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TOPOLOGICAL MODELS OF THE FLOW AND KINETICS OF COAGULATION-CRYSTALLIZATION STRUCTURE FORMATION OF DISPERSE SYSTEMS

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This paper analyzes the processes of structure formation of disperse systems under dynamic and static conditions in terms of synergetics and the theory of catastrophes. The efficiency of using these methodological approaches together with adopted instrumental methods of investigating the properties of structured dispersions is shown.

The traditional method of collecting data necessary for establishing the laws of evolution of disperse structures under dynamic conditions consists of plotting and analyzing complete rheological curves. The latter represent the dependences of the effective viscosity η on the shear stress P (or the deformation rate gradient $\dot{\varepsilon}$) and the dependence of $\dot{\varepsilon}$ on P with the necessary fulfillment of the isotropy condition of the structure destruction in the running clearance of the viscosimeter.

According to the classification of [1], structured disperse systems are characterized by the existence of two types of flow curves. The fairly well studied rheological curves of type I feature a unique stress dependence of the viscosity and the rate of shear. The less-studied curves of type II have domains of variability of the viscosity or the rate of deformation development, to which there corresponds an indefinite change in the stress: a decrease in P in a certain range of $\dot{\varepsilon}$. Such an anomalous effect shows up as an S-shaped form of the above curves.

Rheological S-shaped curves were obtained in [2] for some cleye suspensions and investigated in [3] in terms of the molecular-kinetic theory of a non-Newtonian flow proposed therein (Fig. 1). Analogous ambiguous dependences were also explained in [4–8}. In particular, Figure 2 shows a plot of such a kind for the water suspension of cellulose.

A possible interpretation of the anomalous flow as a consequence of the appearance of a local discontinuity of the structure (i.e., when the shear does not propagate throughout the volume of the system) was likely first given in [9, 10]. The theory of this phenomenon was developed in [11–13] on the basis of notions about the presence in the structure of local microdefects whose coalescence under the shearing conditions gives rise to a macroinhomogeneity. In this case, the ratio between the relaxation times of the processes proceeding in the vicinity of the discontinuity nucleus at its development is taken into account. A discontinuity is detected experimentally [9] by a sharp decrease in the shear stress as it reaches the critical, for a given system, deformation rate $\dot{\varepsilon}$. The subsequent increase in P with increasing $\dot{\varepsilon}$ reflects the behavior of the system only in the region of the discontinuity and not throughout its volume.

The hypothesis about such a mechanism of destruction in the shear flow was confirmed in [11, 14] by microphotographs of the structure of aqueous dispersions of calcium bentonite. The kind of discontinuity thereby strongly depends [8] on the solid-phase content in the dispersion medium and correlates [9] with the graphically general view of the dependence of the structure strength on the particle concentration. The following variants are possible: true discontinuity under the conditions of liquid-phase deficiency ($\varphi >> \varphi_{2c}$); the formation of one ($\varphi \geq \varphi_{2c}$) or several ($\varphi << \varphi_{2c}$) slip zones at an excess content of the liquid phase with the formation of solid-like layers.

The appearance and further development of a discontinuity in the deformation process prevents [9] the shear from propagating throughout the volume of the system. Such a phenomenon leads to a measurement data corruption and, consequently, to the impossibility of plotting a rheological curve. This is evidenced [15] by the absence of the reproducibility of flow curves in the case of downward and upward motion (the presence of hysteresis loops, Fig. 3). This effect

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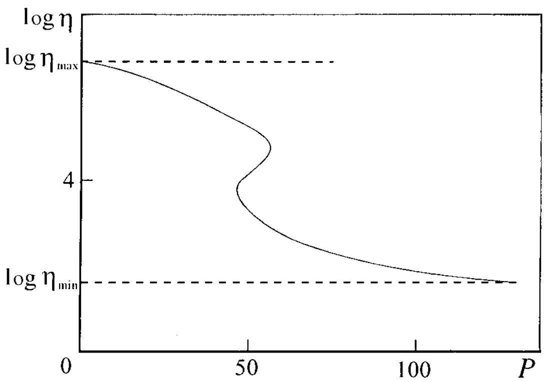

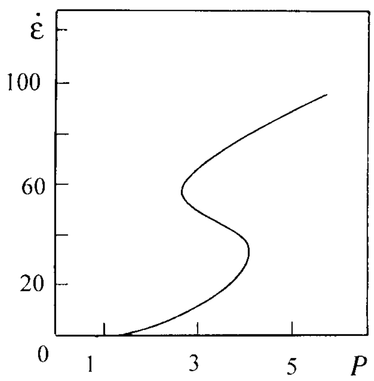

Fig. 1. Viscosity logarithm η as a function of the shear stress P for 10% suspension of Na-bentonite [3]. η, Pa·sec; P, Pa.

