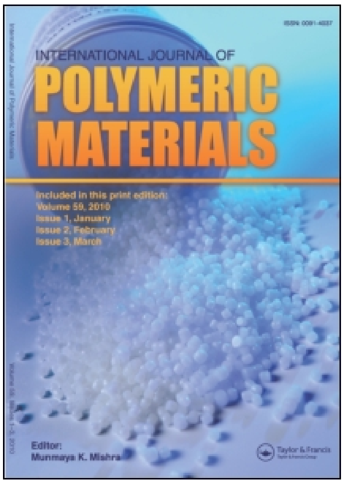

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Criterion for Transition of a Liquid Flow to a Dispersion Flow

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Interlayers between two solid surfaces determine behavior and properties of quite a number of systems: wetting powder, soil and ground, dispersed polymer & mineral binder. Model experiments show two types of interlayer deformation between moving solid surfaces: with very high or very low interlayer deformation velocities. In dynamic interlayer deformation (high velocity) discontinuity, i.e. liquid dispersion, always takes place. Transition from turbulent liquid flow to dispersion takes place when deformation velocity has a certain critical value. Capillarity number Ca $= \sigma/\eta$ may be considered as the limit velocity of liquid deformation without discontinuity. The ratio of actual liquid interlayer deformation velocity W to the limit velocity, multiplied by geometrical coefficient is the criterion $(W/\mathrm{Ca}) \cdot L$ of liquid deformation or dispersion conditions.

KEY WORDS Liquid flow, high deformation rate, instability, dispersion.

1. INTRODUCTION

This report is devoted to defining the conditions at which the mode of liquid goes over from flow to the mode of its dispersion. The basis of this concept is that layers of liquids cannot move relative to each other with the velocity exceeding some limit value of W_m without losing continuity, Yakhnin & Chadov.[1,2] Untangling of the physical essence of the quantities W and W_m results in the following form of this relation:

$$Y = \frac{W}{\sigma/\eta} \cdot L \tag{1}$$

Here W = the linear velocity of liquid body deformation in some arbitrary direction, L = dimensionless parameter determined by the system geometry, σ and η-surface tension and viscosity of liquid, correspondingly. This relation was obtained on the basis of qualitative reasoning set forth below. The possibility of its physical interpretation as a criterion defining the behavior of liquid body being deformed has been confirmed in our experiments, Yakhnin.[3] We believe the above-mentioned relation to be effective in solving various technical problems.

2. EXPERIMENTS

Let's consider the behavior of a thin cylindrical liquid interlayer between two flat solid surfaces parallel to each as they other move apart with some velocity W. At small velocity values of moving their surfaces apart, a liquid interlayer reduces its cross-section and the wetting line of both surfaces recedes to the axis of the interlayer. The requirement of liquid volume constancy V = const leads to a necessary reduction of the interlayer width (diameter) α by increasing its thickness (height) h = distance between solid surfaces Figure 1a. By increasing velocity W to some critical value W_m the width of interlayer on contour practically stops changing in the process of moving solid surfaces apart, i.e. in the process of h increase. It seems that a liquid interlayer increases in volume proportionally to its thickness h increase. However, thorough consideration cinematograms (successive images by speedy filming) on extension process of liquid layer shows that the apparent volume increase and preservation of image width on contour is stipulated by the initiation of cavities inside the extensible liquid layer Figure 1b.

Thus, after reaching and exceeding the critical value W_m in the extension velocity, a disturbance of continuity in liquid can be observed, i.e. its disintegration to separate parts, its dispersion. The width α of the reducing interlayer at its most narrow part by $W < W_m$ at the moment of rupture is very small, almost zero. By $W \geq W_m$ the interlayer width on contour remains constant and is practically equal to the original width. A typical curve of $\alpha(W)$ dependence is shown in Figure 2, curve 6. The moment of cavities initiation in the volume of liquid interlayer corresponding to $W = W_m$ is also clearly determined by the change of the mass-transfer coefficient $K(W)$. The mass-transfer coefficient of the liquid interlayer part remained on one of the surfaces after they were moved apart equals $K = m_1/(m_1 + m_2)$ Figure 2, curves 1–5.

The moment $W = W_m$ the mass-transfer coefficient becomes equal to 0.5 for all liquids and any combination of solid surfaces with different wettability. In our experiments systematic investigations were based on measurements of the mass-

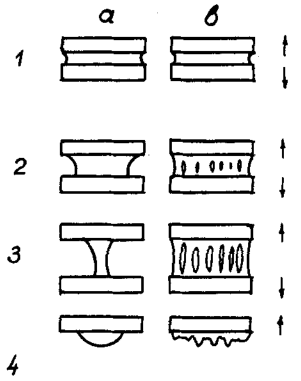

FIGURE 1 Diagramatic representation of deformation and rupture cinemagrams of water-glycerol liquid interlayer between surfaces of metallic zink and Teflon by small (a) and high (b) velocities of extension W.

