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In situ gas generation in dispersed systems to control structure formation

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Abstract. *Dispersed structures represent an important class of materials not only in science but also in technological processes; however, a number of effects manifested during the flow are still absent. This work aims to validate certain aspects of the heterogeneous dispersed fluid flow under conditions of a volatile external environment and variable composition. This study provides important insights into the thixotropy of an oil sample with a complex structure, the rheological characteristics of oil compositions with structured additives of a dispersed phase were studied. An abnormal value of the concentration of additives resulting in thixotropic structuring of a heterogeneous mixture is shown. Effective control of the structural features of dispersed systems of different concentrations can be implemented by methods of external mechanical effects that cause physical-chemical changes in the structure. These results emphasize the importance of new method of gas generation in dispersed systems to control structure formation. It has been shown experimentally that the "jamming" effect in pipelines can be controlled by in situ gas generation in transported dispersed fluids.*

Keywords. dispersed system · structuring · oil · rheopexy · heterogeneous fluids.

Mathematics Subject Classification (2010): 76-05

1 Introduction

Heterogeneous systems are widespread in many industrial processes, and anomalous effects occur when certain classes of such mixtures flow in pipes and porous media. Fundamental physical-chemical features common to all dispersed systems are heterogeneity, that

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is, the interface between the phases and dispersion (fragmentation) [1]–[3]. Dispersed systems include aerosols, ashes of metals and natural minerals, fine-grained sands, crude oil, natural bitumens, concrete mixtures, water-coal suspensions, etc. In this case, one of the phases forms a continuous dispersion medium, in which the particles of the dispersed phase are distributed [4]. Such structures radically change the colloidal-chemical and structural-mechanical properties of dispersed systems [5]. The main properties of such systems are strength, elasticity and hardness, and they are also influenced by the nature (type) of contacts between particles, the degree of dispersion, anisometry of particles of dispersed phases, and concentration in the dispersion medium [6], [7].

In disperse systems there is an increase in the stability of deposition, spontaneous formation (structurization) of phase structures even when the concentration difference changes. Among the many factors determining the complex properties of structured systems, two main groups of fundamental parameters can be identified [6]:

- f_c force and coupling energy E_c (interaction) in contacts between particles of dispersed phases;

- the number of contacts between particles of dispersed phases per unit volume n.

The force and energy of interaction in contacts between particles depend on the type (nature) of contacts (Uryev, 2019). Naturally, for each of the considered types of contacts, the values of force and energy of the interparticle interaction should be taken into account. In each specific case, the chemical nature, shape and state of the particles of the dispersed phases can change taking into account the chemical composition and physical properties of the dispersion medium [9]–[11]. This state is characterized by the thixotropy, if after destruction it can arbitrarily return to the initial state when external physical impact cease. This thixotropy feature is characteristic of many paraffin oils, sandy clays, etc. The rheology of such systems is defined by the processes of dissociation and formation of structures, which occurs in the case of a direct and reverse chemical reaction [12], [13].

The main issue is the kinetics of structural changes, whereby the hydrodynamic characteristics of the system depend on external influences that lead to an increase or decrease in fluid flow. The process of spontaneous thixotropic dissociation and restoration of binding in structural systems is represented by many authors in the form of a kinetic equation [2, 19]:

$$-\frac{dN_t}{dt} = k_1 N_+^n - k_2 N_-^m, \tag{1.1}$$

where N_+ and N_- are concentrations of dissociated and non-dissociated bonds;

$k_{1,2}$ – coefficients of the rate of destruction and restoration links;

n and m - coefficients determining the degree of dissociation and bond restoration by analogy with a chemical reaction; t - time.

However, it is known that the viscosity of the system is determined by the number of bonds present in the composition at a given time. The concentration of the inseparable part of the bonds, of course, is determined by how far it is from the dissociating state, which is determined by the value of its parameter in which:

$$\begin{array}{l} N_+ = \left[\eta\left(t\right) - \eta_\infty\right] / \left(\eta_0 - \eta_\infty\right) \\ N_- = \left[\eta\left(0\right) - \eta\left(t\right)\right] / \left(\eta_0 - \eta_\infty\right) \end{array} \tag{1.2}$$

It is clear that under destruction and restoration of bonds as a result of deformation, the dynamic equilibrium and, accordingly, the degree of destruction of the structure increase. Moreover, it is felt [15, 19, 25] that there are many small shear stresses during the flow. Such instability cannot be described by Eyring-Powell [18], [19] and Mikhailov-Lichtheim [20] and other models, because only the equilibrium dependence $n_{ef} = n_{ef}\left(\dot{\gamma}\right)$ is determined in this approach.

