ON THE QUESTION OF A CHANGE OF LIQUID PROPERTIES DUE TO THE GENERATION OF CAVITATION

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Experimental study of the influence of the cavitational process on the viscosity of a liquid is described. For the first time, the cavitational regime of the sonocapillary (SC) effect has been used as a method for investigation of properties of a liquid in the ultrasound field. It is shown that a momentary cavitation action causes the viscosity of a liquid to decrease by several times. The effect is reversible, i.e. over the capillary length, there takes place a partial or complete viscosity relaxation to its initial value. Possible causes of the phenomenon revealed are analyzed; these include the local heating of a liquid and the partial decomposition of its supermolecular structure.

Introduction

The possibility of creation of new cavitation technologies and the efficient use of the existing ones are largely determined by investigation of physical processes occurring inside a cavitation medium. The character of these processes depends, firstly, on the dynamics of a separate cavity and, secondly, on the conditions of formation and evolution of a cavitation-cavity conglomerate called “cavitation cloud”. Undoubtedly, the evolution of cavitation processes depends on such parameters as surface tension of the liquid, its viscosity, and saturated vapor pressure [1, 2].

Recent studies of molecular properties of liquids give grounds to suppose the existence of an inverse effect, i.e., the cavitation excitation does introduce a radical change in properties of liquid in the perturbed area. It is shown experimentally that the surface tension coefficient σ_{dyn} of a newly formed surface may be considerably higher than its static value σ_0 traditionally presented in reference books. Relaxation of the dynamic surface tension coefficient σ_{dyn} to its static value σ_0 occurs relatively slowly, approximately by 10^{-3} s (and up to several minutes in some cases) [3, 4]. The formation of cavitation cavities in hydrodynamic flows and, especially, in ultrasound-perturbed liquids occurs during a time interval $\tau \approx 10^{-5}$ s. Therefore, it is the dynamic surface tension coefficient that should be used with more expedience when studying the cavitation-perturbed medium.

Furthermore, in the literature, investigations of high-molecular complexes and their solutions are described, establishing that the cavitation causes a decrease of viscosity of such liquids as a result of molecules' decomposition and lowering of their average molecular mass [5, 6]. But these investigations have not been preceded because, firstly, the effect manifested itself in a relatively narrow class of liquids giving only the 15 or 20-percent reduction of viscosity and, secondly, the technique employed was too cumbersome.

Note that the cavitation medium investigations are always connected with the problem of localization of such a medium. The SC effect, manifesting itself by the formation of a stable cavitation cloud with controlled parameters under a capillary channel, can be considered not only as an investigation object [7—9], but also as a means for localization of the cavitation medium for studying the properties of the cavitation-perturbed liquid. In particular, such a localization method was employed when measuring the specific resistance of a cavitation-perturbed localized volume of a liquid [10].

Thus, this work is targeted at the investigation of viscosity of cavitation-subjected liquids with the use of SC technique.

1. Experimental Setup and Substantiation of the Method

1.1. Traditionally, cavitation experiments are carried out in an ultrasound bath of volume of 200 cm^3 and more. Experimenter immerses a vibrator-disperser into the bath filled with a liquid. The cavitation process occurs at the surface of the vibrator-disperser. Under such conditions, the volume of the cavitation-perturbed liquid in reality does not exceed 0.2 to 0.5 cm^3. The cavitation-subjected liquid that, probably, experiences a change of its properties, is continuously mixing with ambient non-perturbed liquid. To increase a percentage of the cavitation-undergone liquid, the process lasts for more than tens of minutes [6]. Employment of spherical concentrators does not resolve the problem, and a time of "sonication" of the liquid in work [5] constituted between 80 and 120 minutes. After that, viscosity of the liquid is measured with a viscosimeter. In the case if the viscosity-change effect is reversible and its relaxation time is comparable with the corresponding average molecular parameter, i.e. from milliseconds to minutes, then a probability exists that the measured values are of a large error.

1.2. A peculiarity of the SC effect is that the cavitation process is excited strictly beneath the capillary channel with the simultaneous formation of a fluid flow inside the channel. And this means that all the cavitation-undergone fluid is moving out from the ultrasound bath through the capillary thus avoiding the intermixing with the non-perturbed liquid. Secondly, a capillary is the main component in traditional viscosimeters. In our experiment, a capillary is also available necessarily. So, parameters of the fluid flow, formed inside the capillary as a result of the SC effect, depend on viscosity of the fluid experienced the cavitation action immediately at the capillary inlet. Thus, one can characterize the cavitation-caused viscosity variation by determining a velocity of the sonocapillary fluid flow.

