RHEOLOGICAL PROPERTIES ON A VISCOELASTIC MELT −
SOLID-PARTICLE SYSTEM IN A MELTING CHAMBER

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Results are presented of a study of the viscosity and limiting shear stress of a disperse system simulating the rheological dynamics of a molten film in a heating chamber.

The melting of finely divided material under modern practice is in some instances characterized by the presence of a moving film on the walls of the melting chamber. The film is a rheological disperse system. The melt constitutes the dispersion medium and separated solid particles make up the disperse phase.

Improvement of the reliability and efficiency of melting units requires study of the rheological character- istics of viscoplastic melt−solid-particle systems. For a system describable by the Shvedov−Bingham model, such characteristics are the limiting shear stress τ_0 and the relative viscosity μ/μ_0 (the ratio of the plastic viscosity to the viscosity of the dispersion medium).

Analysis of the rheology of this system suggests that τ_0 and μ/μ_0 are functions of μ_0, the volume fraction of solid phase V, particle size d, and several other factors. The latter factors may be considered negligible in the first approximation.

Questions related to modeling the phase transformation of particles in conducting rheological investiga- tions of a melt−particle system are extremely complicated and have yet to be addressed. Thus, the rheology of the film may be simulated, if not modeled. We chose a melt of sodium silicate (53% SiO_2, 47% Na_2O) with an addition of corundum particles to simulate the disperse system. The dependence of the viscosity of the melt on the temperature T is known:

$$\mu_0 = 23.37 \exp\left(-8.69 \cdot 10^{-3}(T - 1173)\right). \tag{1}$$

We chose particles sizes of 0.315-0.500 mm for the experiments. Fixing d reduces the empirical pro- blem to determining the two-factor relations $\tau_0(V, \mu_0)$ and $\mu/\mu_0(V, \mu_0)$.

Under the conditions of the experiments (time no longer than 4 h, temperature below 1470°K), the corund- um hardly dissolved in the sodium silicate. This is the reason we selected it as the solid-phase material. Study of the system allows us, in a first approximation, to evaluate the rheological characteristics of the film in the melting chamber.

The factor V had values of 0.24, 0.31, and 0.38 in the tests. Preliminary selection of values for μ_0 was difficult. As a result, we made measurements for several values for μ_0 at each level of V, here having had to ensure that the individual series of μ_0 values overlapped. Assuming that this requirement is met, the method of factorial experiment planning can be used in statistically analyzing the test data.

The experiments were conducted on a VTI high-temperature viscometer [1]. It became clear during the experiments that, during prolonged deformation of the disperse system, its relative viscosity and maximum shear stress remained constant for the first 10 min and then decreased, despite the constancy of μ_0 and V. If the system were kept still for 20 min, then μ/μ_0 and τ_0 would return to their original values. Thus, the simulating system has a reversible self-destructive structure. The period of deformation of the film as a disperse system is equal to the time of melting of the particles of the disperse phase, so that it is significantly less than the time required for the beginning of breakdown of the structure. Due to this, the measurement cycle for determining the flow curve was no longer than 10 min, and the system was left standing at least 20 min before each cycle.

The experiments showed that the dispersion medium is a Newtonian fluid and that the rheology of the disperse system is adequately described by the Shvedov−Bingham model (Fig. 1). The results of analysis of the empirical data are shown in Table 1.
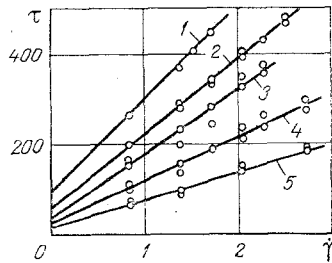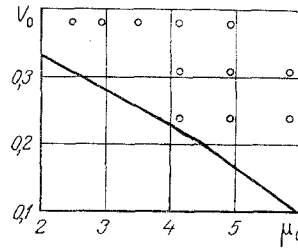
Fig. 1. Flow curves of the disperse system at V = 0.38 for different μ_0: 1) μ_0 = 4.88; 2) 4.10; 3) 3.46; 4) 2.91; 5) 2.44. τ, Pa; γ, sec^{-1}, μ_0, Pa·sec.

Fig. 2. The relation $V_0(\mu_0)$. The points correspond to the parameters of the experiments.

TABLE 1. Values of Relative Viscosity and Maximum Shear Stress

T	1333		1353		1373		1393		1413		1433	
μ_0	5,82		4,88		4,10		3,46		2,91		2,44	
V	μ/μ_0	τ_0	μ/μ_0	τ_0	μ/μ_0	τ_0	μ/μ_0	τ_0	μ/μ_0	τ_0	μ/μ_0	τ_0
0,38			41,5	100,0	41,3 40,0	51,0 60,5	39,7 41,5	29,0 41,3	31,3 34,8	21,6 26,5	24,9 24,9	15,6 17,7
0,31	26,0 27,9	65,0 57,3	24,0 24,7	38,9 31,4	17,7 17,0 20,3	14,2 23,1 14,2						
0,24	18,6 19,3	23,7 25,3	12,3 13,8	10,12 9,62	8,08	3,65						

Approximation of μ/μ_0 as a function of two variables by a second-degree polynomial, done on a Mir-2 computer for the entire set of empirical data, did not adequately describe the test results. Use of the condition μ/μ_0 (V = 0) = 1, giving six additional points, also failed to produce the desired result, as did an attempt to approximate the data in the form of ln (μ/μ_0).

