THICKNESS OF A FILM OBTAINED BY THE VERTICAL WITHDRAWAL OF A PLATE FROM A SUSPENSION DESCRIBED BY THE SHVEDOV—BINGHAM MODEL

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UDC 532.62

A model for describing the film flow of a liquid during the withdrawal of a plate from it has been checked experimentally. It has been established that the material of the solid substrate influences the thickness of the coating which is applied.

The withdrawal of a solid substrate from a liquid is widely used in industrial practice for making a number of products (motion-picture and other photographic materials, ceramic condensers, etc.), and also for depositing protective and decorative coatings. The thickness of the liquid films formed on withdrawal has been the subject of a number of theoretical and experimental investigations [1-8].

Several equations have been proposed for calculating the thicknesses of films of Newtonian liquids which differ in the extent to which the various forces acting are taken into account and in the methods for combining the solutions for the different zones of flow (see Fig. 1). In carrying out experimental checks of the equations use has been made of the withdrawal of both infinite plates [1-3] and plates of finite dimensions [1, 2]. It has been found that with plates of length 5-10 cm results are obtained which are in agreement with the data for infinite plates [2].

Often the liquids which are used to form coatings have non-Newtonian properties. Relationships have therefore also been proposed in the literature for predicting the thickness of films of liquids which are described by various rheological models: Ostwald—de Waele [1, 4, 5], Ellis [5, 6], and Shvedov—Bingham [4, 5, 8]. The latter has the form

$$\tau = \tau_0 + \mu_p \dot{\gamma} \tag{1}$$

and describes the behavior of concentrated suspensions. On the basis of this model Shul'man and Baikov [4] by combining the flow zones 1 and 2 in the withdrawal zone and by merging the solutions for these zones with the solution for zone 3 obtained a differential equation of the third order for describing the flow rate of the film flow. For high rates of withdrawal of the plate ($2B < D_0$) its partial solution can be represented as

$$D_0 = 0{,}944\,\mathrm{Ca}^{2/3}\left(1 + \frac{BD_0^2}{\mathrm{Ca}}\right)^{2/3}. \tag{2}$$

Solutions are also given for moderate ($\mathrm{Ca} \ll 1$) and low ($\mathrm{Ca}/BD_0 \ll 1$) rates of withdrawal.

On the basis of Eq. (1) and by combining the solutions for the zones of the dynamic meniscus 2 and the static meniscus 3, it was found in [5] that

$$T_0 = 0{,}944\,\mathrm{Ca}^{1/6}\left[1 - 3T_0^2\left(\frac{\xi_0^2}{2} - \frac{\xi_0^3}{6}\right)\right]^{2/3}. \tag{3}$$

The dimensionless parameter $\xi_0 = y_0/h_0$ takes into account the presence of the yield stress

$$\tau_0 = \rho g (h_0 - y_0). \tag{4}$$

Bearing in mind the relationships among the groups containing the effects of various forces

$$D_0 = T_0\,\mathrm{Ca}^{1/2}, \tag{5}$$

Higher Chemical-Engineering Institute, Sofia, Bulgaria. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 55, No. 6, pp. 920-924, December, 1988. Original article submitted June 9, 1987.

0022-0841/88/5506-1355$12.50

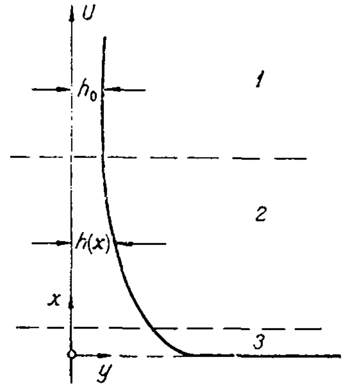

Fig. 1. Sketch of flow of film entrained on a moving plate.