Fig. 2. Deformation rate $\dot{\varepsilon}$ as a function of the shear stress P for water suspension of cellulose (sulfate white, concentration of 2.1%) [7], $\dot{\varepsilon}$, $\sec^{-1}$; P, Pa.

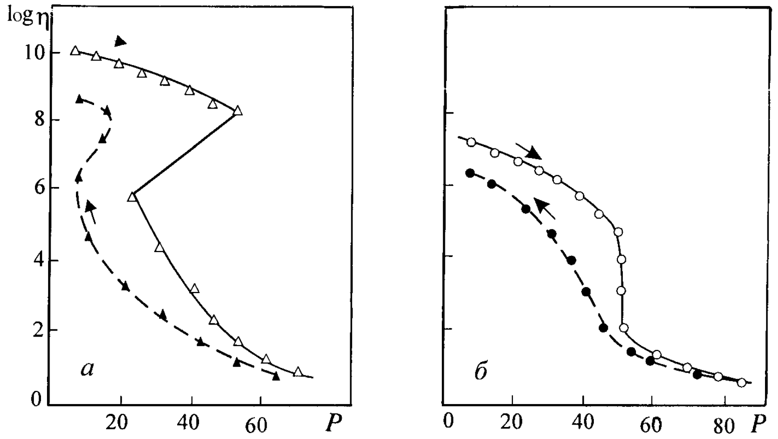

Fig. 3. Full rheological flow curves log η(P) of water dispersions of calcium bentonite for systems with $\varphi = 20\%$ ($\varphi > \varphi_c$) (a) and $\varphi = 11\%$ ($\varphi < \varphi_c$) (b); solid lines with open circles indicate measurements with increasing P, dashed lines with solid circles — with decreasing P; arrows show the directions of measurements of P [15]. η, Pa·sec; P, Pa.

is most pronounced at $\varphi > \varphi_{2c}$. It should be noted that the anomalous dependence of viscosity on the shear stress, inherent in type-II curves, is revealed [16–19] even in low-concentrated colloid gels with a fractal structure (Fig. 4).

Thus, with increasing intensity of external actions qualitative changes in the behavior of disperse systems are observed: the initial structure is destroyed and a new, layer structure is formed. This phenomenon finds reflection in a nonstandard shape of rheological curves.

To further develop the notions on the laws and mechanism of formation, stability, and destruction of structured dispersions, it is expedient to add [20, 21] to the explanation of their possible anomalous behavior as a specificity of coagulation under dynamic conditions the analysis of the processes in terms of synergetics and the theory of catastrophes taken together. As is known, synergetics deals [22–28] with the investigation of the processes of self-organization of structures of various nature formed in systems that are far from equilibrium, and the theory of catastrophes describes [29–31] those threshold situations in which dissipative self-organized structures arise, are maintained, and lose stability. Within the framework of this approach, disperse systems under dynamic conditions are interpreted as self-organized systems whose evolution in space and time is accompanied by the formation of dissipative structures. It should be noted that the whole variety of real stepwise changes of states of such systems (their qualitative restructuring) caused by smoothly varying external actions is described by a small finite number of canonical models — catastrophes. And although there is still no [26, 27, 32–34] rigorous evolution criterion or a unanimous opinion about its

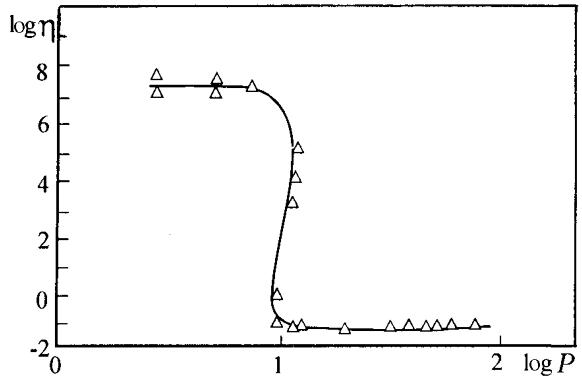

Fig. 4. Full rheological curve log η(log P) for 2.5% suspension of monodisperse spherical SiO_2 particles (d = 7 nm) in ester (triangles — experiment, curve — calculation) [16]. η, Pa·sec; P, Pa.

choice, the concept of dissipative structures can offer much [32, 35, 36] for understanding the problems of self-organization and structure formation.