The experimental setup is shown in Fig. 1. The working fluid was contained in ultrasound bath *1*, on the bottom of which ultrasound emitter *2* was mounted whose operation frequency f was close to 20 kHz. Capillary *3* was immersed into the fluid perpendicularly to the surface of emitter *2* so that the distance between the capillary end and the mentioned surface was equal to 12 mm approximately. Emitter *2* was fed from generator *4* and the amplitude of the supplied voltage U_{em} uniquely defined the pressure amplitude P_m of the ultrasound wave at the capillary end. Capillary *3* is soldered into glass measuring tube *5*. To stimulate the cavitation and control the fluid flow speed, compressor *6* is connected with the capillary system. Manometer *7* controls a stated level of higher static pressure inside the capillary system. The flow speed is measured by using two point light sources *8* and *8'* fixed stringently on measuring tube *5*; their beams are directed to optical receivers *9* and *9'*(photodiodes). The received signals are transferred to electronic converter *10* giving two sequential pulses entering, in turn, into a frequency meter. The frequency meter measured a time interval between the moments for the meniscus to pass by each pair of "source — receiver", thus measuring a time interval needed for filling in the tube volume confined between the two beams. In this way, the volumetric flow discharge of fluid was measured, and the average fluid flow speed in the capillary was determined from the relationship between diameters of the capillary and the measuring tube. The cavitation cloud formation time is of the order of milliseconds and is comparable with the time interval needed for the fluid to flow through the capillary. To measure the steady flow parameters, measuring tube *5* was widened in its bottom part. The time needed for filling in the additional volume is considerably larger than that of the cavitation development and formation of a stationary flow inside the capillary. Thus, a possible error that may result from nonstationarity of the initial stage of the process is eliminated.

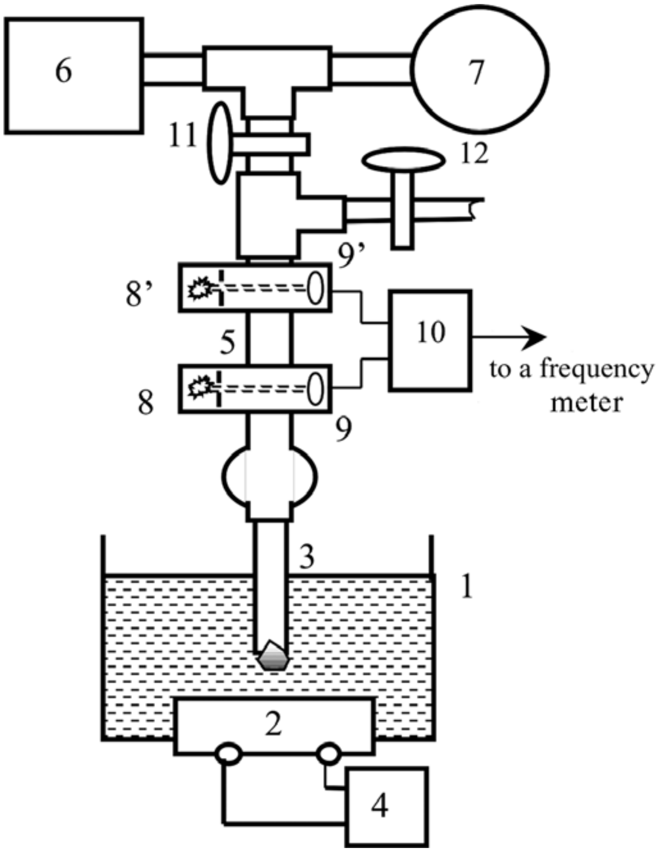

Fig. 1. Experimental setup layout

1.3. When amplitude P_m exceeds the cavitation excitation threshold, a stationary cavitation cloud is generated beneath the capillary channel. In the capillary, the stationary fluid flow is formed as a result of the action of SC pressure P_{SC} on the fluid. If a static pressure P exists in the capillary system, then the fluid flow velocity v inside the capillary is determined by the pressure difference $\Delta P = P_{\rm SC} - P$. In the previous investigations devoted to a flow of distilled water inside a capillary of inner diameter of $d_{\rm cap} = 0.5$ mm, flow-rate velocity values of 1 to 2 m/s were measured experimentally, i.e. such a flow possesses the Reynolds number

$$\mathrm{Re} = \frac{\rho v d_{\rm cap}}{\mu} = 500$$

that is considerably less than its critical value, and the flow was considered as a laminar one [9]. In this work, we consider liquids possessing the viscosity values which essentially exceed the viscosity of water, i.e the $\Re e$ parameter is less than its critical value as well. This means that there exists a linear dependence described by the Poiseuille formula between the flow velocity and the difference of end pressures of the capillary, provided that the viscosity is constant:

$$v = \frac{\Delta P R_{\rm cap}^2}{8\eta l_{\rm cap}} = \frac{(P_{\rm SC} - P)\, R_{\rm cap}^2}{8\eta l_{\rm cap}}. \qquad (1)$$

In traditional rheological studies, a deviation of the rheological curve $v(\Delta P)$ from linearity is interpreted as a manifestation of non-Newtonic properties of a liquid. Note that our experiments allow the unambiguous determination, with a certain error, of such parameters as the capillary radius $R_{\rm cap}$, capillary length $l_{\rm cap}$, and counterpressure P of the capillary system. SC pressure $P_{\rm SC}$ is determined by the amplitude of alternative sound pressure P_m, but also is known to depend on the gas-holding ability of liquid, on size of the cavitation cloud, and on the counterpressure value P [7—9]. Because of this, one may find the analysis of traditional rheological curves $v(\Delta P)$, obtained in our experiments, to be incorrect in determining the specific features of viscosity. But if formula (1) is represented in the form

$$\frac{1}{v} = \frac{8\eta}{(P_{\rm SC} - P) R_{\rm cap}^2} l_{\rm cap}, \qquad (2)$$

then it is seen that, under the given conditions, the curve described by dependence $1/v = f(l_{\rm cap})$ is linear, provided that the viscosity of liquid is constant or slightly varying during its passing through a capillary. The curve inclination angle tangent unambiguously characterizes viscosity of the liquid in the capillary channel.

