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INFLUENCE OF LIQUID GLASS CHARACTERISTICS ON QUALITY OF COATING FORMATION OF WELDING ELECTRODES

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The viscosity of 6 % dispersions of Na-CMC in liquid Na- and K-glasses depending on temperature, as well as viscosity of pure liquid Na, K- and NaK-glasses depending on excess pressure and temperature was studied. Each of them represents a consistent medium of real electrode coating mixtures. With the use of the obtained results by mathematical methods, the functioning of the model of a joint effect of excess pressure and dissipative heating on viscosity, velocity profile and stability of pressure flow of electrode coating mixtures in the step channel under the conditions of coating formation by extrusion deposition on steel bars was verified. Although two competing sources of change in shear viscosity of the coating mass (temperature and pressure) are available, the calculations did not reveal situations with unstable (pulsating) flow modes through a suddenly narrowing channel, which could cause instability of the coating mixture flow and, therefore, electrode coatings with a thickness variation. At least, they were not revealed in the studied range of capillary sizes $L/R_k < 10$ and pressures, at which the electrodes are actually pressed. 10 Ref., 1 Table, 8 Figures.

Keywords: *arc welding, coated electrodes, production technology, coating thickness variation, rheology, viscoelasticity of coatings*

Variable coating thickness is the most dangerous defect of coated electrodes in fusion arc welding. It deteriorates technological characteristics of welding process, weld quality and reduces the operational reliability of products manufactured by welding.

Variable coating thickness occurs while manufacturing electrodes by extrusion deposition of a paste coating transformed into a high-gradient nonisothermal pressure flow in the forming head of the electrode extrusion press on steel rods with a layer of a circumferential cross-section. The speed of process is up to 800 electrodes with a rod diameter from 2 to 6 mm per minute, each from 250 to 450 mm length. The forming pressure on the mass P is up to 80 MPa. As a result of dissipative heating, the surface of the coating sheath at the outlet from the die can reach 90–100 °C.

Due to the reasons that have not yet been fully clarified, the pressure flow of the coating suddenly transfers to the mode of elastic turbulence. Interacting in this state with the elastic metal core located inside the flow, the coating covers it with a nonuniform layer. In this case, the channel between the core and the calibration bushing is overcome by the filling mixture and the energy consumption is as lower, as the more it differs from the symmetrical circumferential configuration, although the total cross-sectional area of the channel remains unchanged.

The rheological characteristics of electrode coating masses, as well as other extrusion-formed paste materials, in the state of pressure flow are determined by the gradients of the rate of shear γ, longitudinal ε, and circulating (rotational) deformation ω.

The natural convergent zone directly adjacent to the flat inlet of the calibration channel in the head of the electrode extrusion press or capillary viscosimeter is formed by a mutual competition between the shear and longitudinal deformation [1]. It acquires a narrowing profile that minimizes the energy consumption for overcoming resistance to shear (with viscosity η) and longitudinal flow (with viscosity λ) by the flow.

The value of the effective shear viscosity in this state depends, first of all, on the degree of destruction of its coagulation structure. The higher the stress or shear rate, the more the structure is destroyed and the lower the viscosity of the coating. The effect of temperature and excess pressure in the channel is taken into account by adjusting the activation energy of viscous flow α, and, accordingly, the piezoelectric effects and the coefficient β. The combined effect of temperature T and excess pressure P on the effective

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shear viscosity of non-Newtonian polymeric fluids is calculated according to the formula [2]:

$$\eta = \eta_0 e^{-\alpha\Delta T}\eta_0 e^{-\beta\Delta P}. \qquad (1)$$

From the formula (1) it follows that the value of viscosity decreases with an increase in temperature, and grows with an increase in pressure.

According to our data, the viscosity of liquid glass suspensions of CMC and liquid glasses, on the base of which they are composed, decreases with an increase both in temperature and pressure. And the latter, according to our data, is increased at least within the limits not exceeding the values at which the electrodes are crimped. At higher pressures, the viscosity of liquid glasses like in many other liquids increases [3].

It is known that an effective viscosity of the vast majority of suspensions is unambiguously proportional to the viscosity of the dispersed medium, and their activation energies and baric viscosity coefficients are the same, even when the viscosity of the former ones exceeds the viscosity of the latter by hundreds and thousands of times [4]. In this regard, we used liquid glasses and their 6 % Na-CMC dispersions as rheological models of electrode coating mixtures in evaluation of the effect of heating and excess pressure on them.