Since the theory of catastrophes gives a method for modeling certain discontinuities of developing processes of various kinds, Trofimova [37] suggested interpreting the possible forms of qualitative structural changes in the shear flow as catastrophes. In particular, a graphic illustration of radical changes in the character of the flow of structured disperse systems is the S-shaped bends of the rheological curves (Figs. 1–3). Their anomalous form is identical to the standard curve of stationary states. According to [23], "...the number of stationary states of an open system can strongly increase away from equilibrium," and in an S-shaped model of a system with several stationary states X "...upper and lower values of X are stable and intermediate values are unstable." This fact permits the existence of three stationary modes at the same values of some (control) parameter, by virtue of which hysteresis phenomena are possible [25]. The bend points of the curve correspond [25, 38–40] to the bifurcation values of the parameters at which the number of stationary states changes stepwise ("catastrophically") with a simultaneous change in the type of stability. In so doing, the unstable states in the middle portion are practically never realized [39] in real systems.

Thus, characteristic of the curves of stationary states are features which in the general case are typical of flow curves II. It should be noted that the analogy is not only in appearance but in meaning as well. According to [3], in some zone of a sharp decrease in viscosity at one and the same shear stress two stable and one unstable flow conditions are observed (Fig. 1). Consequently, the theoretical S-shaped curve adequately reproduces the real picture of the behavior of structured dispersions under dynamic conditions. Such an assumption in situations where experimental data are difficult to obtain permits predicting the character of the flow curves.

In the case of rheological curves (Fig. 3) on which the region of recovery of tresses is due to the discontinuity, this model takes into account the phenomenon of stepwise transition of a deformable system from the state with a practically undestroyed structure to a qualitatively new state with a specific (layered) kind of destruction. The "threshold" stresses at which changes in the shape of rheological curves are noted are considered as bifurcation stresses. The anomalous portion between the bend points corresponds to unrealizable states of the volume isotropic damage of the structure, since a full rheological curve in the region where the effective viscosity changes from η_{max} to η_{min} can only be obtained [15] when "a pure uniform shear" is realized. The lower portion of the plot [15] corresponds to corrupted measurement data.

As mentioned above, for certain systems a family of rheological curves with a more pronounced S-shape with increasing concentration of the solid phase can be obtained. In particular, this trend is clearly seen [11, 15] in analyzing the flow curves of calcium bentonite water dispersions (Fig. 3). It was suggested [41] to use an assembly-type catastrophe to investigate the features of the flow at a shear deformation, since the considered curve of stationary states represents the cross-sections of this model at fixed values of φ (Fig. 5). A catastrophe of such a type describes the process under investigation by one state variable (η or $\dot{\varepsilon}$) and two control parameters P and φ and is represented as a qualitative model (surface) in a three-dimensional space of these generalized coordinates (Fig. 5a). The most interesting property of this surface is the presence of two lines of wrinkles originating at the so-called assembly point B and