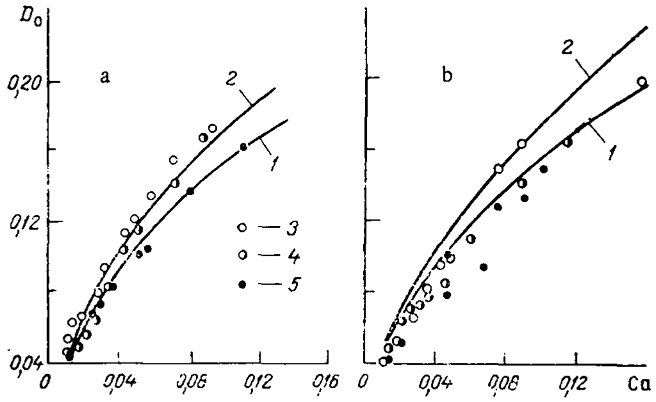

Fig. 2. Comparison of the theoretical and experimental values of the dimensionless film thickness ((a) and (b) refer respectively to 35% and 40% suspensions of $CaCO_3$ in 90% glycerol): 1) calculation by the Shul'man—Baikov model; 2) calculation by the model of Spiers et al.; 3) textolite plates; 4) steel plates; 5) glass plates.

Eq. (3) can be converted to the form

$$D_0 = 0{,}944\,\mathrm{Ca}^{2/3}\left(1 + \frac{3}{2}\frac{BD_0}{\mathrm{Ca}} - \frac{D_0^2}{\mathrm{Ca}} - \frac{1}{2}\frac{B^3}{\mathrm{Ca}\,D_0}\right)^{2/3}, \tag{6}$$

which is more convenient for comparison with the Shul'man—Baikov solution.

In the derivation of Eqs. (2) and (6) it is assumed that the flow of the suspension is pseudohomogeneous, which is not always the case under real conditions. This is why in the present work one of the objectives was to confirm experimentally the validity of these equations for predicting the thicknesses of films obtained during the vertical withdrawal of plates from suspension described by the Shvedov-Bingham rheological model.

The experiments were carried out at a temperature of 20°C with suspensions of calcium carbonate in 90% glycerol. The concentration of the solid phase was varied over the range 20-40 wt.%. The density of the suspension was determined with a pycnometer and the surface tension by the stalagmometric method. Over the investigated range, the latter appeared to be independent of the concentration of the solid phase and practically equal to the surface tension of the disperse phase, σ = 0.062 N/m. Rheograms for the suspension were produced using a Rheotest RV2 concentric cyclinder viscometer using cylinder S1. A few experiments using cylinder S2 showed that layers of the disperse medium adjacent to the walls were absent, which might have influenced the results of the measurements. The values of the rheological coefficients appearing in Eq. (1) were determined from the flow curves by the method of least squares, and these are given in Table 1.

Thin plates of finite dimensions (5 × 10 cm, 5 × 5 cm, and 5 × 2 cm) made of textolite, glass, and steel were used in the experiments. Various rates of their withdrawal were pro-

TABLE 1. Properties of the Suspensions Used

c	ρ	τ_0	μ_p
20	1357	0,53	0,476
30	1407	1,00	0,766
35	1432	1,12	0,924
40	1456	1,20	1,230

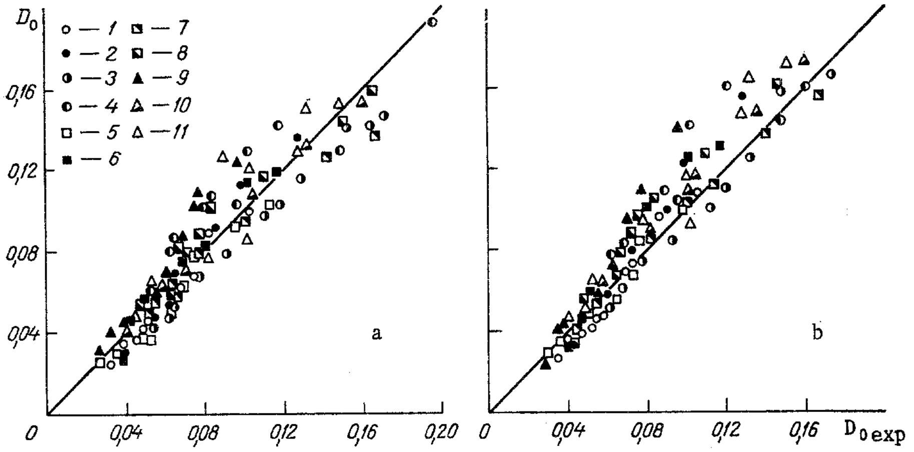

Fig. 3. Comparison of the experimental results which have been obtained with values calculated from the models of Shul'man and Baikov (a) and Spiers et al. (b): 1) textolite, 20% suspension; 2) textolite, 30% suspension; 3) textolite, 35% suspension; 4) textolite, 40% suspension; 5) steel, 20% suspension; 6) steel, 30% suspension; 7) steel, 35% suspension; 8) steel, 40% suspension; 9) glass, 30% suspension; 10) glass, 35% suspension; 11) glass, 40% suspension.

vided by using the electromechanical parts of a dynamometer, which made it possible to vary the rate over the range 0.56-5.6 mm/sec and at the same time ensured its constancy in the course of the individual measurements. The rate was checked by means of a stopwatch.