A similar relationship between the structure and viscosity of dispersed systems was experimentally investigated and qualitatively describes the kinetics of viscosity of non-Newtonian media under shear loading [21], [22]. Identical processes occur in the technology of fluid flow, which proceed more intensively under pulsating operating modes [15, 25].

It is important to study the "unsteady" flow in which the structure of rheologically complex fluids is destroyed and to establish at what volume fractions of the dispersed phase and intense perturbation amplitudes (shear rate) the main flow will improve [23]. In this regard, some aspects of the behavior of heterogeneous liquids under conditions of variable component composition of fluids and variable external conditions are considered in our work.

2 Material and methods.

In the experimental study of the thixotropic behavior of non-Newtonian oil, the task was to determine the dynamics of stress, strain time, and loading mode. For this purpose, the rheological behavior of the compositions including oil and additives in certain volume fractions of the dispersed phase, reflecting the structuring of the system, has been studied. The physical and chemical characteristics of the oil sample used are given in Table 1:

Table 1. Physical and chemical characteristic of the oil sample

Volume factor under saturation pressure	Oil density under normal conditions, g/sm^3	Oil viscosity under normal conditions T=20^{o}C, MPa·s	Oil content, %		
			Sulfur	Paraffine	Asphaltene
1,093	0,974	1478,0	0,37	3,12	4,19

In the first series of experiments, studies were carried out on a HAAKE Rheostress-600 viscometer at adjustable shear rates and a temperature control temperature equal to 25^oC. The research method consisted of placing the studied samples of oil and an oil polymer mixture between the coaxial cylinders of the reoviskozimeter, one of which is movable. At certain angular shear rates, the values of the shear stress τ (Pa) were determined and the effective viscosity η_{ef} (MPa$\cdot s$) was estimated. The experimental results showed that the equilibrium state between the shear rate and the shear stress is established with some delay. Fig. 1 – 4 shows the characteristic rheological curves obtained as a result of laboratory studies for a sample of "light" oil (Fig. 1) and resin-asphaltene oil containing 5.0; 7.0; 9.0 and 10.0 vol. % of asphaltenes.