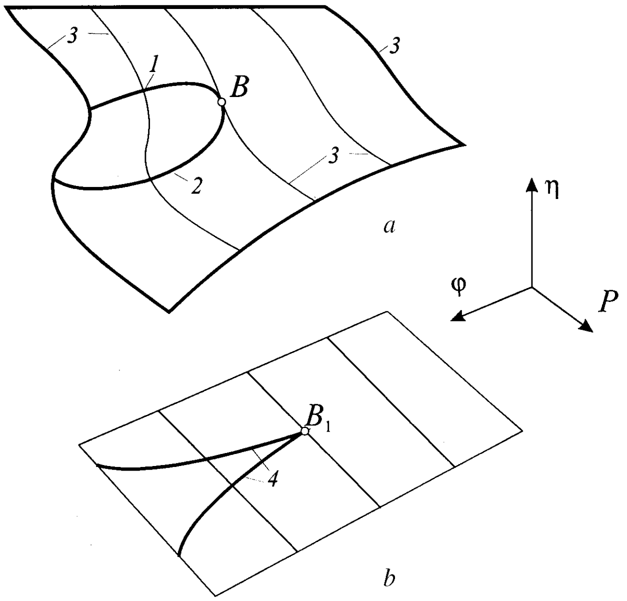

Fig. 5. Viscosity η of calcium bentonite water suspension as a function of the shear stress P and the dispersed phase content φ (assembly-type catastrophe, maximum delay principle): a) model surface in the coordinates of η, φ, and P [1 and 2) lines of folds; 3) cross section of the model; B, assembly point]; b) projection of the model onto the plane of control parameters P and φ [4) bifurcation curve, B_1, bifurcation point]. η, Pa·sec; P, Pa; φ, %.

forming on the plane of control parameters P and φ a bifurcation curve — a semicubic parabola with a cusp at the point B_1 (Fig. 5b). These points correspond [9] to the first critical concentration φ_{1c}, upon reaching which there appears a spatial structural net and anomalies in the mechanism of dispersion system flow begin to show up. Stable stationary regimes correspond geometrically to the points of the surface of the variety of assembly-type catastrophes lying on the upper and lower sheets on the outside of the wrinkle curve, and unstable ones — to the point on the middle sheet inside the wrinkle curve ("inaccessibility region," which can be interpreted as a zone of unrealizable states of isotropic damage of the structure).

The qualitatively different behavior of the system is determined by different combinations of control parameters. In the case under consideration, the parameter φ is called the splitting parameter, since when its critical value is exceeded the model surface splits into two sheets, i.e., its change specifies the very probability of indefiniteness of the dependence of η on P and the appearance of jumps. If the condition $\varphi > \varphi_{1c}$ is met, then, when the second (normal) control parameter P changes, the right edge of the assembly is reached, which leads to a jump from one stable stationary regime of flow with a practically undestroyed structure on the upper sheet to another, but with a local slip zone on the lower sheet. The wrinkle lines (the right and left edges of the assembly) correspond to exactly those combinations of control parameters which initiate stepwise changes of state. Such a notion, integrating in one scheme the whole set of possible variants of the above rheological curves, is fairly consistent with the known experimental results [11, 15] and gives complete enough information about qualitative changes in the rheological behavior of disperse systems under continuous shear deformations caused by discontinuities.

It should be noted that in modeling real situations with sudden catastrophic changes of regimes, it is necessary to take into account [25] the presence of two main directions connecting the geometry of catastrophes to the system being investigated (maximal delay and Maxwell principles). The choice of one of the principles is determined by the nature of the phenomenon itself. For instance, in the above-considered case, the first principle is realized according to which the system makes a jump to another state only if it has no other choice. Moreover, it is expedient to use it, in particular, in describing and analyzing phenomena associated with the loss of physicochemical stability and hysteresis effects [11, 15]. Hysteresis is [29] one of the basic qualitative features of the assembly-type catastrophe in the case of using the maximal delay principle.