In the present article, the results of our investigations on the joint role of effective, temperature and baric viscosity as a possible source of rheological instability of coating mixtures under the conditions of a shear deformation are presented.

Effect of temperature, stress and strain rate on shear viscosity of liquid glass suspensions of Na-CMC. In Figure 1 the viscosity polytherms of liquid glass suspensions of Na-CMC are compared, which are produced using a rotary viscometer Reotest II.

It is seen that η of liquid-glass dispersions of CMC in the temperature range to which the coating mixture spontaneously heats up during the process of deposition on the electrode rods, represents an exponential function of temperature $\eta(T) = \eta_0 e^{\alpha_{(\dot\gamma,\tau)}/RT}$ and simultaneously the velocity $\dot\gamma$ and the shearing stress τ. Figure 1, *a*, *b*, the values of $\dot\gamma$ (curves *1* and *2*) amount to 1 and 100 s^{-1}, respectively.

At the «c» position, they are denoted by nominal values of $\dot\gamma$ in the range from 0.8 to 175 s^{-1} and located along the viscosity polytherms. As we see, as the temperature increases, the viscosity of the suspensions really decreases, and its extent is as greater, the higher $\dot\gamma$ and τ, as well as the more sensitive the structure of the test material to thermal and mechanical fracture. In the flow modes $\dot\gamma$ = const and τ = const, potassium modifications of glasses and suspensions of Na-CMC based on them are characterized by a higher activation energy than sodium ones, which, according to [5], can be represented as

$$\alpha_\tau > \dot\gamma\frac{\alpha_\tau}{\alpha_{\dot\gamma}} = 1 - \dot\gamma\left(\frac{\eta}{\tau}\right)_T; \qquad (2)$$

$$\alpha_\tau = \frac{d\ln\eta}{d(T^{-1})}\ \text{at}\ \tau = \text{const};$$
$$\alpha_{\dot\gamma} = \frac{d\ln\eta}{d(T^{-1})}\ \text{at}\ \dot\gamma = \text{const}. \qquad (3)$$

Effect of excess pressure on viscosity of liquid glass. The effect of excess pressure on the viscosity of liquid Na-, K-, and combined NaK-liquid glasses is shown in Figure 2.

As follows from the abovementioned data, the nature of the baric changes in the viscosity of liquid glasses can, in principle, be represented by the power function $\eta(P) = \eta_0(1 - P)^2$. Depending on the composition and concentration of the liquid glass, its di-