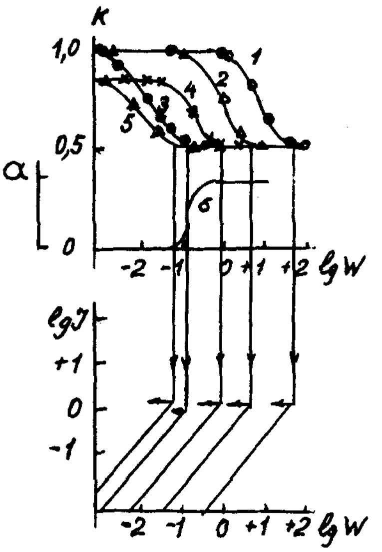

FIGURE 2 Comparison of transfer curves $K(W)$ of different systems from Teflon to zink (numeration of curves corresponds to the table) and criterion relation. Curve 6 of change in interlayer width (volume).

transfer coefficient. The analysis of these experimental results in the mass-transfer coefficient dependence of the velocity of moving solid surfaces apart led us to this idea, Yakhnin & Chadov.[1,2] The course of this analysis follows:

3. THEORETICAL ANALYSIS

During extension of liquid interlayer, a decrease in its width, a recession of its wetting perimeter to the center and general movement of liquid layers without rupturing is possible due to cohesive forces or liquid strength P_m, Kornfeld[4]. The product of strength P_m as an ultimate possible stress in liquid and the increase of mean distance between its adjacent molecules ΔZ (by which their separation from each other will take place) equals the cohesion energy or twice the energy of unit area formation of new liquid surface, i.e.

$$P_m \cdot \Delta Z \sim 2\sigma \text{ and } P_m \sim 2\sigma/\Delta Z \tag{2}$$

In deformation of liquid in some direction X stresses P arising in it are proportional to the product of its viscosity η and the velocity of relative deformation $(dx/d\tau)\cdot(1/x)$. There are such velocities of liquid deformation at which their corresponding stresses P exeed its strength P_m. It means that an ultimate possible velocity of liquid deformation without discontinuity will be proportional to the quotient of ultimate possible stress in the given liquid and its viscocity. Considering equation (2) it follows:

$$\left(\frac{dx}{d\tau}\cdot\frac{1}{x}\right)_m \sim \frac{P_m}{\eta} \sim \frac{2\sigma/\Delta Z}{\eta} \tag{3}$$

On examination of any specific geometrically defined liquid system the ultimately possible absolute velocity of its deformation in some direction (in our case in the direction of thickness h of the interlayer $W_m = (dh/d\tau)_m$ will be also proportional to the factor $2\sigma/\eta$ or σ/η but multiplied by the dimensionless relation $h/\Delta Z = E$. Thus the criterion determining the transition from conditions where liquid flow takes place to conditions where rupture and dispersion begins can be expressed as the relation of the actual velocity of deformation to the ultimately possible velocity:

$$W/W_m = \frac{W}{E \cdot \sigma/\eta} \tag{4}$$

In transformation of the present deformation velocity W_x in some direction X to the velocity W_y corresponding to the expected direction of discontinuity, the dimensionless parameter L determined by the system geometry will appear by W_x. Accordingly the criterion relation (4) will take the form:

$$W_y/W_m = \frac{W_x}{\sigma/\eta} \cdot \frac{L}{E} \tag{5}$$

We believe that the transition from flow deformation to rupture and dispersion should take place for all liquids at a constant value of the ratio W/W_m.

4. DISCUSSION

The interpretation of the physical essence of such constant value W/W_m will be much easier if it were equal to unity. Then for $W_y/W_m << 1$, all liquid systems would undergo flow deformation and at $W_y/W_m > 1$ the conditions of liquid rupture, dispersion would take place. But considering the intricacy of geometry of hydrodynamic behavior for the majority of real liquid systems and also the experimental data rupture, i.e. manifestation of liquid strength properties, Kornfeld,[4] proposed that the critical value of this relation in various cases can be different. Thus experimental determination of the corresponding value W_y/W_m for some specific system should be especially important and done first. In our case we could determine only the value of the product $J = (W_y/W_m) \cdot E = W_x L/(\sigma/\eta)$ at which transition to dispersion takes place because E is not determined experimentally and the factor L for cylindrical interlayer of regular shape is equal to α/h where α = width and h = thickness of interlayer. In our experiments the minimum thickness of clearance between investigated surfaces was $h \approx 10^{-2}$ cm, the volume of liquid interlayer $-0.5 \cdot 20^{-2}$ cm^3 and the maximum diameter of the interlayer was 0.8 cm. Thus, at the initial moment of liquid interlayer extension the geometric coefficient was $L = 0.8 \cdot 10^2$. Figure 2 shows the comparison of curves $K(W)$ and $J(W)$ for various liquids with the similar viscosity and various surface tension (2:4 and 3:5) and also with the similar surface tension and various viscosity (1:2:3) correspondingly to the numbers of curves. The composition and properties of investigated liquid systems are given in Table I.