Taking into account that the parameters entering into the relation of Eq. (2), including the SC pressure, must be independent of the capillary length, we have determined experimentally the SC liquid flow velocity in capillaries of various length values $l_{\rm cap}$.

2. Main Experimental Results

2.1. Choice of a liquid to be investigated is determined by the existing working hypotheses on possible causes of the viscosity variations. Relying on experimental data [8, 9], we expect that a decrease of viscosity of high-molecular substances or their solutions will take place as a result of partial decomposition of their molecules. At the same time, it is well known that viscosity depends essentially on temperature of a liquid and, hence, the viscosity decrease may be caused by a local heating of the SC-specific liquid inside a capillary, as it was studied in work [12]. For this reason, the castor oil solution in dibutylphthalate (DBF) was chosen as one of the working liquids. In such a solution, not only the solute (castor oil) is a high-molecular compound or mixture, but the DBF ($C_{16}H_{22}O_4$) solvent itself possesses considerable mass as compared with such traditional solvents as distilled water or carbon tetrachloride. Furthermore, in such a liquid, both the solvent (DBF) and the castor oil are stable liquids in respect to cavitation. This provides an exact localization of the cavitation process beneath the capillary channel, i.e. in the area of induced initiation of the process. In this case, there is occurs no a spontaneous initiation of random cavitation processes in other localities thus providing a high accuracy of an experiment. For comparison, investigation of a relatively low-molecular glycerin/water solution has been conducted, for which the local heating was of the same order of magnitude as for the oil/DBF solution [12].

2.2. The dependence of the liquid flow speed v in a capillary on the static contrapressure value P has been measured for capillaries of different lengths. The SC pressure $P_{\rm SC}$ was determined by means of the compensation technique or by approximating the $v(P)$ dependence to the region of values of $v = 0$. From the array of experimental data $v(U_{\rm em}, P)$, we selected values for which the parameter $\Delta P = P_{\rm SC} - P$ is practically of the same value and drew the lines $1/v = f(l_{\rm cap})$. Fig.2 shows the results of measurements carried out on the castor oil/DBF solution with viscosity of $69 \cdot 10^{-3}$ Pa·s. Curve *1* shows the characteristic dependence $1/v = f(l_{\rm cap})$ and is essentially nonlinear. For comparison, in Fig. 2, a linear dependence is represented (curve *2*) that was obtained by applying a hydrostatic pressure difference equivalent to the pressure difference $\Delta P = P_{\rm SC} - P$ (here, for $P_{\rm SC}$, we took a value that equals the pressure measured by the compensation method). The shape of the comparative curve corresponds to the Poiseuille formula (2), and the angle of its inclination

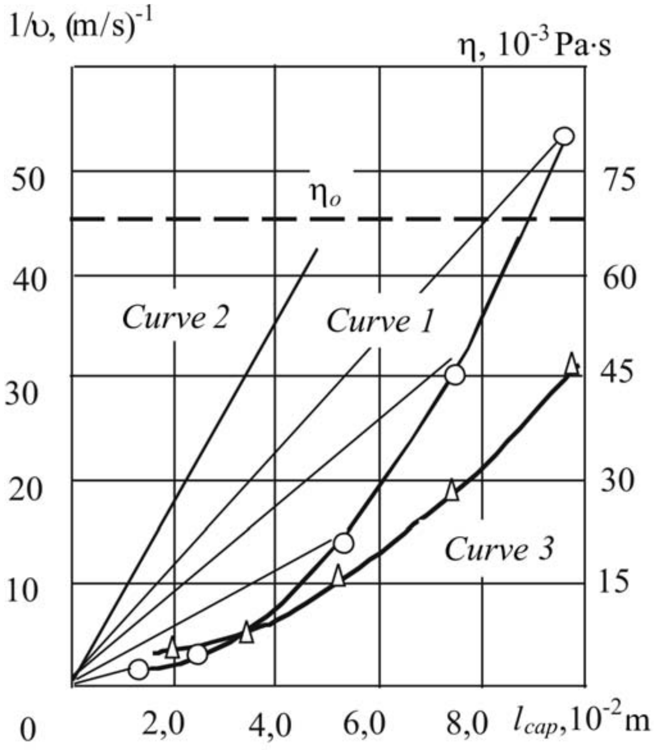

Fig. 2. Influence of $l_{\rm cap}$ on reciprocal velocity of the sonocapillary flow (*1*) and of the unperturbed liquid flow (*2*), and on average viscosity η^* (*3*) for castor-oil/DBF solution