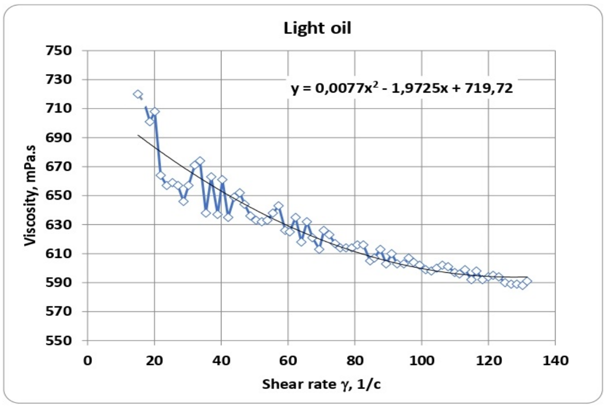

Fig. 1. Rheological characteristics of the light oil sample

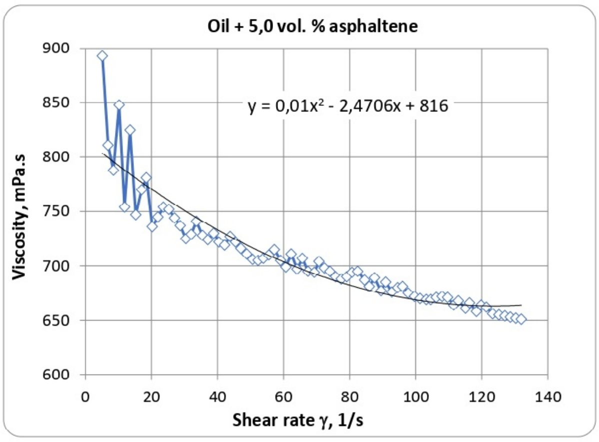

Fig. 2. Rheological characteristics of the oil sample with 5 vol. % asphaltene

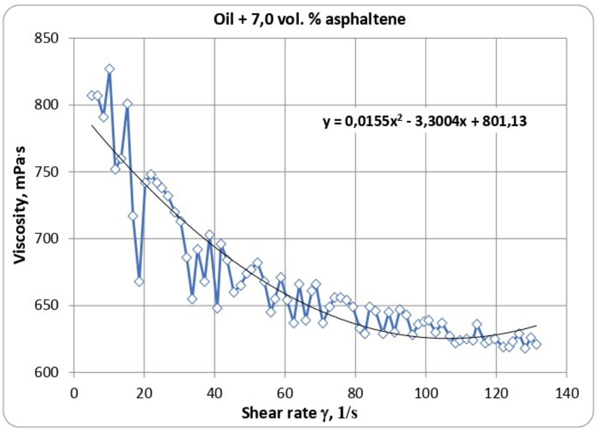

Fig. 3. Rheological characteristics of the oil sample with 7 vol. % asphaltene

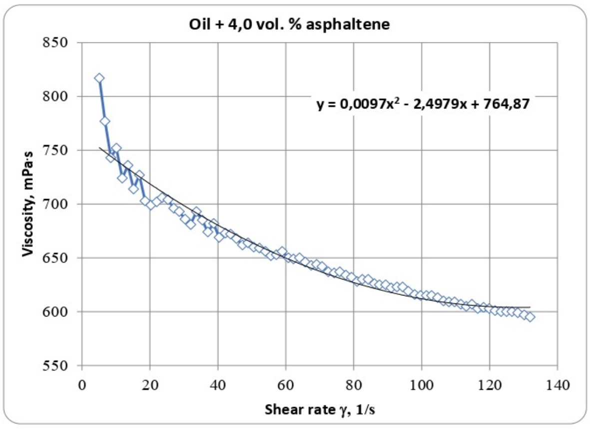

Fig. 4. Rheological characteristics of the oil sample with 9 vol. % asphaltene

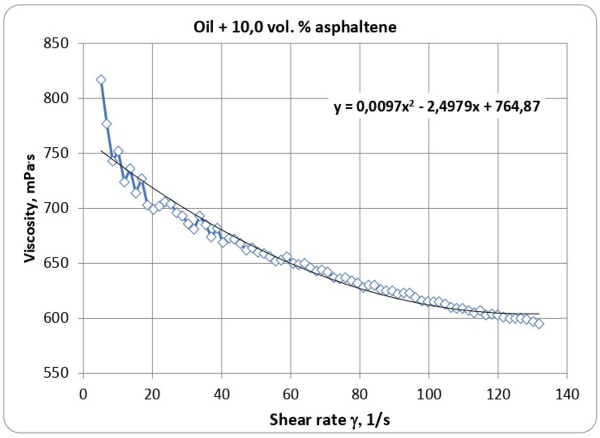

Fig. 5. Rheological characteristics of the oil sample with 10 vol. % asphaltene

The study found, that if there is a paraffin and resins in oil structural elements in the hydrocarbon system forms, characterized by the relaxation thixotropy property [15, 19, 25]. At low shear rates, the property of the mixture is determined by the lattice structure of asphaltenes, resins, paraffins originally contained in oil. With an increase in the shear rate, a transitional property occurs in oil, when neither the oil system nor the polymer inclusions have an ordered structure and this phenomenon is observed with a further rapid transition to an ordered structure.

Transitional character has taken place in compositions with a lack of stability in the internal structure and reversible viscosity fluctuations. The relaxation-thixotropic characteristic of periodic deformation is a function of shear deformation. This mainly refers to small-amplitude deformations, and the boundary is determined by the absolute value of the dynamic viscosity and the amplitude of the deformation rate [24].

Consider the general patterns of changes in the viscosity properties of oil under continuous deformation. As experiments have shown, with an increase in the shear rate in areas of intense fluctuations in the viscosity of the liquid, the flow regime changed from the deformation one, gradually taking the character of a steady flow with different intensity of viscosity changes. In an area of small shear rates, there is a single curve describing the dependence of different frequencies with different "amplitudes" of deformations by the $|n^*| = f\left(\dot{\gamma_{min}}\right)$ dependence.

