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NOSTATATIONAL FLOWS OF ELASTIC STICKING FLUID IN FLAT CHANNELS

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ABSTRACT *The [1-7, 11-13] researches show that problem solving which about nonstationary flow of elastic adhesive fluid in flat channels and pipes leads to serious mathematical difficulties. Therefore simplification methods are used to solve problems , or problem [5-10] is solved on the basis of average velocities along the pipe section. In some sceintific works ([11-13]) In most cases in a nonstationary flow, fluids flowing in them, the occurrence of anomalous (non-traditional) events in the transition processes that depend on their rheological properties. In this article, specific problems of nonstationary flow of elastic viscous fluids in flat channels are solved. The main goal in this, study the motion of elastic viscous fluids on the basis of simplified mathematical models and compare the results with the laws of transition processes in a non-stationary Newtonian fluid, is to identify new hydrodynamic effects that differ from it.*

Keywords. *Elastic viscous fluids, simplified mathematical models, average velocities along, transition processes, transition processes, Newtonian fluid, Nonlinear relaxation, Laplace-Carson substitution.*

MAIN PART AND CALCULATION

Based on the rheological models of the elastic adhesive fluid proposed by Shulman in [11-13], the fluid is an elastic adhesive and incompressible, and its motion solves the problems of nonstationary flow in channels occurring in a laminar symmetrical axis. The motion of such a fluid in the canals is represented by the system of simplified equations proposed below, taking into account its rheological properties:

$$\begin{cases} \rho\dfrac{\partial u}{\partial t} = -\dfrac{\partial p}{\partial x} + \dfrac{\partial}{\partial y}\left(\tau_{xy}\right), \qquad \dfrac{\partial p}{\partial y} = 0, \\ \tau_{xy} = \sum\limits_{k=1}^{N} \tau_{k,xy}, \qquad \dfrac{\partial \tau_{k,xy}}{\partial t} + \dfrac{g_k}{\lambda_k}\tau_{k,xy} = p_k \dfrac{\partial u}{\partial y}, \\ \dfrac{\partial p_k}{\partial t} + \dfrac{g_k}{\lambda_k} p_k = \dfrac{\eta_k}{\lambda^2{}_k} f_k . \end{cases} \tag{2.1}$$

To solve the system of equations (2.1) we need to form the initial and boundary conditions. For this at $t = 0$ we assume that the fluid is in the initial “calm” state, that is

$$t = 0 \ \partial a \ \ u = 0 \,, \ \ \frac{\partial p}{\partial x} = 0; \tag{2.2}$$

when $t \geq 0$, the pressure gradient in the channel is greater than zero, creates a nonstationary flow. These boundary conditions are appropriate for this case

$$t \geq 0 \ \textit{ва} \ \ y = 0 \ \ \partial a \ \ \frac{\partial u}{\partial y} = 0; \ \ t \geq 0 \ \textit{ва} \ \ y = h \ \ \partial a \ \ u = 0 \tag{2.3}$$

In order to solve the system of equations (2.1) analytically on the basis of the initial and boundary conditions formed (2.2) and (2.3), the $f_k, \ g_k$ functions in the system of equations (2.1) must be $f_k = 1, \ \ g_k = 1$ and the spectra of relaxation time are finite.

$$\lambda_k = \frac{\lambda}{k^{\alpha}}, \qquad \eta_k = \frac{\eta}{\xi(\alpha)k^{\alpha}}. \tag{2.4}$$

Nonlinear relaxation involves the use of complex methods of mathematical physics or a finite number of methods in the study of the most complex flows of a

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fluid with a time spectrum.. However, the system of linear equations (2.1) using the Laplace-Carson [8-9] substitution for time based on the above conditions, taking into account the initial (2.2) conditions, using the following formulas on the t variable,

$$\bar{u} = s\int_0^\infty \ell^{-st} u dt, \quad \bar{\tau}_{xy} = s\int_0^\infty \ell^{-st} \tau_{xy} dt \tag{2.5}$$

Here - S is the switch parameter. Using the following substitutions

$$\frac{\partial u}{\partial t} \to s(\bar{u} - u_0), \qquad \frac{\partial u}{\partial y} \to \frac{d\bar{u}}{dy}$$

$$\frac{\partial \tau_{xy}}{\partial t} \to s\bar{\tau}_{xy}, \qquad \frac{\partial p}{\partial x} \to \frac{d\bar{p}}{dx} \tag{2.6}$$