The mean film thickness was determined from the mass of suspension on the plate, the surface area of the plate, and the density of the suspension. At each velocity 3-5 measurements were carried out; the relative error between their averaged value and the values for the individual experiments did not exceed 5.5%. The weight method of determining the mean film thickness has also been used by other authors [2, 7].

The vertical edge effect was eliminated by the method of Morrey [2], in which the ratio of the mass of suspension to the height of the plate is plotted on a graph as a function of the reciprocal of the depth of submergence, and the relationship is extrapolated to infinite height. The side edge effects were found to be negligibly small for the widths and thicknesses of the plates used.

The experimental results for the corresponding values of B were treated as relationships between the dimensionless film thickness D_0 and the dimensionless rate of withdrawal Ca. A part of the experimental data is shown in Fig. 2. This figure also shows the theoretical relationships calculated from Eq. (2) (curve 1) and from Eq. (6) (curve 2). Because of the nonexplicit form of the relationships $D_0 = \varphi(\mathrm{Ca})$, Eqs. (2) and (6) were solved iteratively using a computer. It can be seen from the figure that the models of Shul'man and Baikov [4] and of Spiers, Subbarman and Wilkinson [5] give practically the same results for the predicted film thicknesses at low values of Ca. As Ca increases, the difference between the two models increases continuously. It can also be seen that the material of the plate has an appreciable effect on the film thickness. The film thicknesses have the largest values for the textolite plates (wetting angle of $\alpha = 62°$) and the smallest values for the glass plates ($\alpha = 35°$). The steel plates have an intermediate position ($\alpha = 53°$). However, this effect is not taken into account in the proposed models for the withdrawal of a solid substrate from the liquid [4, 5].

A comparison of all the experimental data which we have obtained with the theoretical results is shown in Fig. 3. From this it can be seen that the model of Shul'man and Baikov [4] gives a better accuracy (Fig. 3a). It should be noted that the value of the dimensionless yield stress B does not play a decisive role in the theoretical results which have been obtained. However, the comparison of the results shown in these figures must be carried out on a wider basis, since low molecular weight liquids [8] or polymer solutions [1, 5] were used in all of the investigations on the withdrawal of plates before ours. In the specific cases the properties of the real systems (densities, surface tensions, flow curves) were determined by methods which are strictly speaking only valid for homogeneous liquids. The liquids are also assumed to be homogeneous in the derivation of equations (2), (3), and (6), so that a comparison of the experimental data with the theoretical results is a means of verifying the treatment of pseudohomogeneous flows in the mechanics of heterogeneous systems [9]. The good agreement which is found is probably due to the fact that the viscosity of the disperse medium is sufficiently high (μ = 0.2597 Pa•sec), the experiments were carried out with very concentrated suspensions, and the rates of withdrawal (and hence the velocity gradients at the plate surfaces) are relatively small. Under these conditions, the processes of particle deposition and the formation of layers of the disperse medium adjacent to the wall are greatly slowed down and will not lead to appreciable effects.

NOTATION

τ, shear stress, Pa; τ_0, yield stress, Pa; μ_p, plastic viscosity, Pa·sec; $\dot{\gamma}$, shear rate, sec^{-1}; σ, surface tension, N/m; $B = \tau_0/(\rho g \sigma)^{1/2}$ is the dimensionless yield stress; c, concentration of suspension, kg solid phase/100 kg of liquid; $Ca = \mu u_0/\sigma$ is the capillary number (the dimensionless withdrawal rate); $D_0 = h_0/(\rho g/\sigma)^{1/2}$, $T_0 = h_0(\rho g/\mu u_0)^{1/2}$ are dimensionless film thicknesses; ξ_0, dimensionless parameter of the model of Spiers et al., $\xi_0 = y_0/h_0$, where y_0 is a parameter of the zone of constant film thickness; g, accelerating force of gravity, m/sec^2; h_0, film thickness; u_0, rate of withdrawal of plate, m/sec; ρ, density of suspension, kg/m^3.

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