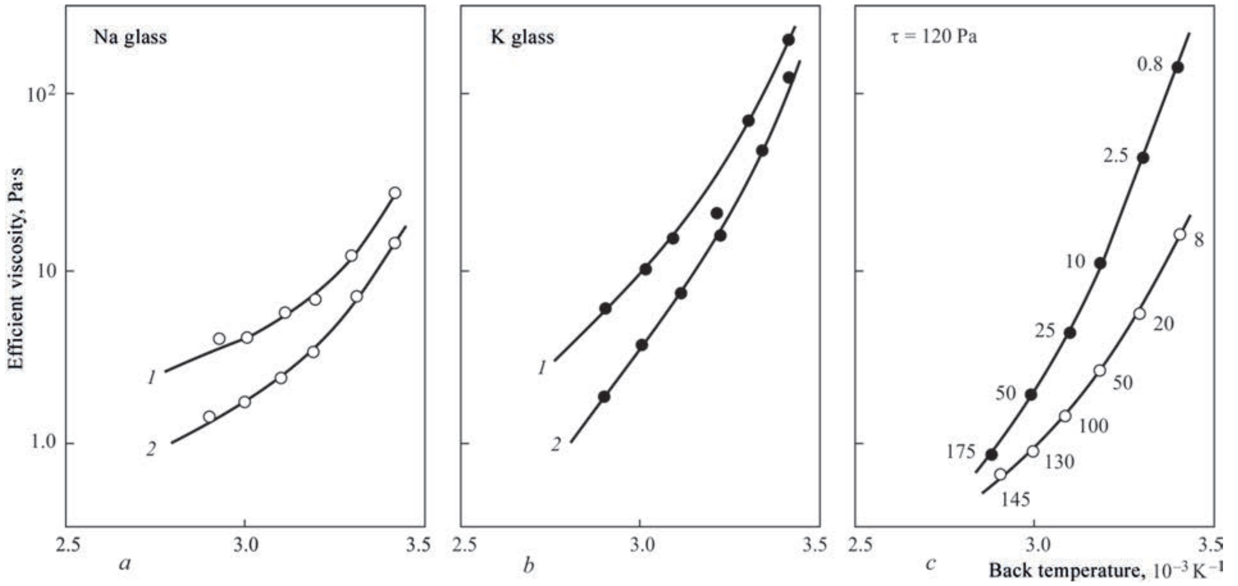

Figure 1. Viscosity polytherms of 6 % dispersions of CMC of grade 72/470 in liquid Na- and K-glass with M = 2.9. Flow mode: $\dot\gamma$ = = const (*a*, *b*) and τ = const (*c*). See the rest of the symbols in the text

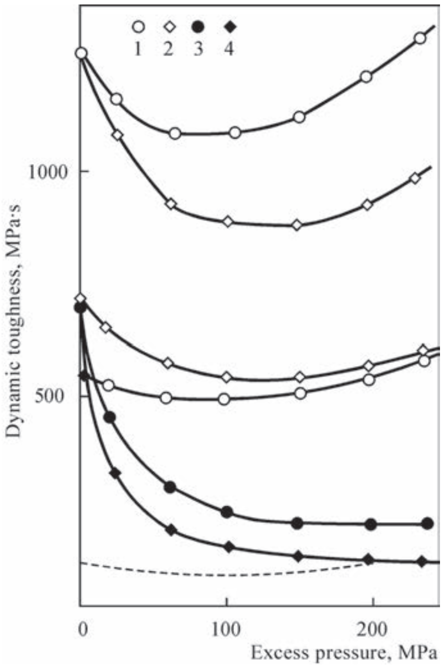

Figure 2. Effect of excess pressure on viscosity of Na (1), NaK (2) and K (3) liquid glasses with a modulus of 2.9, as well as NaK (4) liquid glass with M = 3.4; initial viscosity of glasses is 500, 700 and 1250 mPa·s [3]

agram takes the form of either a complete parabola or its left or right branch within the pressure range we use. In low-viscosity liquid glasses, the parabola degenerates into a straight line.

In liquid glasses, which to a greater or lesser extent reacted to the increase in pressure, the diagrams η(*P*) have an extreme rather than a monotonically incrementing form, as in the case of polymeric objects. The greatest decrease in viscosity is mostly observed in the values of pressures, which are usually not recommended to be exceeded while crimping electrodes.

The parabolic form η = *f*(*P*) was revealed in liquid 2.9NaK- and 2.9Na-glasses with a viscosity of 1250 mPa·s. At the first glass the minimum of viscosity and the left asymmetry of the parabola are more brightly expressed, at the second one — the left asymmetry of the parabola at a smaller minimum of viscosity.

As the viscosity of the compared glasses decreases to 570–500 mPa·s, the extremity of the η = *f*(*P*) curves decreased significantly, but the shape of asymmetry remained the same. When the viscosity of the glasses is reduced to 100 mPa·s, the extremity and asymmetry of curves are completely degenerated (in Figure 2 they are presented by a dotted line).

From the technological point of view, the most favourable form of the curves is η = *f*(*P*), which was revealed in potassium and sodium-potassium liquid glasses with values of modulus of 3.0 and 3.3, respectively, because from the technological point of view they do not have a dangerous ascending parabolic branch.

Since the baric viscosity of liquid glasses was measured in our experiments with a Heppler viscosimeter, the obtained results cannot be graded by τ and $\dot{\gamma}$. Taking into account that the course of the baric dependence η(*P*) in principle coincides with the temperature change in the viscosity η(*T*), the baric viscosity coefficients by analogy with the activation ones can be represented as [5]:

$$\beta_{\dot{\gamma}} = \frac{1}{\eta}\left(\frac{\eta}{P}\right)_{\dot{\gamma},T} = \frac{1}{\tau}\left(\frac{\tau}{P}\right)_{\dot{\gamma},T}, \qquad (4)$$

and their correlation in the form

$$\beta_{\tau} = \frac{\tau}{\dot{\gamma}}\frac{\gamma}{\tau}\beta_{\dot{\gamma}} = \frac{d\ln\dot{\gamma}}{d\ln\tau}\beta_{\dot{\gamma}} \qquad (5)$$

Moreover $\beta_{\tau} \geq \beta_{\dot{\gamma}}$, as far as $\frac{d\ln\dot{\gamma}}{d\ln\tau} \geq 1$.