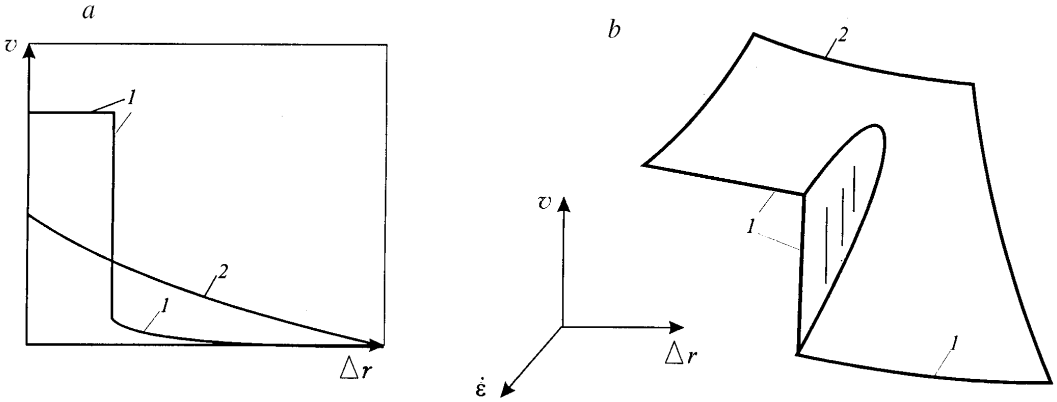

Fig. 6. Distribution of velocities v in the flow of high-concentration disperse systems in the spacing Δr between the surfaces of coaxial cylinders of a rotational viscosimeter: a) at $\dot{\varepsilon}$ = const [1) $\dot{\varepsilon} > \dot{\varepsilon}_c$; 2) $\dot{\varepsilon} < \dot{\varepsilon}_c$] [9]; b) at continuously varying $\dot{\varepsilon}$ (assembly-type catastrophe, Maxwell principle: model surface in the coordinates of v, Δr, and $\dot{\varepsilon}$). v, m/sec; Δr, mm; $\dot{\varepsilon}$, sec^{-1}.

As is known from [11], the appearance of a discontinuity means that the continuum in the change of velocity v in the cross section of the viscosimeter running clearance Δr at $\dot{\varepsilon} > \dot{\varepsilon}_c$ is broken (Fig. 6a). The analysis of the velocity distribution scheme at a continuous shear deformation has shown that the observed effect can be described fairly well [24] by a model whose geometry obeys the Maxwell principle. In this case, there arises a situation analogous to the formation of the so-called shock wave (break) characterized by sharp changes in the profile. With increasing velocity of shear in passing through some critical value of $\dot{\varepsilon}_c$ the shock wave suddenly kicks the system into a new state. It should be noted that the profile of velocities v given in Fig. 6b is interpreted in [42] as assembly-type catastrophe cross sections for various $\dot{\varepsilon}$. Here the deformation rate acts as a splitting parameter predetermining the possibility of a considerable change in the clearance linear velocity profile.

Extending the list of possible kinds of schematic representations of v profiles corresponding to different variants of structural changes in systems in a shear flow by using the nonlinear wave theory seems informative as well. Since a rigorous mathematical analysis is rather difficult, it makes sense to qualitatively determine the most important features of the break formation on the basis of an analogy with the investigations of collective phenomena in plasma, which also use [43] the model notion of the shock wave. The character of the structure of the latter depends on the viscosity of the system being investigated. If the viscosity is small enough, then the general qualitative profile shape corresponding to the velocity jump is a shock wave with a decaying oscillating structure located ahead of its front (soliton packet). The lower the viscosity, the larger the number of oscillations (breaks). With increasing viscosity an ordinary shock wave without oscillations with a monotonous structure takes place. Thus, ordinary aperiodic shock waves and soliton packets are interpreted as various limiting situations for one and the same nonlinear process. As applied to disperse systems, these model notions agree with experimental results: to monotonous and oscillating profiles there correspond single and multiple discontinuities.

As is shown in [11, 15], a possible cause of a discontinuity is a jump of the solid-phase concentration in the vicinity of macrononuniformity boundaries with the formation of shear planes. In terms of the theory of catastrophes, to establish the most important features of the appearance of higher-density zones, one can draw on the analogy [42] with Ya. B. Zeldovich's "pancake production" (formation of particle clusters). The theory of "pancakes" describes [30, 31, 44] such structure transformations by means of an assembly-type catastrophe (taking into account the existence of two scenarios of the development of the processes of compacted structure formation). In the first case, the model of the appearance of three-flow (S-shaped) configurations is considered. Such an approach is appropriate in interpreting the effect of structured dispersions; a collapse leads to the appearance of layering and breaks in the system. The second approach illustrates, by means of notions of the shock wave, the generation of compacted regions at a shear deformation. This model takes into account the collisions of particles. Therefore, the stepwise transition of the system to a new state at a certain value of $\dot{\varepsilon}_c$ is accompanied by the transfer of particles and their "sticking" to the structure of