This means that there are amplitudes of viscosity change at certain shear rates, which correspond to the transition from the deformation mode with small amplitudes to large ones. The process of spontaneous relaxation-thixotropic damped oscillation of the destruction-restoration of bonds in a structured system can be described as follows.

Let ω_0 be the natural frequency of the system – the attenuation coefficient. Then the attenuation process is represented by the differential equation [19]:

$$\frac{\partial^2 x}{\partial t^2} + 2\xi\omega_0 \frac{\partial x}{\partial t} + \omega^2 x = 0$$

The characteristic roots of the equation are as

$$\lambda_1 = \omega_0 \left(-\xi + \sqrt{\xi^2 - 1}\right)$$

$$\lambda_2 = \omega_0 \left(-\xi - \sqrt{\xi^2 + 1}\right)$$

In this case, weak attenuation occurs – weak attenuation corresponds to $\xi < 1$. Then the solution of the characteristic equation is two complex-conjugate roots:

$$\lambda_{1,2} = -\omega_0\xi \pm i\omega_0\sqrt{1-\xi^2}$$

The solution of the equation can be written as follows:

$$x(t) = e^{-i\omega_0 t}\left(C_1 \cos\left(\omega_0 t\right) + C_2 \sin\left(\omega_0 t\right)\right)$$

where, $\omega_d = \omega_0\sqrt{1-\xi^2}$ - the natural frequency of damped oscillations, constants C_1 and C_2 are determined from the initial conditions.

$$x(0) = a,\ \frac{\partial x}{\partial t}(0) = b$$

The value τ, determined from $\xi = \frac{1}{\tau}$, is the relaxation time, and the amplitude decreases in time.

Thus, in the presented work, some aspects of the flow of heterogeneous fluids with varying component composition and variable external conditions are considered, the consideration of which is relevant in the problems of fluid flow in porous medium and pipes. It is established that at certain volume fractions of the dispersed phase and the value of the shear rate, an improvement in the characteristics of the flow and mutual displacement of fluids is observed.

On the other hand, the phenomenon of thixotropy makes it difficult to study the rheological parameters of dispersed systems, since their viscosity and tangential stress depend not only on the deformation rate, but also on its previous state.

Lab experiments.

Deformation of some dispersed thixotropic systems leads not to a decrease, but to an increase in viscosity. This rare situation is called “rheopexy”, which is less common than thixotropy. According to Reiner’s definition, rheopexy is the solidification of thixotropic systems under slow deformation. A feature of relatively weak structures with contacts of the first and second types is their full power output. The state is characterized by the properties of thixotropy and rheopexy if after destruction it can randomly return to the initial level when external mechanical influences cease.

The properties of dispersed systems, which are rheologically complex media, largely depend on the properties of phase inclusions that determine the formation of the structure and the physical-mechanical properties of solutions [13, 29].

The results of the study show that the flow structure of such solutions during transport in pipes can change and cause various types of technological complications for a number of reasons [19, 23, 29]. The resulting complications consist in the formation of plugs under the flow of dispersed systems, results in an increase in hydraulic resistances. The analysis of numerous works shows that this effect manifests itself regardless of the spatial orientation of the pipes - in practice there are often “suspended” or “cartridge” plugs. The authors [15] have shown that such systems are characterized by an angle of internal friction and an adhesion coefficient A, which characterizes a freely flowing medium associated with the “jamming” effect.

Experimental studies have been undertaken to study other mechanisms that arise here. For this purpose, an experimental setup has been assembled (Fig. 6) to investigate the flow of bentonite clay solution with density ρ = 1210 kg/m^3 and a viscosity of η = 0.022 Pa with the addition of quartz sand particles with a diameter $d < 0.001$ m in an amount of 10-40 vol. % according to the scheme shown below.

The dispersed system flows from a container (3) connected to a compressed air cylinder (1), and with the help of a micro-reducer (2), the pressure P at the input is controlled.

With the addition of transformer oil to the top layer of the clay solution to ensure uniform displacement of the system under study into the tank, the gradual flow rate of the system in glass tubes (8, 9) was investigated. As can be seen in Fig. 6, if there was a “top-down” flow in the first tube (9), then in the other tube (8) the flow was in the “bottom-up” direction. When the system is continuously loaded, the flow in the “top-down” direction stops despite a further increase in pressure. At the same time, there was a continuous flow directed vice versa upwards. For 30 minutes after the flow stopped, the downward pointing system was not driven by gravity.