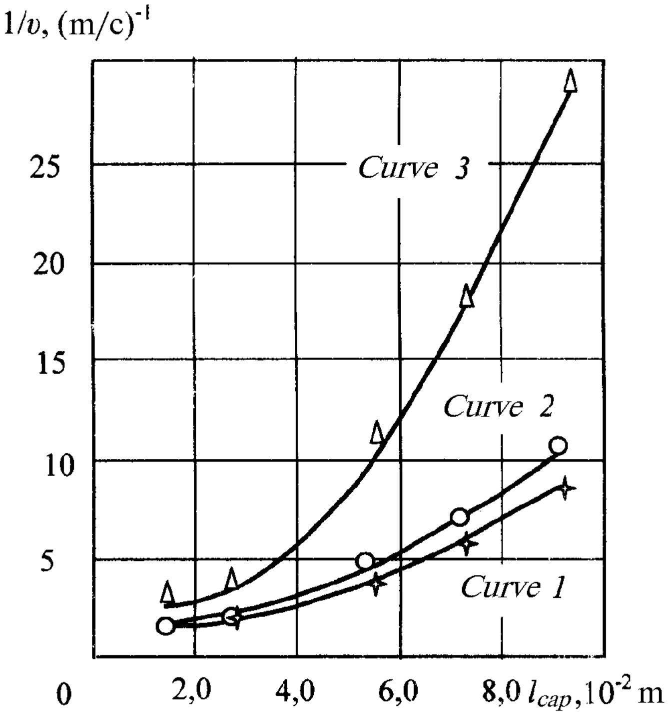

Fig. 3. Influence of $l_{\rm cap}$ on reciprocal velocity of the sonocapillary flow in glycerin solutions: initial solutions' viscosity of 16.8·10^{-3} Pa·s (*1*); 23.6·10^{-3} (*2*); 44.9·10^{-3} (*3*). ΔP= 30.4 kPa (*1, 2*), 20.3 (*3*)

determines, with a sufficient accuracy, the initial value η_0 of the non-perturbed liquid. As is seen, the experimental points of the SC-flow dependence $1/v = f(l_{\rm cap})$ (Fig. 2, curve *1*) are situated beneath the corresponding hydrostatic-flow points (Fig. 2, curve *2*). Therefore, we can affirm unambiguously that the mean velocity of a liquid flowing along the capillary is much higher, after a momentary cavitation action, than the velocity without such an action. That is, in the case of viscous oil solution, local cavitation action at the capillary end induces a decrease of the liquid viscosity, as was expected.

The results of similar investigations on glycerin-in-water solutions of various concentrations are shown in Fig. 3. Values of the initial viscosity η_0 of the used solutions equal 16.8·10^{-3}, 23.6·10^{-3}, and 44.9·10^{-3} Pa·s. It is seen that, in spite of the solution molecules' structure change and the viscosity values involved, the rheological curves $1/v = f(l_{\rm cap})$ repeat characteristic features of the curve *1*, Fig. 2. All the curves are nonlinear and are well-below situated on the graph as compared with the linear ones characterizing the liquid flow caused by the equivalent hydrostatic pressure difference ΔP. Thus, for all the solutions employed, a viscosity decrease takes place after the cavitation is excited at the capillary end; as a result of the SC effect action, a liquid flows through the capillary that essentially differs in its viscosity from the rest of liquid in the ultrasound bath.

2.3. Non-linearity of the $1/v = f(l_{\rm cap})$ curves (Figs. 2 and 3) means that the viscosity decrease is not irreversible, and the viscosity of the liquid passing through the capillary gradually relaxes to its initial value. Liquids with viscosity values between 40 and 100 Pa·s, by passing through a capillary of between 0.3 and 0.7 mm diameter, possess the Reynolds' number of about unity and the flow of such solutions is laminar. Let us issue from the supposition of a gradual variation of viscosity of the liquid inside the capillary and let us assume that the feature of laminarity is retained. Then the complete capillary length can be broken into elements dl on which their viscosity values are considered to be constant. The following pressure difference is formed on each of the dl elements:

$$dP = \frac{8v\eta(l)dl}{R^2_{\rm cap}}, \qquad (3)$$

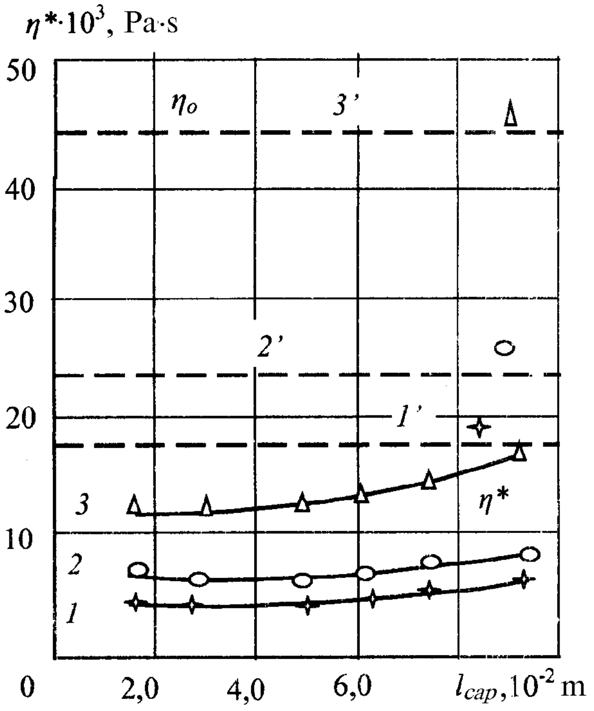

Fig. 4. Influence of capillary length on average viscosity of glycerin solutions. The used symbols correspond to those of Fig. 3