By applying the Laplace-Carson substitution (2.1) to the system of equations, taking into account the given initial conditions, it appears following form

$$\begin{cases} \rho s\bar{u} = -\dfrac{d\bar{p}}{dx} + \dfrac{d}{dy}\left(\bar{\tau}_{xy}\right), \\ \bar{\tau}_{xy} = \displaystyle\sum_{k=1}^{N} \bar{\tau}_{k,xy}, \quad s\bar{\tau}_{k,xy} + \dfrac{1}{\lambda_k}\bar{\tau}_{k,xy} = \bar{p}_k \dfrac{d\bar{u}}{dy}, \\ \bar{p}_k = \dfrac{\eta_k}{\lambda_k}. \end{cases} \tag{2.7}$$

The boundary conditions take the following form

$$y = 0 \ \partial a \ \frac{d\bar{u}}{dy} = 0; \ y = h \ \partial a \ \bar{u} = 0 \tag{2.8}$$

We now define $\bar{\tau}_{xy}$ from Equation (2.7) as follows:

$$\bar{\tau}_{xy} = \sum_{k=1}^{N} \frac{\eta_k}{1 + s\lambda_k} \frac{d\bar{u}}{dy} = \eta(s)\frac{d\bar{u}}{dy} \tag{2.9}$$

where $\sum_{k=1}^{\infty}\frac{\eta_k}{1+s\lambda_k}=\eta(s)$ is the relaxation function found for the Shulman-Husid model [11]. Instead of its:

The $\frac{\eta}{(1+s\lambda\ )}=\eta(s)$ [7,10] function for the Maxwell model, For the oldroid model [7,10], the $\frac{\eta\ (1+Bs\lambda_1)}{(1+s\lambda_1)}=\eta(s)$ function can be cited, here $B=\frac{\lambda_2}{\lambda_1}$. Substituting the expression (2.9) into the first equation of the system of equations (2.7) we obtain

$$\frac{d^2\bar{u}}{dy^2}-\frac{\rho s}{\eta(s)}\bar{u}=\frac{1}{\eta(s)}\frac{d\bar{p}}{dx}. \quad (2.10)$$

In this equation, $\frac{d\bar{p}}{dx}$ does not depend on the channel length, therefore its solution y – can be obtained in the form of a trigonometric function on a variable x – the variable bleeds in the form of a constant parameter in the equation. In this case, the solution of equation (2.10), taking into account the boundary conditions (2.8), is as follows

$$\bar{u}(y,s)=\frac{1}{\rho s}\left(-\frac{d\bar{p}}{dx}\right)\left(1-\frac{cos\left(i\sqrt{\frac{\rho s}{\eta(s)}}y\right)}{\cos\left(i\sqrt{\frac{\rho s}{\eta(s)}}h\right)}\right). \quad (2.11)$$

The resulting solution (2.11) is the pictorial solution of equation (2.10), found a solution to the given problem by bringing it to its original state.

To do this, we find the solution in Figure (2.11) using Laplace-Carson's return formula

$$u(y,t)=\frac{1}{2\pi i}\int_{\sigma-i\infty}^{\sigma+i\infty}e^{st}\frac{1}{\rho s}\left(-\frac{dp}{dx}\right)\left(1-\frac{cos\left(i\sqrt{\frac{\rho s}{\eta(s)}}y\right)}{\cos\left(i\sqrt{\frac{\rho s}{\eta(s)}}h\right)}\right)\frac{ds}{s} \tag{2.12}$$

We use the theory of deductions (balances) to calculate the integral of a complex variable (2.12). To do this, we find the values that make the fractional denominator under the integral zero. These values will be the special points of the integral. In Integral (2.12), such special points are as follows

$$s=0,\quad s=-v\frac{s_{1,n}}{h^2},\qquad s=-v\frac{s_{2,n}}{h^2} \tag{2.13}$$

The special points in these values consist only of simple poles. Therefore, we use the meromorph function to extend to a simple fraction [8]. To do this, we write the expression under the integral in fractional form in this view

$$\frac{F_1(s)}{F_2(s)}=\frac{C_0}{s}+\sum_{k=1}^{\infty}\frac{C_{1n}}{s-s_{1n}}+\sum_{k=1}^{\infty}\frac{C_{2n}}{s-s_{2n}} \tag{2.14}$$

Here C_0 - to find the discount (balance) by multiplying both sides of equation (2.14) by s, then by pushing the s to zero, we calculate this limit

$$C_0=\lim_{s\to 0}\frac{sF_1(s)}{F_2(s)}=\frac{1}{2\eta}\left(-\frac{\partial p}{\partial x}\right)h^2\left(1-\frac{y^2}{h^2}\right) \tag{2.15}$$

To find C_{in}, multiply both sides of equation (2.14) by, we calculate the limit of the generated expression $s\to s_{in}$ aspiration. That is

$$\lim_{s\to s_{in}}\frac{F_1(s)}{\dfrac{F_1(s)-F_2(s_{in})}{s-s_{in}}}=\frac{F_1(s_{in})}{F_1'(s_{in})}$$