The higher the temperature, velocity and shear stresses, the lower the values of the piezoelectric coefficients [5].

Let us note that to identify the conditions, under which the values of viscosity P_0 and other rheological characteristics are obtained, along with the consistent variables τ and $\dot{\gamma}$, the mode symbols of the pressure-flow characteristics *Q* and *P* are used.

The decrease in viscosity under the influence of excess pressure and temperature is most likely caused by the destruction of relatively weak structural bonds in the liquid glass. Moreover, these are those bonds that are formed by the structural elements of silicon-oxygen anions (SOA), and not the solvent.

Indeed, to the effect of pressure the viscosity of potassium and high-modulus potassium-sodium liquid glasses is mostly subjected. According to the concepts of the polyelectrolytic nature of aqueous solutions of alkaline silicates, the structure of namely such liquid glasses, as a rule, is formed by weak, chaotic and synergistic bonds.

The structures themselves belong to the cluster type, which determines their low resistance to mechanical, activation and baric destruction [6, 7].

In terms of effect on the structure of objects, the comparable types of influence can be considered almost equal to each other. This agrees with the results of an experimental evaluation of the effect of pressure and temperature on viscosity, which are shown in Figures 3 and 4.

On the other hand, this is agreed with the strength of the structural bonds of Q^n_i, which were revealed in the structure of SOA of liquid K-, as well as high-modulus NaK-glasses by the method of MRS spectroscopy. The total fraction of elastic bonds ($Q^2 + Q^3$) prevails in the structure of SOA of potassium M = 3.65 (76.5 %) and combined NaK M = 3.15 liquid glasses (78.5 %). The minimum fraction of the hardest siloxane bonds Q^4 is revealed in the SOA structure of combined liquid NaK (11.5 %), the intermediate fraction is in LiNa (22.5 %), and the maximum is in LiK modifications (27.0 %), containing about 30 mol.% of the accompanying component. As a rule, the same glasses also showed the highest synergistic growth in viscosity [8].

Combined effect of pressure and temperature on pressure flow of electrode coating mixtures in a suddenly narrowing channel. The combined effect on the nature of flow of the coating mixture of two factors — excess pressure and temperature, was investigated using mathematical modeling. The flow and heat transfer of a viscous fluid in a cylindrical channel with a sudden narrowing were analyzed. The system of equations of movement and heat balance was solved numerically applying the finite difference method [9]. To evaluate the technological properties of the coating mixture, the following ratio was used

$$\eta(T, P) = \eta_0\varphi(T)\psi(P), \qquad (6)$$

where η_0 is the viscosity at a room temperature and atmospheric pressure.

The temperature decrease in viscosity was considered as the coefficient

$$\varphi(T) = A \exp (B/T), \qquad (7)$$

and the baric changes were considered by the power law (by the square trinomial):

$$\psi(P) = \left[1 - 5.7\left(\frac{P}{10^9}\right) + \left(\frac{P}{10^9}\right)^2\right], \qquad (8)$$

where A is a pre-exponential factor; B is the activation energy of viscous flow.

The accepted rheological correlation (6) allows obtaining pressure drops in the channel from 20 MPa at a flow rate of 1 l/min to 170 MPa at a flow rate of 10 l/min.

The flow region was modeled by coupling a cylindrical tank (supply cylinder) and the capillary with a ratio of diameters $D_R/d_k > 5$, at which the steric effect is absent, i.e. the nature of the flow in the capillary is independent of the flow in the tank. The dimension of the used computational grid (15×15 in the tank and 8×6 in the capillary) was chosen for the reasons of combining an acceptable accuracy and economy of calculations. The consumption of the coating mixture was taken equal to 10 l/min: in this case, the real conditions of the flow are simulated, under which in the capillary a section of both decreasing and increasing viscosity of liquid glass is realized [3]. A series of numerical experiments demonstrated the role of each of the mentioned factors (temperature and pressure drop) in the formation of a flow in the capillary. The calculations show that the main part of the pressure drop in the channel with a sudden narrowing is formed in the capillary.