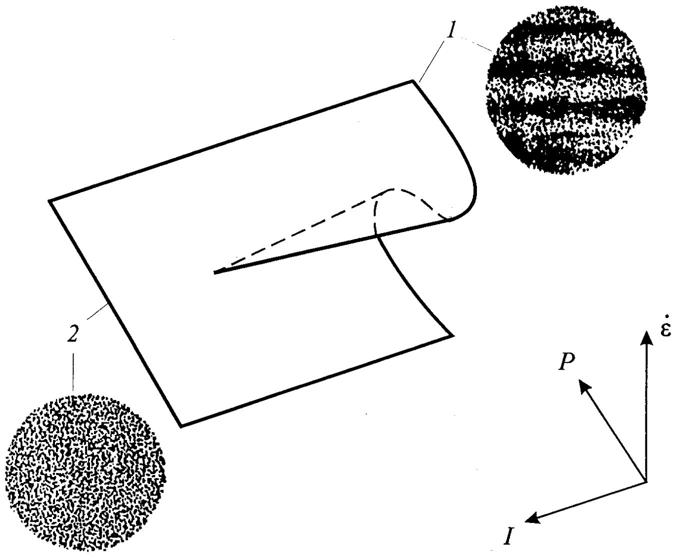

Fig. 7. Transformation of the flow curves $\dot{\varepsilon}(P)$ with increasing vibration intensity I in a combination of a continuous shear with an oscillation orthogonally directed to it (model surface of the assembly-type catastrophe in the coordinates of $\dot{\varepsilon}$, P, and I); dependences $\dot{\varepsilon}(P)$ and their corresponding structures of dispersions: 1) without vibration; 2) at a vibration with optimum parameters. $\dot{\varepsilon}$, sec^{-1}; P, Pa; I, $\mathrm{m}^2 \cdot \mathrm{sec}^{-3}$.

the main layer. Such an interpretation describes the process of "lamination" of solid-phase particles promoting the formation of a compacted structure [11].

Because the notions of the shock wave are identical to the notion of the phase transition of the first kind in the region of coexistence of various phases [24], it is suggested to consider, from this point of view, the anomalous behavior at a shear of the above-mentioned 2.5% colloid gels with a fractal structure. This weakly defined but clearly detectable anomaly is characterized [16–19] by a stepwise transition from the state with a solid-like (large) viscosity to the state with a liquid-like (small) viscosity at a continuous increase in the shear stress and is accompanied by a stepwise change in η by nine orders of magnitude on passing over the threshold value of P (Fig. 4). In measuring the gel viscosities in the regime of a continuous shear in the 10^{-8}–10^{-3} sec^{-1} range of deformation rates, we [18] obtained on one flow curve regions of solid- and liquid-like states and a region of transition from one state to another, in which a coexistence of solid- and liquid-like layers is presumed. The possibility of system layering into two phases with a different concentration of particles is evidenced by the presence on the flow curve of a characteristic Van der Waals loop. As is known [29], the restructuring of the isotherms of the Van der Waals equation of state is a typical example of the application of an assembly-type catastrophe whose geometry is in agreement with the Maxwell principle. The fact that a real disperse system can have two states is interpreted by the theory as a bimodality and, along with the stepwise change in viscosity, serves as a confirmation of the presence of a "catastrophe."

As mentioned above, structured dispersions away from the thermodynamic equilibrium in the field of external actions are typical synergetic dissipative systems. In the course of their evolution, under dynamic conditions, a considerable reorganization of the microstructure at a certain critical value of the velocity of shear (parameter corresponding to the bifurcation point) occurs. The initial structure is split into layers (i.e., local volumes bounded by the slip surfaces). Inside these volumes contacts between dispersed-phase particles are not broken and the degree of nonuniformity, which corresponded to the moment of the appearance of the initial (static) structure in the system, is preserved. A breakage of cross-links, with respect to the flow direction, between the structural elements of the initial cellular-type space mesh and a displacement of the liquid phase from the spacing between particles when the cell boundaries break down are observed. There is a clear tendency for a transformation of the cellular structure to a layer structure, which becomes most pronounced when the solid phase concentration decreases within limits sufficient for self-organization. The cells extend in the shear direction and dissipative layer structures are formed. The development of these structures

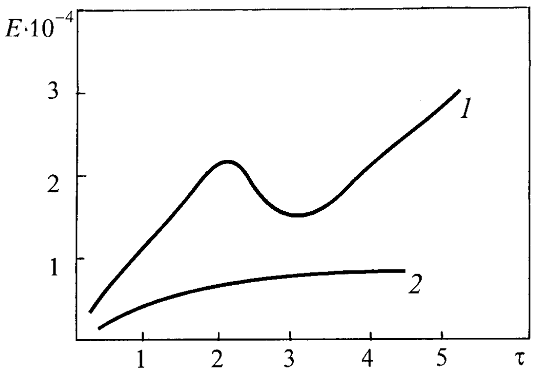

Fig. 8. Curves of change with time τ in the fast elastic deformation modulus *E* of MgO suspension: 1) without SAS; 2) with a 1% content of citric acid [50]. τ, h; *E*, Pa.

was preceded [11] by a compaction in local volumes of particle microaggregates with a gradual formation of shear planes in the zones of the largest aggregations of packing defects.

