous solution of polyacrylamide (PAAM).

From the results, we plotted curves of $\lg C_f = f(\lg \mathrm{Re}_{ge})$ (Fig. 1). The drag coefficients are calculated from

$$C_f = \frac{8}{3} ag \frac{\rho_1 - \rho_2}{\rho_2} \cdot \frac{\Phi_s}{v^2}. \tag{2}$$

The sphere velocity is determined from the experimental results by a graphical differentiation of the trajectory for a selected rotation radius r. The separation factor is calculated for the same radius:

$$\Phi_s \frac{\omega^2 r}{g}. \tag{3}$$

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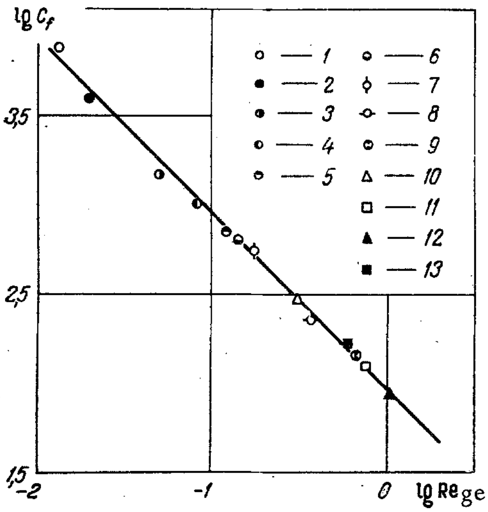

Fig. 1

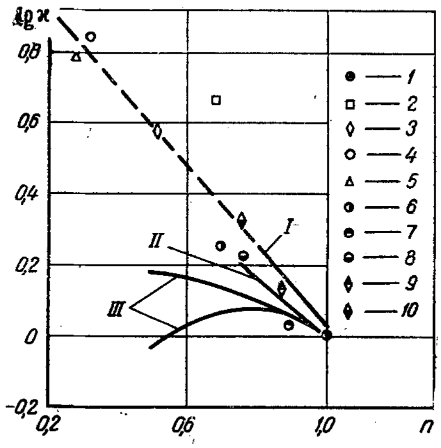

Fig. 2

Fig. 1. Drag coefficient as a function of the generalized Reynolds number for a 10% CMC solution in a 0.6% aqueous solution NaOH. 1) n_{pm} = 600, Φ_s = 30; 2) 600, 38; 3) 700, 49; 4) 900, 63; 5) 900, 72; 6) 900, 81; 7) 1000, 88.9; 8) 1100, 107.6; 9) 1100, 134.4; 10) 1200, 104; 11) 1200, 144; 12) 1300, 150.2; 13) 1400, 130.7.

Fig. 2. Comparison of experimental data and the data of [8] with the theoretical solutions I) Tomita [1]; II) Slattery [2]; III) Wasserman–Slattery [3]. 1) Newtonian liquid; 2) 8% CMC in 0.6% NaOH; 3) 10% CMC in 0.6% NaOH; 4) 4.5% NR in toluene; 5) 7% PAAM; 6) 0.6% CMC [8]; 7) 1.5% CMC [8]; 8) 2.5% CMC [8]; 9) 4% CMC [8]; 10) 5% CMC [8].

The ordinate intercept of the plot of $\lg C_f = f(\lg Re_{ge})$ is, according to Eq. (1), $\lg(24\varkappa)$. By plotting $\lg \varkappa = f(n)$ we can compare the theoretical solutions of [1-3] with experimental data found by Slattery and Bird [8] for precipitation of spheres under the influence of gravity and with the present experimental data (Fig. 2). This comparison shows that the solution of Wasserman and Slattery [3] disagrees both quantitatively and qualitatively with the experimental data. The solutions of Tomita [1] and Slattery [2] agree satisfactorily with the experimental data, but they were obtained for the n range from 0.8 to 1.0. The dashed line in Fig. 2 shows our extrapolation of the Tomita solution for small values of n.

The constants k and n are determined from the flow curves recorded with a constant-pressure capillary viscosimeter.

The experimental data on the motion of the sphere were converted to the form $\lg C_f = f(\lg Re^*)$ (Fig. 3), where Re^* is the modified Reynolds number

$$Re^* = \frac{2av\rho_2}{\eta_0}. \tag{4}$$

The maximum Newtonian viscosity of the solutions studied is determined by the procedure described in [9].

The experimental points (Fig. 3) typically conform to straight lines, displaced various distances from the Rayleigh curve for each anomalous-viscosity liquid and having various slopes. The greater the deviation of the properties of the liquid from Newtonian properties (i.e., the smaller the value of n), the larger the angle β for these lines (Fig. 4). For a Newtonian liquid, this angle is 45°.

Figure 4 gives a qualitative idea of the influence of the rheological properties of the anomalous-viscosity liquids on the precipitation process. This figure compares the experimental data for liquids with various rheological properties under identical conditions: a given sphere diameter and a given range of sphere velocities.

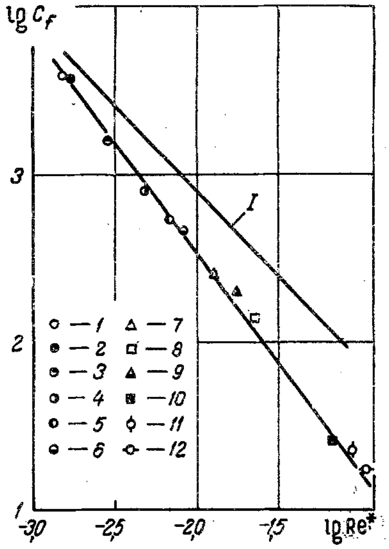

Fig. 3

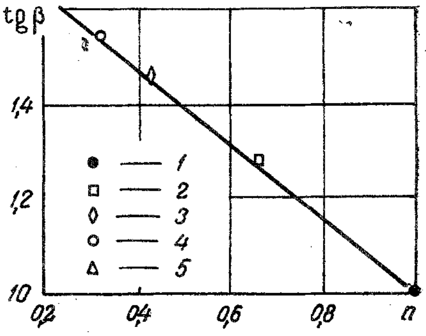

Fig. 4

Fig. 3. Drop coefficient as a function of the modified Reynolds number for an 8% CMC in a 0.6% aqueous solution of NaOH. I) Rayleigh curve. 1) $n_{pm} = 300$, $\Phi_s = 4$; 2) 300, 4.5; 3) 350, 6.13; 4) 400, 8; 5) 450, 11.25; 6) 500, 12.5; 7) 600, 18; 8) 600, 28; 9) 700, 24.5; 10) 800, 51.5; 11) 900, 72.5; 12) 900, 87.9.

Fig. 4. Slope of the lines (the tangent of the angle β) as a function of the rheological constant n. 1) Newtonian liquid; 2) 8% CMC in 0.6% NaOH; 3) 10% CMC in 0.6% NaOH; 4) 4.5% NR in toluene; 5) 7% PAAM.

NOTATION

C_f, drag coefficient; Re, generalized Reynolds number, $Re_{ge} = 2\rho_2 v^{2-n} a^n / k$; k and n, rheological constants of the power-law equation; η_0, maximum Newtonian viscosity; ρ_1, density of the sphere material; ρ_2, density of the liquid; a, sphere radius; v, sphere velocity; $\varkappa$, Stokes law correction coefficient; n_{pm}, rotor revolution velocity (rpm); ω, angular velocity; Φ_s, separation factor; g, acceleration due to gravity.

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