Qualitative analysis of the test data shows that, for V = 0.38, the value of μ/μ_0 increases significantly in the region μ_0 < 3.46 Pa·sec but remains constant with a further increase in μ_0. This sharp change in the character of the function μ/μ_0 = f(μ_0) is one of the main obstacles to satisfactory analytical description of the entire volume of empirical data.

With V = 0.38 and μ_0 > 3.46 Pa·sec, the experimental points μ/μ_0 lie almost on a horizontal straight line μ/μ_0 = 40.8. If this relation is extrapolated to μ_0 = 5.82 Pa·sec, i.e., if we suppose that μ/μ_0 = 40.8 at V = 0.38 and μ_0 = 5.82 Pa·sec, then an orthogonal central factorial plan (OCFP) can be used in the range μ_0 = 4.10-5.82 Pa·sec to analyze the data. An OCFP can be used here because the temperature levels at which the tests were conducted were separated by a constant interval of 20°C, this interval performing the role of the interval of variation.

Judging from preliminary estimates, it would be most expedient to seek a regression equation for ln (μ/μ_0) as a function of the arguments X_1 = (T − 1353)/20 and X_2 = (V − 0.31)/0.07. A check by the t-criterion shows that the coefficients in the quadratic terms are insignificant. In sum, by expressing T from (1) and substituting into the formula for X_1, we have

$$\mu/\mu_0 = \exp(3.134 + 0.208X_1 + 0.590X_2 - 0.210X_1X_2),$$

$$X_1 = -9 - 5.75\ln(\mu_0/23.37), \quad X_2 = (V - 0.31)/0.07.$$

(2)

The maximum shear stress is seen in disperse systems with a solid-phase content above a certain limiting level V_0. Thus, to ensure good agreement between the correlative relations physically describing the test data, we need to add points satisfying the condition

$$\tau_0(\mu_0,\ V_0) = 0. \tag{3}$$

The values of V_0 for $\mu_0 = 5.82$, 4.88, and 4.10 Pa·sec are determined from the test results by the least-squares method and are 0.20, 0.21, and 0.22, respectively.

The test data on τ_0, together with the three points satisfying condition (3), are described by the following regression equation:

$$\tau_0 = 439 - 99\mu_0 + 5.4\mu_0^2 - 2062V + 2414V^2 + 237\mu_0 V. \tag{4}$$

A check by F- and t-criteria shows the statistical adequacy of this equation and the significance of all of its coefficients.

The experimental results lead us to conclude that the viscosity of a disperse system depends nonlinearly on the viscosity of the dispersion medium, so that the ratio μ/μ_0 is a function of two arguments, μ_0 and V, rather than one — V — as has been suggested by several works.

Let us turn our attention to the character of this function: the dependence of μ/μ_0 on μ_0 decreases with an increase in V, and even becomes degenerate when V and μ_0 increase simultaneously: at $V = 0.38$, there is no change in μ/μ_0 for $\mu_0 > 3.46$ Pa·sec. The character of the test data shows that the degeneration of μ/μ_0 (V, μ_0) into a function of a single argument μ/μ_0 (V) may also occur at $V < 0.38$, when the value of μ_0 is higher than 5.82 Pa·sec, i.e., there is a region of (V, μ_0) in which the two-factor relation μ/μ_0 (V, μ_0) degenerates into a one factor relation μ/μ_0 (V). The test results in this region qualitatively correspond to the expressions for μ/μ_0 cited in the other works.

Thus, on the whole the results obtained do not contradict, but rather add to and expand the available information on the hydrodynamics of disperse systems. The reasons for the substantial quantitative difference of μ/μ_0 from known estimates are, first, a range of values which exceeds the ranges investigated in [2, 3, etc.] and, second, a different mechanism governing the appearance of the solid phase in the melt compared to [4, 5]. This difference in mechanisms affects the character of interaction of the particles.

It follows from the test that the maximum shear stress is also a function of two arguments, the viscosity of the dispersion medium and the volume fraction of solid phase. This is consistent with the conclusion reached in [5]. The formula obtained here (4) makes it possible to establish the relation $V_0(\mu_0)$. Figure 2 shows the curve of $V_0(\mu_0)$. The investigated disperse system manifests plastic properties in the region above this curve.

No rheological system similar to the one studied here has previously been investigated. The value of τ_0 differs sharply from the values for other types of disperse systems, which precludes the application of published results of studies of other rheological media to evaluating the maximum shear stress for conditions in a melting chamber.

Thus, the results obtained in the present experimental study currently most closely approximate the rheological dynamics of film in melting chambers.

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