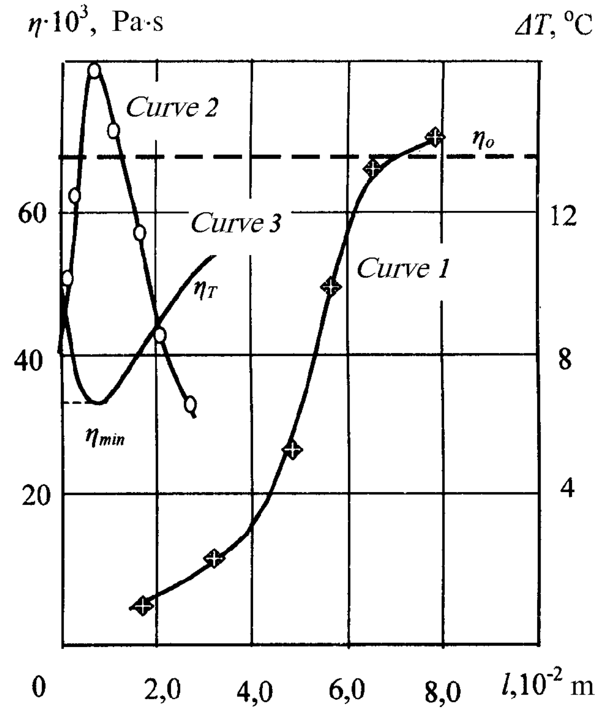

Fig. 5. In-channel variation of viscosity η (*1*), overheating ΔT (*2*), and corresponding η_T value for castor oil solution

and the complete pressure difference $\Delta P = P_{\text{SC}} - P$ that is formed along the total capillary length and measured in the experiment, could be obtained by integration

$$\Delta P = \frac{8v}{R_{\text{cap}}^2}\int\limits_0^{l_{\text{cap}}} \eta(l)dl = \frac{8v}{R_{\text{cap}}^2}\eta^* l_{\text{cap}}. \tag{4}$$

The latter equation is written in supposition that the in-capillary liquid is characterized by some average viscosity η^* satisfying the following equation:

$$\int\limits_0^{l_{\text{cap}}} \eta(l)dl = \eta^* l_{\text{cap}}. \tag{5}$$

If we rewrite relation (4) in the form of Eq. (2), then it could be seen that the average viscosity η^* over a certain capillary length may be found from the experimental curves $1/v = f(l_{\text{cap}})$ (Figs. 2 and 3) by determining a tangent of inclination of the secant drawn from the coordinate origin to the corresponding point of the curve. In Fig. 2, secants of the dependence $1/v = f(l_{\text{cap}})$ are shown that have been used for determination of the η^* parameter characterizing the castor oil/DBF solution; in this figure, the obtained average viscosity values η^* for capillaries of various lengths are shown as well. For comparison, the graph shows (dotted line) initial viscosity values η_0 for a liquid, which did not undergo the cavitation action. As seen, the viscosity diminution effect is more manifested for the shorter capillaries.

A similar technique was used for the determination of average viscosity of the glycerin solutions, and the corresponding results are shown in Fig. 4. It is seen that the average viscosity value η^* is by several times less as compared with viscosity η_0 for the non-perturbed liquid, as well as for the oil solution. It is characteristic that the solution of maximal concentration, whose viscosity ($44.9\cdot 10^{-3}$ Pa·s) only slightly differs from that of the oil-like liquid ($69\cdot 10^{-3}$ Pa·s), is described by dependence $\eta^*(l_{\text{cap}})$ (curve *3*, Fig. 4) which repeats the shape of the corresponding curve *3* of Fig. 2: the least viscosity value is observed for the shortest capillaries, and the η^* parameter increases with elongation of a capillary. For less concentrated solutions, a weak viscosity depression is observed on short capillaries with subsequent, quite slow, relaxation to the initial value of η_0. These specific effects need to be investigated in more details, but they not affect the main conclusion that the local cavitation action at the capillary end leads to a stable viscosity diminution of a liquid flowing through the capillary channel.

Note that curve *3* of Fig. 5 and curves *1, 2*, and *3* of Fig. 4 demonstrate the dependence of average viscosity η^* on the capillary length l_{cap} and are not immediate characteristics of molecular viscosity variation along the capillary channel. But these are the curves important in development of actual SC-effect-based liquid-pumping devices. In addition, shape of the curves is a witness of the fact of viscosity diminution at the capillary end, where the cavitation process is excited. The longer the capillary, the weaker the influence of the active region on the average viscosity value. Nevertheless, this influence should not be neglected for all the capillaries used: as it is seen, the average viscosity slowly increases and then relaxes approaching the table value. But even for the longest 10 cm capillary the viscosity value not reaches the table value. It should be stressed that the relaxation to the initial viscosity values of the glycerin solutions goes too slowly, and even for the longest capillaries, the η^* parameter remains to be for several time smaller as compared to the initial value η_0.

3. Discussion

3.1. Let us consider physical effects of the cavitation nature which may affect the viscosity of liquid. As was already mentioned, one of such effects is the decomposition of molecules and the diminution of average molecular mass of a dissolved high-molecular compound. As experiments show [5, 6], the depolymerization phenomenon manifests itself in the case if a liquid is exposed to the ultrasound action for tens of minutes (and, sometimes, up to several hours). It is significant that even such a prolonged action introduces the solution's viscosity variation that does not exceed 25 or 30 % as compared to its initial value. One more specific feature of the cavitation depolymerization is its irreversibility, i.e. after the cavitation process is decayed, the initial properties of a liquid not restored in full.