Thus, at a deformation in the disperse system irreversible processes of restructuring caused by the cooperative interaction of defects can proceed [25]. A deformable dispersion with defects (initial local imperfections) displays a behavior which can be represented as an asymmetric bifurcation diagram. In terms of the theory of catastrophes to such an evolution pattern there corresponds the above-mentioned assembly-type catastrophe. It also seems informative to describe the mechanism of layering of disperse systems as a process of formation of contrast dissipative structures [45]. Since for the existence of such a structure the presence of a set of "activator-inhibitor"-type parameters in the literal sense is not necessary, it is expedient to consider, as a deforming variable, the initial nonuniformity [46].

Consequently, the moment of the appearance of a layering is a precursor of the transition to the accumulation of reversible damages under the action of external force fields. The superposition on a deformable system of a vibration with optimum parameters radically changes [9] the character of its destruction in the shear flow. A destruction of compacted layers with an avalanche formation of microaggregates of particles with simultaneous formation of a structure in the form of cells with loosened coagulation contacts is observed [14], and the slip zones thereby disappear. From the point of view of synergetics such an effect can be explained [47] by the increase in the degree of nonequilibrium of the system under an additional action of the vibration, as a result of which the structure is shredded, as a rule. This interpretation is in qualitative agreement with experimental results: a combination of a continuous shear with an oscillation orthogonally directed to it causes [11] the structure to break down into aggregates whose size decreases and whose number increases with increasing vibration intensity $I = a^2w^3$. The assembly-type model arranged as shown in Fig. 7 illustrates the features of the structural changes in disperse systems with increasing *I*, which show up as a change in the shape of the flow curves.

It also seems to be expedient to describe and analyze from the above standpoint the kinetic curves of the structure formation of solidifying disperse systems. In the initial stages of the process of spontaneous evolution of these systems, there occur qualitative jumps registered on the plots of such kinetic characteristics as fast elastic deformation modulus, resonance frequency, and limiting shear stress. The effective theoretical description of such transitions is hindered, since the structure formation of disperse composite materials is continuous processes of dissolution, solvation, coagulation, etc. that are superimposed on one another. From the point of view of synergetics, solidifying disperse composites are interpreted [24, 48, 49] as complex nonequilibrium physicochemical systems whose development is accompanied by a self-organization of dissipative structures. Therefore, to reveal the general laws of the behavior of such systems, it is expedient to use [20, 21] the approach based on the possibility of modeling the transition of smooth quantitative changes to qualitative ones, i.e., the theory of catastrophes.

The literature data [50–52] point to the existence of a certain group of structure-formation kinetics curves whose extreme form (Fig. 8) reproduces the geometry of the simplest fold-type catastrophe (Fig. 9). Agreement between experimental and model curves manifests itself not only in the above-mentioned superficial resemblance of the character of the curves, but in their logical generalization as well.

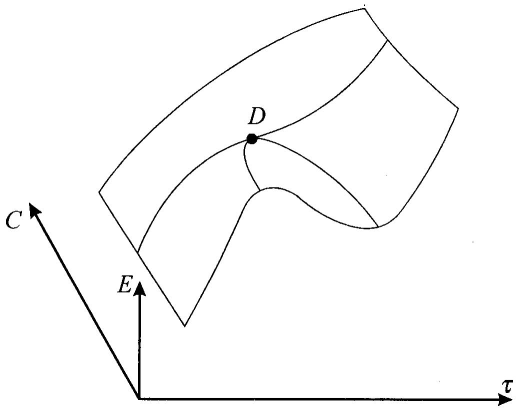

Fig. 9. Transformation of the curves of change with time τ in the fast elastic deformation modulus *E* of MgO-containing suspension with increasing concentration *C* of citric acid (fold-type catastrophe; *D*, fold point). τ, h; *E*, Pa; *C*, %.