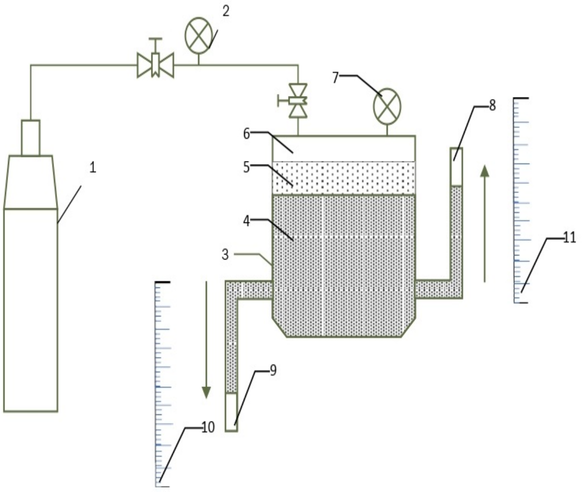

Fig. 6. Experimental setup

This effect was more evident when quartz sand particles with a diameter $d < 0.001$m was added in an amount of 20%.

In the next stage, the experiments were carried out with horizontal fluid flow. Here, in a metal pipe with a diameter of 0.016 m and a length of 2.0 m, the flow of the water solution of clay with the addition of quartz sand (20% by weight) was simulated under the laminar mode at a constant temperature (T= 287^{o}C). The pressure/flow characteristic curve at different pressure values under the flow of systems was studied.

Fig. 7 shows the results obtained at different values of the pressure drop. As can be seen from the figure, with a constant pressure drop, there was a decrease in flow and, eventually, an overlap (“jamming”) of the solution flow.

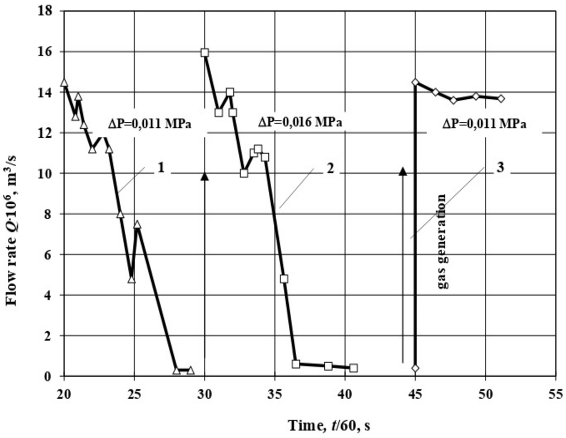

Fig. 7. Change in mass flow rate during the flow of the dispersed mixture in the pipe

Here, curve 1 shows the change in flow rate over time with a constant pressure drop ΔP = $1.1 \cdot 10^4$ Pa for a clay-sand mixture. It can be seen from the Fig. 7 that the flow characteristic tends to decrease, and after a certain time it is completely interrupted. The scattering of the observed experiment points before the beginning of the stationary state can be explained by a gradual shift of the dispersed phase. It should be noted that a similar spread is observed with the influx of other rheopectic suspensions.

An increase in the inlet pressure to a value of P=$1.3 \cdot 10^4$ Pa leads to the restoration of the flow rate of the system under study. It should be noted here that mainly in the suspension under study, the dispersion medium has a relatively high viscosity and resistance to settling. This is confirmed by the fact that the concentration of sand at the outlet of the tube remains almost constant.

Considering a dispersed clay solution as a nonlinear viscous-plastic medium, we assume the following relationship between the pressure drop and the average flow velocity:

$$v = 4M/\pi\rho d^2,$$

$$v = \begin{cases} k_0\left(\frac{\Delta P}{l} - Q\right)^{\mu}, & \Delta P/l > Q \\ 0 & , \quad \Delta P/l \leq Q \end{cases}$$

where ΔP is the value of the initial pressure gradient; ρ- the density of the system; $k_0, \ \ \mu$ - some positive coefficients.