The process investigated in this work may be naturally broken into two successive phases: i) the diminution of viscosity of the liquid during its passage through the cavitation-perturbed area, and ii) the partial relaxation of viscosity to its initial value during the liquid flow through the capillary. With using the experimental values of the liquid flow velocity, the characteristic time parameters have been determined. The cavitation zone length does not exceed 5 mm, and any liquid volume passing through it with the average velocity of (0.40 – 0.02) m/s, experiences the cavitation action during a time period of $\tau_{\text{cav}} \approx 0.2$ s which corresponds to the least velocity of the ones obtained from the castor-oil/DBF experiment. (In the case of the glycerin solutions, the τ_{cav} parameter is of even less value.) In such conditions, in short capillaries, the oil solution viscosity decreases by almost 10 times as compared to its initial value η_0 (in contrast with tens of percents as it takes place in the above mentioned experiments [5, 6]). Basing on the flow-velocity values, and using the data of Figs. 2 and 3, conclusions could also be made on the relaxation time τ_r of viscosity to its initial value. For the castor-oil/DBF solution, this value constitutes 0.75 s, whereas it exceeds 3 s in the case of glycerin/water solutions. Therefore, the decomposition of a small part of molecules, even if it takes place, does not play a noticeable role in the observed effect of viscosity reduction.

Let us also draw attention to the fact of similarity between the rheological curves $1/v = f(l_{\text{cap}})$ and the dependences $\eta^*(l_{\text{cap}})$ for the solutions of castor oil and glycerin, although the glycerin/water solutions do not belong to high-molecular compounds, and as such they do not subject to the destructive role of cavitation.

3.2. On the other hand, it is well known that viscosity of liquids substantially depends on their temperature. Exact localization of the cavitation medium beneath the capillary channel is a specific characteristic of the SC effect, and the capillary-confined volume of a liquid, along a certain capillary portion, is of the same value of magnitude as the volume of a cavitation cloud. Therefore, the local heating of the in-capillary liquid close to the cavitation area [12] is the manifestation of cavitation action that is a characteristic feature of the SC effect. Thus, it is naturally to suppose that this is the thermal effect that is a cause of the diminution of viscosity of the in-capillary liquid.

In analysis of the role of thermal effects, the dependence $\eta(l)$ that characterizes the molecular viscosity variation along the capillary is more useful rather than the average viscosity η^*. If we recur to Eq. (5) determining the average viscosity, we could see that it includes the integral with a variable upper limit. Derivative of such an integral with respect to its upper limit is equal to a value of integrand with its argument being equal to the upper limit [13]. So, we can write in this case:

$$\frac{d}{dl_{\text{cap}}}(\eta^* l_{\text{cap}}) = \eta(l) \quad \text{for} \quad l = l_{\text{cap}}. \tag{6}$$

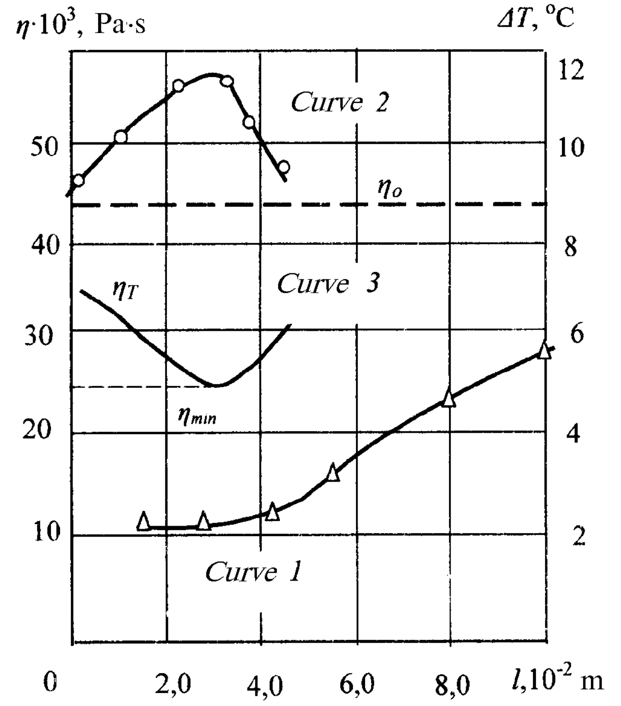

Fig. 6. The same as in Fig.5 for glycerin solution ($\eta_0 = 44.9$ Pa·s)

If we rewrite Eq. (4) in the form

$$\frac{1}{v} = \frac{8}{(P_{\rm SC} - P)R^2_{\rm cap}} \int\limits_0^{l_{\rm cap}} \eta(l)dl, \tag{7}$$

then it is seen that one can obtain the relaxation curves $\eta(l)$ by means of graphic differentiation of the dependences $1/v = f(l_{\rm cap})$ (shown by curve *1*, Fig. 2, and curves *1, 2*, and *3*, Fig. 3).