The dependence of viscosity on temperature increases the nonuniformity of viscosity and temperature fields both in the radial and also in the longitudinal section of the capillary. The pattern for distribution of viscosity in the capillary at a fixed flow rate is shown in Figure 5. Heating of the near-wall layer due to the dissipative factor is accompanied by the outflow of material from the central zone. However, neither the change in the velocity field, nor the temperature significantly (not more than 0.5 %) affects the radial pressure distribution. Dissipative heating of the material grows with an increase in the flow rate (Figure 6). However, in this case, the heated layer does not propagate into the flow core. The revealed regularities are agreed with the experimentally observed «plug» flow mode through the calibrating bushing. However, in real conditions, the recorded viscous heating temperature in the near-wall layer is twice higher than its calculated value.

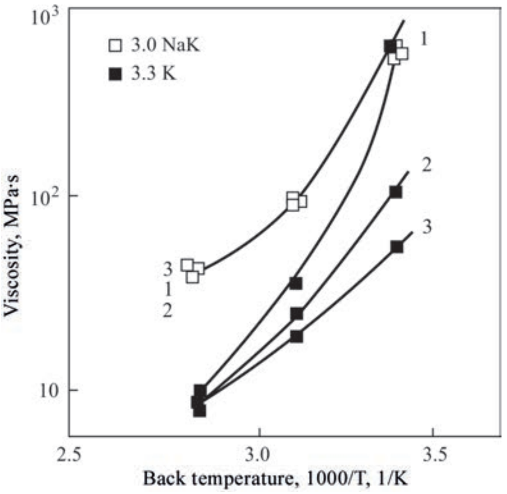

Figure 3. Combined effect of temperature and pressure on viscosity of K (M = 3.3) and NaK (M = 3.0) liquid glass with a viscosity of 700 mPa·s: 1, 2, 3 — atmospheric and excess pressure of 10 and 20 MPa [3]

A different pattern is observed when modeling a flow, the viscosity of which depends only on the increase in pressure. In this case, as follows from the calculations, the viscosity changes only along the capillary, while along its cross-section it remains unchanged.

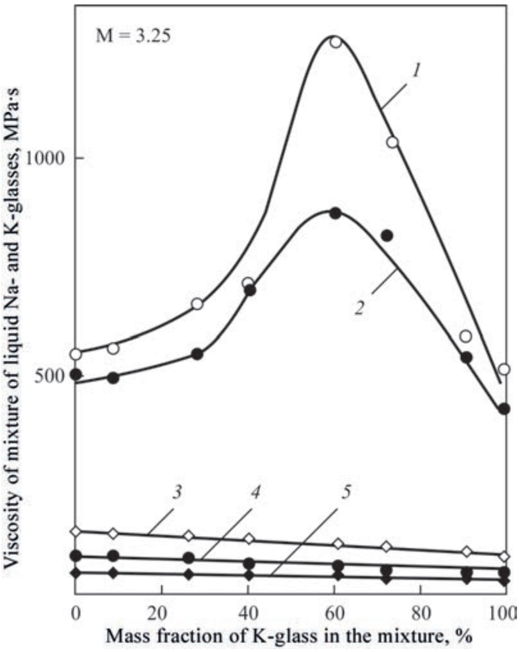

Figure 4. Dependence of viscosity of binary liquid Na- and K-glasses immediately after mixing (*1*) and after thermostating at a temperature of 20 (*2*), 40 (*3*), 60 (*4*) and 80 °C (*5*)

