ON THE FLOW OF LIQUIDS IN NARROW GAPS BETWEEN APPROACHING PLANE SOLID BODIES

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ON THE FLOW OF LIQUIDS IN NARROW GAPS BETWEEN APPROACHING PLANE SOLID BODIES

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The dependence of the time t of approach or separation of plane-parallel circular disks in a liquid with viscosity η on the gap between the disks is given by the Stefan–Reynolds equation of the form

$$t = \frac{3\pi r^4 \eta}{4F}\left(\frac{1}{h_1^2} - \frac{1}{h_2^2}\right), \tag{1}$$

where r is the radius of the disks; h_1 and h_2 are the initial and final gaps between them; F is the normal force bringing the disks together or separating them. Equation (1) has been theoretically substantiated (^{1}) and experimentally confirmed for the case of wide gaps in experiments by a number of authors (^{2,3}), including ours (^{4}).

In the case of separation of adhering disks, as a rule, $h_2 \gg h_1$, and equation (1) may be rewritten in the following form:

$$t = \frac{3\pi r^4 \eta}{4F h_1^2}, \tag{2}$$

i.e., the separation time is inversely proportional to the square of the magnitude of the initial gap.

Moving F and η to the left-hand side of the equation, after which only the geometrical dimensions of the disk and the gap remain on the right-hand side, and dividing both sides of the equation by the area of the disks S, we obtain

$$\frac{t\sigma}{\eta} = \frac{3\pi r^4}{4h_1^2 S} = \psi, \tag{3}$$

where $\sigma = F/S$ is the specific force separating the disks. The product $t\sigma$ has the dimension of dynamic viscosity, and the ratio $t\sigma/\eta$ is a dimensionless coefficient characterizing the mobility of the liquid in the gaps between the disks.

Introduced on the basis of somewhat different considerations (4), it was called the coefficient of boundary thickening and denoted by the letter ψ.

In previous communications (5,12) a method was described which makes it possible to measure the time of approach and separation of plane-parallel disks with an accuracy up to 0.01 sec and simultaneously the gap between them in the range from 20 to 0.02 μ. Application of this method showed that for disks separated by sufficiently thin layers of mineral and other lubricating oils, solutions of stearic acid in organic solvents, and aqueous solutions of electrolytes, equation (1) is not fulfilled. This is expressed, in particular, in the fact that t and ψ depend strongly on the composition of the liquid and the disks and on the time of their preliminary contact. New experimental data (Table 1 and Fig. 1), obtained by the same method, show that during the flow of the indicated liquids in narrow gaps between approaching disks the following deviations from the law expressed by equation (1) are observed: 1) retarded outflow (and inflow) of the liquid into the gap between the disks; 2) formation of a residual layer which is not squeezed out during the time of measu—

···under loads (up to 36 h) of up to 8 kg/cm^2; 3) an increase of t with increasing duration of contact; 4) a nonlinear dependence of t on $1/F$ and $1/h_1^2$.

Our method is not sufficiently sensitive to judge the change in the thickness of the residual layer with time. Indirect data (6,7) allow one to suppose that it does not remain constant, but above the sensitivity limit of the method this layer is quite stable (see, for example, in Table 1 the gap in NaCl solution after 30 and 60 min of contact).

Table 1

Gap between horizontal plane-parallel disks immersed in liquid, as a function of contact time and pressing force (temperature 20 ± 2°, disk area 1.13 cm^2)

Disk material	Liquid	Pressing force of disks, kg/cm^2	Duration of contact, min	Gap, μ
Quartz	Aq. 0.005N NaCl solution	0.08	60	0.27
»	Aq. 0.1N NaCl solution	0.08	60	0.41
»	Same	4.0	10	1.16
»	» »	4.0	20	0.095
»	» »	4.0	30	0.045
»	» »	4.0	60	0.045

Disk material	Liquid	Pressing force of disks, kg/cm^2	Duration of contact, min	Gap, μ
Steel	0.5% stearic acid in butyl alcohol	2.0	10	0.15
»	Same	2.0	30	0.045
Quartz	» »	2.0	30	0.025
Brass	» »	2.0	30	0.06
Steel	Turbine oil "L"	0.08	10	2.18
»	Same	0.08	60	1.13
»	» »	0.08	120	0.36
»	» »	1.0	10	0.375
»	» »	1.0	60	0.195
»	» »	1.0	120	0.08

The slowed inflow and outflow of liquid from narrow gaps between disks is perceived as a consequence of an increase in its viscosity and is characterized by a change in the coefficient of boundary thickening. During the contact of disks from 1 to 60–120 min, at a pressure of 1 kg/cm^2 and above, ψ of the investigated liquids increases by a factor of 1.5–2.0. The ψ of solutions of fatty acids in oils at a pressure of 0.08–0.4 kg/cm^2 during the indicated contact time increases up to 20-fold and more. The magnitude of the coefficient of boundary thickening depends substantially on the material of the disks and on the composition of the liquid. For a sample of purified turbine oil "L" it is equal to: between steel disks $98 \cdot 10^5$, between quartz disks $4.8 \cdot 10^5$ (in both cases the disk radius is 0.6 cm, specific load 0.6 kg/cm^2, contact duration 10 min, temperature 20°). Under the same conditions, ψ of benzene between steel disks is 9000, and between quartz disks 80.