Suppose that the rate of "hardening" of the medium is proportional to the flow rate, and the rate of dispersion of the "hardened" layers is proportional to the stress of the pipe walls $\tau_0 = \Delta Pd/4l$. Then the change in the initial pressure gradient can be described by the equation:

$$\frac{dQ}{dt} = \alpha v - \beta, \Delta P f\left(v\right)$$

where $\alpha_1, \ \ \beta_1$ are the coefficients of hardening and destruction; $f(v)$ is a function, a function that characterizes the dependence of the intensity of destruction on the flow velocity. Suppose the function has $f(n) \sim v$ at $v \to 0$. If the function is approximated as follows

$$f\left(v\right) = \frac{av}{1 + Bv^n}, \quad n > 1,$$

we get $v^{\gamma}\frac{dv}{dt} = -\alpha v + \beta \Delta P v/\left(1 + Bv^n\right)$.

The analysis shows that at $\Delta\rho < \Delta P = \alpha/\beta$ it has a stable equilibrium point $v = 0$, i.e., the pipe is locked. At the $\Delta\rho < \Delta P$, the point $v \neq 0$ loses stability and a new equilibrium point $v = v^*$ appears, the value of which is determined by the intersection of the function $f(v)$ with the line $\alpha/\beta, \ \Delta\rho$. This point corresponds to a stationary flow that sets in the pipe over time.

Results and discussion.

To investigate the mechanism of the above-mentioned phenomenon, theoretical studies of the rheology of dispersed systems were carried out. Here, as noted above, a model of a dispersed system consisting of a clay solution (bentonite) with additives of quartz sand of various fractions (with density $\rho = 2600 kg/m^3$) was studied.

In addition, for the suspension under consideration, the change in shear stress and structural viscosity, estimated by concentration, was studied. Researches have shown that the intensity of tangential stress, estimated with increasing concentration, manifests itself more than the structural viscosity.

The decrease in flow due to subsequent locking during the experiment can be explained by the fact that after a certain time in the pipe there is an outflow of solid particles evenly distributed over a wide cross-section into the suspension. The concentration in the distribution of the dispersed phase increases as it nears the wall of the pipe, leading to an increase in the limiting tangential stress of the system.

Qualitative confirmation of the proposed mechanism is based on the need to control the density difference of the dispersed phase and the dispersion medium.

Using the results obtained in [26], with some modifications, we obtain for the case in question

$$h\,(c) = -\frac{\rho(c)}{2\eta(c)} + \frac{A}{1-r^2}c$$

where: $\rho(c)$ is the density function of concentration. We are looking for a $c\,(r)$ that maximizes $h(c)$ and minimizes fluid flow. For the density function of concentration, we take the dependence from the well-known expression

$$\rho(c) = b + (1-b)\,c$$

b - the ratio of the density of the dispersion medium to the density of the dispersed phase, and for the viscosity function of the concentration according to [26]:

$$\eta(c) = \frac{a}{a-c}, \;\; a > 1,$$

then it will take the following form

$$h(c) = -\frac{(c-a)\,[b+(1-b)\,c]}{2a} + \frac{A}{1-r^2}$$

Differentiating by c, we get

$$h'\,(c) = \frac{2\,(c-a)\,(1-b)+b}{2a} + \frac{A}{1-r^2}$$

$$h''\,(c) = \frac{1-b}{a} \tag{2.1}$$

As can be seen from (2.1), $X(k)$reaches a maximum when $k=0$ or $k=1$. If we define $X(k)$ in these estimates of k, we get

$$h(1) = \frac{1-a}{2a} + \frac{A}{1-r^2};\; h(0) \equiv -\frac{b}{2}$$

Since $h(c)$ decreases with decreasing r, then $(a > b/\,(1-b))$

$$c_m(r) = \begin{cases} 0, \; 0 \le r < \sqrt{1-\frac{2aA}{a(1-b)-b}}, \\ 1, \; \sqrt{1-\frac{2aA}{a(1-b)-b}} < r < 1. \end{cases} \tag{2.2}$$

We get for the average concentration

$$F = \int_0^1 c_m(r)rdr = \frac{aA}{a\,(-b)-b},$$

On condition $A \in \left(0, \frac{a(1-b)-b}{2a}\right)$, $F \in (0,\ 1/2)$ the distribution (2.2) is obtained and a complete stratification of the entire system occurs. It should be borne in mind that in practice the stratification is not fully realized, so it is natural to assume that a relatively small wall layer (δ= 0.3 - 0.5) will have a higher concentration of the solid phase. Here the viscosity coincides with the uniform distribution of the dispersed phase.