Results of the graphic differentiation are shown in Fig. 5, curve *1*, for the castor-oil/DBF solution, and in Fig. 6, curve *1*, for the glycerin/water solution of an initial viscosity of $44.9 \cdot 10^{-3}$ Pa·s. As seen, for both the solutions, the viscosity is minimal in the area close to the capillary end, where the steady-state cavitation cloud is formed. Therefore, a conclusion could be made that this is the cavitation process excited at the capillary end that is a cause of the viscosity diminution. The process of liquid flow and distancing every liquid volume from the active area lead to increase of the liquid viscosity η and to its approaching to the initial value. But it should be stressed that the viscosity of the castor-oil/DBF solution really relaxes to its initial value at a distance of 6 to 7 cm from the excitation area. A fundamentally different situation is observed for the glycerin/water solutions. Even for the length of $l_{\rm cap} = 10$ cm, viscosity of the solutions undergone the cavitation action is much less than that of a non-perturbed liquid.

For comparison, the temperature distributions along the capillary for the solutions of castor-oil (Fig. 5, curve *2*) and glycerin (Fig. 6, curve *2*) are shown (the related investigation technique is described in detail in [12]).

On the vertical axis, the temperature difference $\Delta T = T - T_0$ is presented (the excess of temperature at a given point over the ambient temperature T_0). Zero point corresponds to the thermocouple location at the capillary end; the l axis' positive direction corresponds to a movement into the capillary interior. The temperature curve ΔT (l) for the oil solution possesses a relatively sharp peak, and the temperature is practically approaching the ambient liquid temperature T_0 on the capillary length of 30—50 mm. The glycerin solution possesses a relatively slanting maximum, and the area of maximal heating is considerably deepened into the capillary channel.

In accordance with the obtained temperature distribution, curves $\eta_T(l)$ have been drawn which characterize the solutions' viscosity variation caused solely by the thermal effect (Fig. 5, curve *3*, for the castor-oil/DBF solution; and Fig. 6, curve *3*, for the glycerin/water solution with the initial viscosity of $44.9 \cdot 10^{-3}$ Pa·s). It is obvious that both the curves possess a characteristic minimum corresponding to the peak temperature value. It should be stressed that the minimal value of viscosity for both the solutions, $\eta_{\rm min}$, which is determined by a local heating inside the capillary, also exceeds noticeably the average value η^* for short capillaries and the local values $\eta(l)$ obtained by the graphical differentiation. Hence, the thermal effect could be considered as a probable cause of the liquid viscosity diminution inside the capillary, but it could not be a unique cause of viscosity diminution to the above-mentioned values observed in reality.

3.3. Thus, the influence of the cavitation process on a liquid is not restricted by its local heating only; the structure of the liquid is also affected immediately (for example, here a decomposition of supermolecular structures takes place which, in fact, determine the viscosity of a liquid). As an example of such a supermolecular structure, associated complexes (solvates) may be considered. These substances were investigated in solutions of various types, possessing various physicochemical nature of their intermolecular interaction and, correspondingly, various binding energy [14]. Peculiarities of these complexes have been investigated in detail for the case of electrolytic solutions in which a solvation of separate ions takes place.

Glycerin and its water solutions are not electrolytes but these are rather structured liquids: the solvation occurs in non-electrolytic liquids as well, but structure of solvate complexes and their intermolecular binding energy are of different nature in contrast with solvated ions [14]. Formation of solvates in a liquid affects the temperature-dependent behavior of the viscosity of a solution in contrast with that of a pure liquid [15, p. 150], namely

$$\eta(T) = BT \exp \frac{W + \Delta W}{kT}, \tag{8}$$

where W is the activation energy of the viscous flow of a solvent; ΔW — the additional energy (change of the potential barrier of molecules, according to the terminology of [15]), determined by the formation of solvates; k — Boltzmann constant, T — absolute temperature of the liquid; and B — constant parameter characterizing a given solution.

For the solutions used, the viscosity-vs-temperature dependence was measured without excitation of ultrasound vibrations. The measurements showed that the dependence $\ln(\eta) = f(1/T)$ is, within the accuracy limits, highly linear in the temperature range of (15—90) °C. Thus, to analyze the results, we have employed the simplest Arrhenius formula, which is most frequently used for a narrow temperature range [16, p. 119]:

$$\eta(T) = A \exp \frac{W_0}{kT}. \tag{9}$$

Here, it is accepted that $W_0 = W + \Delta W$, with ΔW being a part of the activation energy connected with interaction between molecules of the solvent and the dissolved substance, and with formation of the associated complexes.

The cavitation action manifests itself, firstly, by a local heating of liquid in the neighboring region, and, secondly, by a partial decomposition of the associated complexes as a result of gaining the additional energy W_{US} by molecules of the liquid. Such a cavitation impact can be analytically represented as a diminution of the viscous flow's activation energy by the value of W_{US}, i.e. $W = W_0 - W_{\text{US}}$, and expression (9) takes a form

$$\eta_{\text{US}}(T) = A \exp \frac{W_0 - W_{\text{US}}}{kT}. \tag{10}$$

Note that the similar approach was used in the consideration of electric conductivity of liquids in strong electric fields [16], and Eq. (10) is analogous in its structure to the temperature dependence of specific resistance for a dielectric liquid to which a high potential difference is applied. To determine the energy addition W_{US}, the following system of equations had been formed:

$$\eta_0 = A \exp \left(\frac{W_0}{kT_0} \right),$$

$$\eta_{\text{US}} = A \exp \left(\frac{W_0 - W_{\text{US}}}{kT} \right), \tag{11}$$