The explanation of the shape of the curves describing the time change in the fast elastic deformation modulus and resonance frequency of magnesium-oxide-containing water suspensions of moulding powders is associated in [50] with the specificity of the behavior of MgO. Dispersions including this component are characterized by a low critical concentration of the structure formation at which a coagulation structure arises and bonding powers of MgO manifest themselves similarly to cement-mineral mixtures. After a few hours, a sharp strengthening of the system due to the interaction of MgO particles with water and the formation, as a result of this, of links between them in the form of OH–Mg–O–$(MgO)_n$–Mg–OH chains is observed. Such chains form with time a spatial skeleton and go into condensation-crystallization structures, which is illustrated by an increase in the deformation modulus (Fig. 8, curve 1). The definite decrease in the values of the kinetic indices after 3.5 h is explained [50] by the possible softening of the suspension in the initial stage of formation of point contacts. To prevent the formation of condensation-crystallization structures and preserve the stability of the rheological properties of dispersions, it is necessary to constrain the growth of structural chains and their interaction. The required effect is achieved by introducing into the suspension 0.5–1.0% (of the solid-phase mass) citric acid $C_3H_5O(COOH)_3$ interacting chemically with a hydrated surface of magnesium oxide particles and molecules that are present in the solution. Since the dissociation constant of citric acid is small, the reaction proceeds slowly. The reaction products formed block the particle surface, which restricts the formation of strengthening structures and determines the constancy of the system's properties (Fig. 8, curve 2).

A similar distinctive character of change in the deformation modulus is also observed [51] on the structure formation curves for butyl-rubber-based vulcanizers filled with black, cement, or chalk. The graphic time dependences of *E*, too, have marked bends that are, most probably, consequences of the destructive processes in the systems under consideration. A similar conclusion was also drawn [52] for the shape of plastograms of binding dispersions. As is emphasized in the above works, although the kinetic effect of the systems under investigation is theoretically not clearly understood because of their complexity, it can be controlled by introducing various surface-active substances (SAS).

In light of the foregoing, with regard for the laws given in Fig. 8, it is supposed that the fold-type catastrophe combines in one scheme two possible, in this case, qualitatively different, "limiting" variants of structure-formation curves (Fig. 9). Such an interpretation is not inconsistent with the physical meaning given for the standard model description. The three-dimensional picture of the fold-type catastrophe reflects the features of the change in *E* (or any other index) as a function of time (in terms of the used theory τ is a generalized coordinate) at various concentrations of SAS (control parameter *C*, %). The family of *E*(τ) curves has a shape analogous to the Van der Waals shape. In the absence of or with a small content of an additive, the dependences have a maximum and a minimum. As *C* increases, these points approach each other and at a certain value of $C = C_c$ (similar to the Van der Waals critical temperature) they merge into one point (fold point *D*). Consequently, the extrema correspond to the destructive drops on the kinetic characteristics as a result of the self-organization processes and the parabola in Fig. 9 bounds the region of thermodynamically unstable states of the system. The results of the investigations of the structure formation kinetics reported in [50–52] are essentially a discussion of a particular case of the theory of catastrophes, and the considered model surface, generalizing individual effects, graphically illustrates the qualitative restructuring in a solidifying dispersion. Moreover, the analysis of the experimental dependences [53] has shown that apart from the jump they feature other so-called "indications of a catastrophe" [29] associated with specific properties of the system (e.g., hysteresis) as well. This fact will make it possible to not only classify real situations according to the standardized types of catastrophes differing in the number of control parameters ("fold," "assembly," etc.) but also elucidate the physicochemical mechanisms responsible for the extreme behavior of developing disperse systems.

Thus, the use of new notions for describing disperse systems under dynamic and static conditions with the aim of establishing universal laws of their evolution not only provides the possibility of generalizing the known experimental results, but also gives hopes of predicting, revealing, and investigating a number of other phenomena that are, in essence, specific variants of the limited number of laws of nonlinear synthesis of complex developing structures.

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NOTATION

η, effective viscosity, Pa·sec; P, shear stress, Pa; $\dot{\varepsilon}$, deformation rate, sec^{-1}; φ, solid-phase concentration, mass %; v, linear deformation rate, m/sec; Δr, working spacing of the viscosimeter, mm; I, vibration intensity, $\text{m}^2\cdot\text{sec}^{-3}$; a, vibration amplitude, m; w, circular vibration frequency, sec^{-1}; E, fast elastic deformation modulus, Pa; C, additive concentration, mass %; τ, time, h. Subscripts: c, critical; 1 and 2, first and second; min, minimum; max, maximum.

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