To estimate the flow rate in the system, the regime of the annular flow of two viscous-plastic liquids in a cylindrical pipe is considered. Here, the structural viscosity η_1 on the pipe wall and the initial shear stress τ_1 in the center, respectively, η_2 and τ_2, which are $\eta_1 > \eta_2$ and $\tau_1 > \tau_2$. If we assume that the core of the flow is relatively small, then the change in R of the viscous-plastic fluid tip in accordance with the simple approach is true throughout the interval.

The flow velocity of viscous-plastic liquids is determined by the following formula:

$$v_j = -\frac{\Delta P}{4l\eta_j}r^2 + \frac{\tau_j}{\eta_j}r + a\ln r + b_j, \tag{2.3}$$

where $\frac{\Delta P}{l}$ - pressure gradient; η_i – fluid viscosity; τ_i - tangential stress; a_i and b_i – constant coefficients. The index 1 is taken for the liquid at the wall, and 2 is taken in the center.

$$\begin{array}{l} r = R_1,\ v_1 = 0,\ r = R_2 \\ -\tau_1 + \eta_1\frac{dv_1}{dr} = -\tau_2 + \eta_2\frac{dv_2}{dr},\ v_1 = v_2 \\ r = 0,\ \frac{dv_2}{dr} = 0 \end{array}$$

where R_1 is the radius of the pipe, R_2 is the radius of the interface between fluids. We get for the total expense:

$$Q = \frac{\pi\Delta P R_1^4}{8l\eta_2}\left\{1 - \frac{8\tau_2 l}{3\Delta P R_1}\left[\frac{\varepsilon}{\varepsilon_1} + D^3\left(1 - \frac{\varepsilon}{\varepsilon_1}\right)\right] - (1-\varepsilon)\left(1 - D^4\right)\right\} \tag{2.4}$$

where $\varepsilon = \frac{\eta_2}{\eta_1},\ \varepsilon_1 = \frac{\tau_2}{\tau_1},\ D = \frac{R_2}{R_1}$.

Analysis (2.4) shows that for $\varepsilon = 1$ and $\varepsilon_1 = 1$, the equation turns into a simplified Buckingham equation. It should be noted that under the condition $\varepsilon_1 \leq \varepsilon$ in accordance with (2.4), the initial shear stress is undoubtedly greater than in the Buckingham model. The mentioned estimates qualitatively confirm the hypothesis that dispersed systems can be used to regulate flow structures.

In addition to the above, effective control of the structural characteristics of dispersed systems widely used in engineering, is carried out by methods of external mechanical impact that cause mechanical and physical-chemical changes in the structure [27].

As can be seen from the experimental results, it is possible to eliminate the jamming effect under the flow of dispersed systems by applying a pressure drop to the system as one of the methods of dynamic impact [28]. Given the limited conditions for the use of this method, a different approach has been applied to control this effect. The results of research have shown that, with the help of certain additives in the composition of dispersed systems, it becomes possible to control rheological properties [29], [30].

In some studies, it was shown that granular particles in dispersed systems as a result of gas inclusions result in changes in the distribution over the pipe area [26], [29], [30]. Here, under the action of the injected gas, its own laws in heterogeneous fluids, rheological, sedimentation, thermodynamic, etc. are understood, that results in instabilities [31], [32]. In contrast to the turbulence of the flow regime carried out during the activation of known solutions, in the proposed method, these conditions can be created as a result of the insertion of gas generated components into the clay-sand mixture. As a result, there are local pressure surges and the formation of a new phase with intensive wandering in solution. If there are any microformations in the structure of dispersed systems, the Laplace stability condition is violated, and they go into a critical state.

The kinetics of the gas phase release and the size of the gas bubbles formed correspond to these conditions. The pressure P in an expanding gas bubble obeys the equation of state:

$$P = \frac{m}{M}\frac{RT}{V_g} = \frac{3}{4\pi}\frac{m}{M}\frac{RT}{r_g^3}$$

This pressure is balanced by the pressure of the surface energy, which is determined by its equation $P_\sigma = 2\sigma_{gf}/r_g$. In addition, it should be borne in mind that when the bubble expands, the viscosity resistance created by the viscosity of the clay-sand solution is also overcome.

Here, when the gas bubble expands, the following condition must be met:

$$\sigma_T r_g + 2\sigma_{fg} r_3^2 < \frac{3}{4\pi}\frac{m}{M}RT,$$

m is the mass of the gas; M is the mass of the gas molecule.