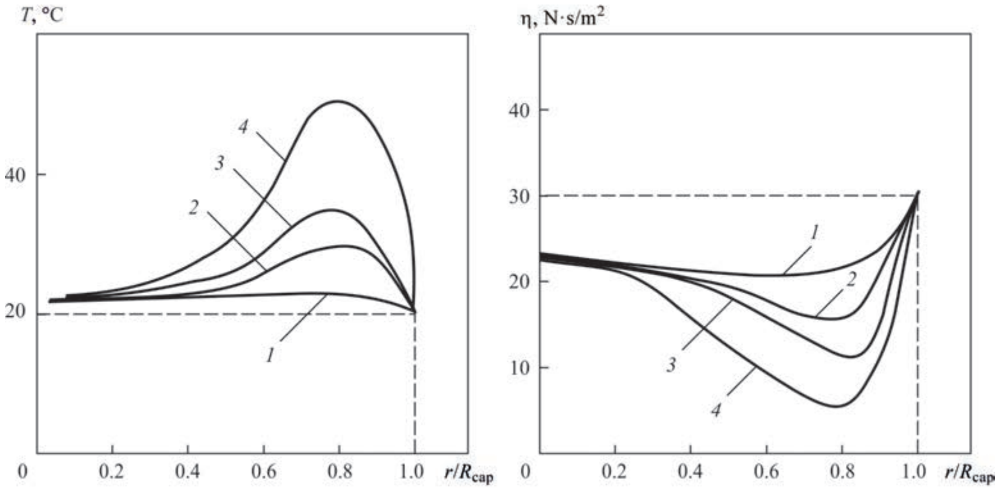

Figure 5. Temperature (*a*) and viscosity (*b*) field in the capillary. Distance from the capillary inlet l/L_{cap}: 0 (*1*), 2 (*2*), 4 (*3*) and 15 (*4*). $Q = 1.67\cdot10^{-4}\cdot m^3\cdot s^{-1}$

In Figure 7 the pressure distribution along the channel for the extruded mass with Newtonian properties (*1*), mass with baric (*2*) and thermosensitive viscosity (*3*) are compared.

Here the curves *1* and *2* refer to the Newtonian and baric viscosity, respectively. It is seen that, in general, the pressure drop for a liquid with a baric viscosity is lower than that for a Newtonian one. Depending on the flow rate, this deviation of the liquid from the Newtonian behaviour is described by an extreme law, and the maximum decrease in pressure falls on the flow rate approximately equal to $8.0\cdot10^{-5}$ $m^3\cdot s^{-1}$.

Thus, the responsibility for reducing the pressure drop in a suddenly narrowing channel mainly falls on dissipative heating. The dependence of viscosity on pressure causes an additional (much smaller) decrease in pressure at a set flow rate (Figure 8).

Despite the presence of two competing sources of decrease in the viscosity of the extruded material in the form of temperature and pressure, at least in the range $L/R_k < 10$, the calculations did not reveal situations in which unstable (pulsating) flow conditions would arise through a suddenly narrowing channel, capable of provoking a variable coating thickness during crimping of electrodes. At higher values of L/R_k, such situations can become quite expected as a result of antibatic changes, on the one hand, in the effective and temperature viscosity, and on the other, in the baric viscosity of the coating mixture.

It was experimentally found that the viscous heating of the mass in the capillary is influenced by the type of coating mixture, chemical composition, viscosity of liquid glass, proportion of alkaline hydrosilicate introduced by the glass into coating mixture, and the grain size composition of the filler. To a certain extent, this may be a consequence of the combined effect of the material composition of the coating and the characteristics of liquid glass on thermophysical characteristics of the coating masses. As follows from the data given in Table, with almost the same thermal conductivity *v*, the thermal diffusivity υ of the UONI 13/55 coating is lower, and the volumetric heat capacity р·с is higher than that of the ANO-4 coating mixture [10].

It is also important that the UONI 13/55 coating mixture, especially made on high-modulus low-vis-

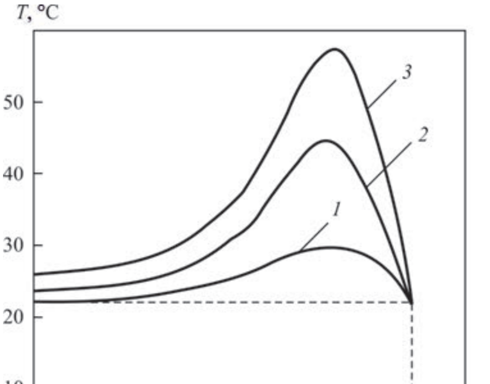

Figure 6. Temperature of coating mixture at the outlet from the capillary at a flow rate per second: *1* — $1.7\cdot10^{-5}$; *2* — $5.0\cdot10^{-5}$; *3* — $1.7\cdot10^{-4}\cdot m^3\cdot s^{-1}$; $\eta = \eta_0 A\exp(B/T)$