An increase in the concentration of surface-active substances and electrolytes leads to an increase in the coefficient of boundary thickening. The typical form of the dependence of ψ on these factors is shown in Fig. 2. With an increase in temperature, the separation time decreases, but ψ may increase, decrease, or even remain unchanged, depending on the ratio of the temperature coefficients, the separation time, and the bulk viscosity.

By calibrating the disks with a liquid that practically does not form a boundary layer (for example, benzene on quartz) and determining by independent methods the separation time of the disks and the gap between them, one can, with the aid of equation (3), calculate the viscosity of the liquid under investigation in the boundary layer. Some results of such measurements are summarized in Table 2. The data obtained show that the viscosity increases with decreasing thickness

Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

of the boundary layer and, up to certain limits, with increasing concentration of surface-active substances and electrolytes, but in general the viscosity of boundary layers is higher than the bulk viscosity by no more than a factor of 5. The obtained ratio of boundary to bulk viscosity agrees in order of magnitude with the latest results of measuring boundary viscosity by the blowing method ([8,9]).

The magnitude of the residual layer, as well as the boundary viscosity, is determined by the nature of the solid body and the liquid. Well-purified benzene generally leaves on quartz no residual layer that could be measured by our method.

Fig. 1. Change in the gap h between disks with time t under a load of 0.2 kg/cm^2 (1 and 2) and 4 kg/cm^2 (3 and 4) in transformer oil (1 and 3) and in a 0.01 N aqueous solution of NaCl (2 and 4)

Fig. 2. Dependence of ψ for turbine oil "L" in the gap between steel disks on the disk contact time t_n (pressure 1 kg/cm^2), temperature t ($t_n = 600$ sec.; pressure 2 kg/cm^2), and concentration of oleic acid c ($t_n = 600$ sec.; pressure 1 kg/cm^2)

The thickness of the residual layer of a vacuum-distillation fraction of turbine oil "L" is, on steel, 0.09μ, and on quartz, 0.04μ (pressing force 2 kg/cm^2). The influence of the remaining essential factors is shown in Fig. 3. It is important to note the difference in the temperature dependence of the separation time and of the thickness of the residual layer. The former always decreases with increasing temperature (if no secondary chemical reactions occur), and the curve $\psi = f(t)$ has a monotonic character. The thickness of the residual layer of mineral oils and fatty-acid solutions at low temperatures does not depend on the latter; with increasing temperature there appears a region of sharp decrease in the magnitude of the residual layer, which may be regarded as a region of partial disorientation of the structure of the boundary layer ("melting"). For different liquids it is not the same, but it is always below the melting temperature of boundary layers measured at high contact pressures, for example in a four-ball friction apparatus (10).

Table 2

Increase in the viscosity of boundary layers relative to the bulk viscosity, measured by the disk-separation method (temperature 20°)

Fig. 3 and Fig. 4

Figure 3: Fig. 3 and Fig. 4

Disk material	Liquid	Initial gap in μ	Ratio of boundary viscosity to bulk viscosity
Quartz	Benzene	0.02	1.0
Steel	Vacuum-distillation fraction of turbine oil, $\eta_{20} = 35.3$ cP	0.10	2.9
Steel	Same	0.12	1.7
Quartz	Same	0.05	1.4
Brass	Same	0.10	3.2
Brass	Castor oil	0.10	4.6
Quartz	0.01 N solution of NaCl	0.07	2.0
Quartz	0.1 N solution of NaCl	0.07	2.7
Quartz	Same	0.12	1.5

Since the thickness of the residual layer depends on the normal pressure,

one can estimate its compressibility by means of a conditional coefficient of uniaxial compression for a specified pressure interval, calculated in the same way as the compression modulus. The change of this index $E_{0.2-2.0}$ in the pressure interval from 0.2 to 2.0 kg/cm^2 is shown in Fig. 4. Noteworthy is the slight compressibility of the residual layer, at least of its peripheral part, and the dependence of the deformability of this layer on the concentration of surface-active substances.

Fig. 3. Residual gap h_{min} between steel disks in a fraction of turbine oil "L" ; σ_n—compressive force in kg/cm^2; C—concentration of stearic acid in %.
Fig. 4. Influence of the concentration of stearic acid on the compressibility of the residual layer of its solution in a vacuum-distillation fraction of turbine oil between steel disks (1), and of the concentration of KCl on the compressibility of the residual layer of an aqueous solution between quartz disks (2). Temperature 20°.

In the effect described, specific molecular-surface properties at the solid–liquid interface are manifested. This is indicated by the dependence of the effect on surface-active substances and electrolytes. It testifies to the formation of a special structure of the surface layer of the liquids investigated to a depth of the order of 0.1 μ (for more detail on the thickness of the boundary layer see ([4,5])).

The nature of the effect described is not uniform; in particular, it is determined by both nonequilibrium and equilibrium phenomena. If the residual layer of an electrolyte solution is compressed and the load is then removed, it is partially, but not completely, restored. In the first effect we see a manifestation of the equilibrium disjoining pressure ([11]), whereas the increased viscosity and the irreversible residual layer are associated with kinetic phenomena. Let us note that the slowed separation and approach of the disks are also a consequence of the decrease in the effective gap as a result of the formation of a quasi-solid residual layer.

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Note: Figure translations are in progress. See original paper for figures.