When the nuclei of gas bubbles are deformed, the condition of their stable equilibrium with the surrounding medium $H\sigma = \varDelta P$, $(H = \frac{1}{R_1} + \frac{1}{R_2})$ is violated. Here R_1, R_2 are the radii of curvature, σ is the surface tension, and $\varDelta P$ is the pressure drop.

When the equilibrium is disturbed, i.e., at $\varDelta P > H\sigma$, the critical state turns into a crisis form.

Estimates show that under the condition $\sigma_T = 10^2 Pa$, $\sigma_{mg} \approx 6,4 \cdot 10^{-3} Pa$, the radius of expansion of the gas bubbles occurs at $r_g > 1,7$. Critical sizes of microformations: $r_{kr} = 2\sigma k/\varDelta G_v N\varepsilon$; $N = \left(1 - \varepsilon^2\right)$, $\varepsilon = 0$ in a deformable medium $(k = 1 - 0,5\varepsilon)$. In spherical form, this is $r_{kr} = 2\sigma/\varDelta G_v$, where $\varDelta G_v$ - free specific energy; $\varDelta P = \left(P_s - P^{'}\right)\left(1 - v^{'}/v^{''}\right)$, where $v^{'}$ and $v^{''}$ - specific volumes of the medium and the resulting gas. If we equalize the right side, then the expression takes the form $\left(P_S - P^{'}\right)\left(v - v^{'}/v^{''}\right) = H\sigma$.

If for gas nuclei the coefficient taking into account the shape is written as $n = (r/2) \times \times \left(\frac{1}{R_1} + \frac{1}{R_2}\right) = VH/2$, then their critical dimensions will be $V = 2rn\left(P_S - P^{'}\right) \times \times \left(1 - V^{'}/V^{''}\right)$. The work done when the critical size of the gas nuclei is reached is defined as:

$$W = \varDelta G\left(V_{kr}\right) = \frac{16\pi\sigma^3 kn}{3\left(P_s - P'\right)\left(1 - V'/V''\right)}.$$

The collapse of bubbles depends on the work performed during the formation of microformations: $k = N_0 \beta exp\left(-\frac{W}{k_B T}\right)$, where $N_0 = 10^{28}\ m^{-3}$, $\beta = 10{\cdot}10\ s^{-1}$ is the pre-exponential multiplier, k_B is the Boltzmann coefficient, W is the work performed during inhomogeneous formation.

Since the pressure change in a viscous medium is nonlinear, the average radius of the bubble changes. The process of bubble expansion and collapse with a "stepwise" pressure change is determined by the *Jacobi* number, which characterizes the absence of achieving a dimensionless parameter of the degree of heating. In the mentioned dispersed systems, the results of experiments aimed at estimating the volume of gas formed depending on the pH of the CO_2-forming chemical agents were used [30]. Assessments were carried out aimed at studying changes in the rheological properties of the clay-sand mixture due to additional gas formation. The results of these studies are presented in Fig. 7 (curve 3).

Thus, the results of the experimental study (Fig. 7, curves 1 and 2) show that with a constant pressure drop, there is a tendency to decrease the flow rate, and after a certain period of time it is completely interrupted, whereas on curve 3, unlike it, there is no decrease in flow and, accordingly, locking of the system.

3 Conclusions

Based on the conducted research, the following conclusions can be drawn:

1 Taking into account the peculiarities of the heterogeneous fluid flow with varying component composition and variable external conditions is relevant in the problems of fluid flow and transportation. It is determined that, at certain volume fractions of the dispersed phase and at the value of the shear rate, an improvement in the characteristics of the flow and mutual displacement of fluids is take place.
2 The decrease in flow rate due to subsequent "jamming" during the experiments can be explained by the fact that after a certain time in the pipe there is an outflow of solid particles evenly distributed over a wide cross-section into the suspension. Concentration in the distribution of the dispersed phase increases as it approaches the wall of the pipe, leading to an increase in the limiting tangential stress of the system.
3 The results obtained can be explained by the migration from particles of the dispersed phase to and from the pipe wall, which can be used to control the flow structure of dispersed systems in pipeline transportation.
4 It has been experimentally shown that the "jamming" effect in pipelines can be prevented with the help of in situ CO_2 gas generation in dispersed fluids transported.

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