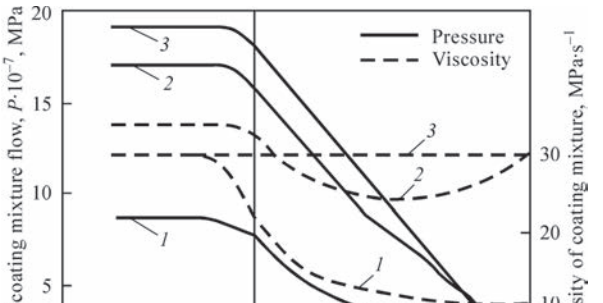

Figure 7. Distribution of pressure and viscosity of the extruded mass along the length of the capillary: *1* — Newtonian; *2* — baric; *3* — heat-sensitive coating mixture properties

Comparison of thermophysical characteristics of coating mixtures for ANO-4 and UONI 13/55 electrodes (humidity is 11.5 wt.%, room temperature) [10]

Type of electrodes	Liquid glass			λ, W/m·K	$\alpha\cdot10^7$,·m^2/s	$\rho\cdot c\cdot10^{-6}$, J/m^3·K
	Modulus	Viscosity, mPa·s	wt.%			
UONI 13/55	2.9	700	29.0	1.30–1.35 1.30	4.60–5.30 5.0	2.50–2.80 2.60
	3.2	50	19.5	1.25–1.40 1.35	2.50–3.75 3.20	3.65–5.55 4.20
ANO-4	2.9	700	29.0	0.95–1.15 1.05	5.70–10.0 7.80	0.95–1.80 1.30
	3.2	50	18.5	1.20–1.25 1.18	4.65–11.5 7.5	1.05–2.35 1.70

Note. In the numerator the minimum and maximum values and in the denominator the average of the three definitions are given.

cosity liquid glass, has a high structuredness. Some part of the energy is spent on the destruction of its coagulation structure, as a result of which its viscous heating is weakened. The restoration of the structure occurs outside the capillary and cannot affect the heat balance in the capillary.

Conclusions

1. According to the results of the carried out rheological studies of liquid glass dispersions of Na-CMC and pure Na- and K- and NaK liquid glasses, which represent a consistent medium of real coating masses, the change in their structural, activation and baric viscosity depending on strain rate, temperature and excess pressure was modeled applying the mathematical methods. The values of the latter were varied within the limits characteristic of real conditions for crimping electrodes.

2. Despite the presence of two competing sources of change in the shear viscosity of the coating mixture (temperature and pressure), the calculations did not reveal the situations with unstable (pulsating) flow modes through a suddenly narrowing channel, at least they were not revealed in the studied range $L/R_k < 10$ and pressures at which the electrodes are actually crimped. At higher values of L/R_k and pressures, such situations are quite possible as a result of the antibate change in the temperature and baric viscosity of some types of liquid glasses and coating mixture made on them: the first stops a decrease, and the second one after reaching a minimum, begins to increase at $L/R_k > 10$ and $P > 100$ MPa.

3. From the technological point of view, potassium and NaK liquid glasses, especially their high-modulus modifications, deserve preference. They provide consistency of coating mixtures, little prone to the appearance of instabilities in the state of the pressure flow, since they do not reveal a dangerous ascending branch of the parabolic dependence of viscosity on excessive pressure.

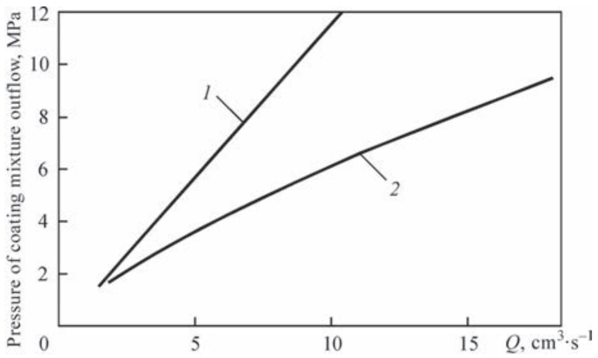

Figure 8. Flow-pressure characteristic of the Newtonian (*1*) and temperature-sensitive (*2*) coating mass: $\eta = \eta_0$ = const; *2* — $\eta = \eta_0 A\exp(B/T)$; η_0 = 30 n·s/m^2; A = 0.52; B = 65

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