where T_0 and T denote temperatures of, respectively, the surrounding non-perturbed liquid and the cavitation-undergone liquid. Values of the W_0 parameter for liquids of various concentrations, quoted in the Table, were determined from the corresponding temperature dependences $\ln(\eta) = f(1/T)$ measured in the absence of ultrasound vibrations. Values of the W_{US} parameter characterize the influence of cavitation on the average energy of molecules of the solution; these were obtained from Eqs. (11). It is typical that diminution of the glycerin concentration and initial viscosity of liquid leads to augmentation of the W_{US} parameter, i.e. the efficiency of cavitation influence on the liquid structure increases. Resolving the system of equations (11) for the castor-oil/DBF solution gives $W_{\text{US}} = 0.259 \cdot 10^{-20}$ J (note that $W_0 = 0.259 \cdot 10^{-20}$ J). This energy is evidently insufficient for breaking the bond of —C—C—. Such a breaking corresponds to the molecules' decomposition and depolymerization. The value of the added part of activation energy ΔW , occurring as a result of ions' solvation in electrolytic solutions falls into the range of $(1.8 \div 0.17) \cdot 10^{-20}$ J depending on the ions type [15, p. 151]. As seen, the determined parameters W_{US} are of the same order of magnitude. This is an argument in favor of the approach proposed: the power of the local cavitation action may be found to be sufficient for partial decomposition of the associated over-molecular structures, thus influencing the viscosity of the investigated solutions.

3.4. The formulated conclusions are based upon the experimental results obtained by a Poiseuille-formula-based technique. This, in fact, stipulates that in the capillary, there is a Poiseuille-type velocity profile, and the edge effects could be neglected. According to estimations of monograph [17], the length of the capillary-end section, along which there occurs a

Concentration of solutions, %	η_0, Pa·s	W_0, J	η, Pa·s	W_{US}, J
65	$16.8 \cdot 10^{-3}$	$5.25 \cdot 10^{-20}$	$5.4 \cdot 10^{-3}$	$0.323 \cdot 10^{-20}$
70	$23.6 \cdot 10^{-3}$	$5.92 \cdot 10^{-20}$	$7.9 \cdot 10^{-3}$	$0.267 \cdot 10^{-20}$
78	$44.9 \cdot 10^{-3}$	$6.31 \cdot 10^{-20}$	$11.1 \cdot 10^{-3}$	$0.243 \cdot 10^{-20}$

formation of the Poiseuille profile, equals $\delta \approx (0.1 - 1.0)\,\mathrm{Re}\,R_{\mathrm{cap}}$. For the distilled water $\mathrm{Re} \approx 500$, this length equals 3.5 cm, i.e. it exceeds the length of capillaries investigated in this work. Liquids possessing viscosity values between 40 and 100 Pa·s have the Reynolds number about unity, and the parameter $\delta \approx 0.5$ mm. This value is considerably less than the shortest length of the used capillaries; therefore, the employment of this capillary viscosimetry method is correct for the castor-oil/DBF and viscous glycerin solutions. For solutions with viscosity of (15—20) Pa·s, the inlet-end length of the capillary, where the Poiseuille profile formation takes place, is larger but does not exceed the value of $\delta \approx 2$ mm. Thus, the chosen range of capillary diameters and viscosity values of the investigated liquids could be considered as optimal. Employment of shorter capillaries or less viscous liquids, from our point of view, is inexpedient.

Conclusions

1. The SC effect could serve as a basis for investigations of properties of the cavitation-perturbed liquid, because of exact localization of the cavitation process beneath the capillary channel; this allows the separation of a liquid undergone a short-term cavitation influence and its through-capillary removal from the ambient non-perturbed liquid.
2. Excitation of the cavitation process initiates: i) local heating of the liquid; because of this, temperature of liquid in the capillary is higher as compared to a liquid filling the ultrasound bath, ii) decomposition of the over-molecular complexes formed in the solutions and determining their viscosity. Both the factors cause the diminution of viscosity inside a capillary as compared with viscosity of the ambient non-perturbed liquid.
3. For the liquids investigated, the viscosity-reduction effect is a reversible one; moreover, a partial or complete relaxation of the viscosity to its initial value could be observed along the capillary length.
4. The phenomenon revealed is of significance from the point of view of cavitation physics, because both the dynamics of a separate cavity and the cavitation cloud development are fundamentally defined by viscosity of a liquid. Results of the work should be taken into account in the design of efficient pumping devices whose operation principle is based upon the sonocapillary flow of a liquid.

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ДО ПИТАННЯ ПРО ЗМІНУ ВЛАСТИВОСТЕЙ РІДИНИ ВНАСЛІДОК ЗБУДЖЕННЯ КАВІТАЦІЙНОГО ПРОЦЕСУ

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Резюме

Проведено експериментальні дослідження впливу кавітаційного процесу на в'язкість рідини. Вперше кавітаційний режим звукокапілярного ефекту використано як метод дослідження властивостей рідини в ультразвуковому полі. Показано, що наслідком короткочасної кавітаційної дії є зменшення в'язкості рідини у декілька разів. Ефект має оборотний характер і на довжині капіляра відбувається часткова або повна релаксація в'язкості до початкового значення. Аналізуються можливі причини спостережуваного явища: локальний розігрів рідини, часткове руйнування її надмолекулярної структури.