Graphic determination of J values corresponding to critical velocity values W_m (shown by arrows) at which for each system dispersion of liquid system begins shows that in all cases the values of J are approximately the same and nearing unity. The constancy of J values for various systems confirms the correctness of the idea about the existence of ultimately possible velocity of deformation of liquid without discontinuity and the validity of the expression $W_y/W_m = [W_x/(\sigma/\eta)] \cdot \{L/E\}$. But the equality to unity of $J = (W_y/W_m) \cdot E$ is to be considered unexpected and the experimental confirmation of the relation $W_x/W_m \approx$ unity is conjectural. The matter is that the value h which is used in the calculation of E should correspond to the minimum value of interlayer thickness, i.e. 10^{-2} cm in our case. As the value ΔZ has the order 10^{-8} cm then $E \approx 10^6$ for our testing conditions. It means that the velocity at which the effect of discontinuity was found was 10^6 times less than the ultimate permissible velocity $W_m = (\sigma/\eta) \cdot E$. Considering the intricacy of hydrodynamic state of interlayer being extended between two surfaces, it is permissible to assume that the correct value will be significantly less. In addition, the presence of defects in liquid, namely the presence of contaminations and solved gases turned out the significant factor. It is quite probable that purification and degassing of the system will cause a shift of $\alpha(W_x)$ and $K(W_x)$ curves to the right.

At present by first rough analysis it would be unjustified to rely on the correct theoretical and experimental quantitative estimation of values W_m, J and Y. But reasonability of W_m interpretation uniquely associated with the relation σ/η (which has dimensions of velocity in cm/cec.) as ultimately permissible velocity of deformation of liquid without its discontinuity seems to be quite justified.

The main physical essence of the criterion relation $W/W_m = [W/(\sigma/\eta)] \cdot \{L/E\}$ is in the comparison of system deformation velocity W with the factor σ/η. Many researchers noted the significance of such a factor for various cases.

Thus in examination of extension laws of liquid form systems into a thread, Hirai[5] obtained an expression for the limit of extension length H for a thread diameter d; the right part of the expression contains the relation of actual deformation velocity to the factor σ/η and thus it formally coincides with the expression (5)

$$H = (3/2) \cdot d \cdot [W/(\sigma/\eta)] \tag{6}$$

In working out a theory of casting of liquid on a movable band, Derjaguin,[6] noted that the thickness of a cast layer follows the relation $[W/(\sigma/\eta)]^n$. Many theoretical-experimental works on roller coating method report that the number

TABLE I

Composition and properties of investigated systems

No.	Composition		Viscosity, cP	Surface tension din/cm
1.	Water/glycerol	50/50	5,1	68
2.	same	30/70	55,0	65
3.	same	20/80	600,0	64
4.	Ethanol/glycerol	30/70	56,0	33
5.	same	20/80	602,0	39

and the size of waves on applied layers, and even the conditions of the onset of wave forming are associated with the relation of roller and band movement speed V to the factor σ/η, Mill & South[7,8]; Pitts & Greiller[9]; Pearson.[10] In this case it is noted that at speeds $V > V_{cr}$ (in our designations $W > W_m$) the number of waves being formed is the function of the relation σ/η.

It should be emphasized that the authors of all above-mentioned works considered the relation $W/(\sigma/\eta)$ as a dimensionless criterion included into formulae to adequately describe the experimental data. There was no analysis of the physical essence of the factor σ/η determining the limit velocity of deformation of liquid without discontinuity. The discussed examples, however, confirm the assumption that the relation $W/(\sigma/\eta)$ or principally more correct $[W/(\sigma/\eta)]\cdot\{1/E\}$ reflects the physical conditions of deformation of liquids.

In our experiments in model application of liquids on movable band by the roller method it was also shown that the wave forming process can be explained using the ideas presented above, Yakhnin.[3] There, the reason of wave forming lies in discontinuities (cavities) emerging in liquid layer before it is divided by the action of roller and by moving band into two streams. Discontinuities are the consequence of liquid layer extension perpendicular to the movement of roller and band surface and exceeding the limiting velocity of layer reduction in the transverse direction given by $W_m = E\cdot(\sigma/\eta)$.

5. CONCLUSIONS

In many cases the relation $W/(\sigma/\eta)$ is of great importance. Although the performed analysis of experimental data was not theoretically strict, the idea of the existence of a highest possible velocity liquid deformation without its discontinuity seems to be well established. Therefore, the use of the criterion $W/W_m = WL/[(\sigma/\eta)E]$ characterizing various physical situations of liquid deformation should prove to be useful for both scientific and technological purposes.

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