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So in this case the value of C_{in} will be equal to $C_{in}=\frac{F_1(s_{in})}{F_1'(s_{in})}$. Now we find s_{in} from the following equation

$$EL\xi(\alpha)\bar{s}^2-\xi(\alpha)k^{\alpha}\bar{s}+\frac{(2n+1)^2}{4}\pi^2=0 \qquad (2.16)$$

Here $EL=\frac{\nu}{h^2}\lambda,\quad \xi(\alpha)=\sum_{k=1}^{\infty}\frac{1}{k^{\alpha}},\quad s=-\frac{\nu}{h^2}\bar{s}$

Equation (2.16) is a quadratic equation whose roots are two and it is defined as follows

$$s_{1n,2n}=\frac{k^{\alpha}\xi(\alpha)\pm\sqrt{k^{2\alpha}\xi^2(\alpha)-(2n+1)^2\pi^2EL\xi(\alpha)}}{2EL\xi(\alpha)} \qquad (2.17)$$

Based on the values found (2.15) and (2.16), we construct the solution of the equation

$$u(y,t)=\frac{h^2}{2\eta}\left(-\frac{dp}{dx}\right)\left[\left(1-\frac{y^2}{h^2}\right)+\sum_{n=1}^{\infty}\sum_{k=1}^{N}\sum_{i=1}^{2}\frac{(-1)^n\xi(\alpha}{(2n+1)^3\pi^3\sum_{k=1}^{N}\frac{\left(k^{\alpha}-2ELs_{in}\right)}{\left(k^{\alpha}-ELs_{in}\right)^2}}\times\right.$$

$$\left.\times\cos\left(\left(\frac{2n+1}{2}\right)\pi\frac{y}{h}\right)e^{-\frac{\nu}{h^2}\bar{s}_{in}t}\right] \qquad (2.18)$$

$$\frac{u(0,t)}{u_0}=\left[1+\sum_{n=1}^{\infty}\sum_{k=1}^{N}\sum_{i=1}^{2}\frac{(-1)^n\xi(\alpha}{(2n+1)^3\pi^3\sum_{k=1}^{N}\frac{(k^{\alpha}-2ELs_{in})}{(k^{\alpha}-ELs_{in})^2}}\times e^{-\frac{\nu}{h^2}\bar{s}_{in}t}\right] \qquad (2.19)$$

here $u_0=\frac{h^2}{2\mu}\left(-\frac{dp}{dx}\right)$

For simplicity, we examine the process of transition of an elastic viscous fluid from the non-stationary state to the stationary state at the asymptotic values of the

Shulman-Husid model. For the Shulman-Husid model, the coefficient of elastic dynamic adhesion is equal to $\eta(\bar{s}) = \eta\bar{\eta}(\bar{s})$, where η is the dynamic viscosity coefficient of the Newtonian fluid. In this case, the coefficient of dynamic adhesion of elasticity in dimensionless form is determined as follows

$$\bar{\eta}(\bar{s}) = \frac{1}{\xi(\alpha)} \sum_{k=1}^{\infty} \frac{1}{k^{\alpha} - EL\bar{s}} \qquad (2.20)$$

For simplicity in solving this equation we use two limit states. That is $t \square \lambda$ when $|\lambda s| \square 1$, It will be $\bar{s} = \frac{2n+1}{2}\pi$. This represents the process of transition of a Newtonian fluid from a non-stationary state to a stationary state. In the case of $t \square \lambda$ it is $|\lambda s| \square 1$, we will examine this point separately. When this $|\lambda s| \square 1$ condition is satisfied, equation (2.20) is reduced to the following asymptotic equation [66]

$$\bar{\eta}(s) = \frac{\pi}{\xi(\alpha)\alpha \sin\frac{\pi}{\alpha}(\lambda s)^{1-\frac{1}{\alpha}}} \qquad (2.21)$$

If we take $\alpha = 2$ here, in which case (2.21) takes the following view

$$\bar{\eta}(s) = \frac{\pi}{2\xi(2)(\lambda s)^{\frac{1}{2}}} \qquad (2.22)$$

We find the solution of this equation by substituting the expression (2.22) into the equation $\frac{ih}{\sqrt{\nu}}\sqrt{\frac{s}{\bar{\eta}(s)}} = \frac{(2n+1)}{2}\pi$

$$\bar{s}_n = \frac{(2n+1)^{\frac{4}{3}}\pi^2}{4\sqrt[3]{\xi^2(2)EL}} \frac{ih}{\sqrt{\nu}} \left(\frac{1}{2} + i\frac{\sqrt{3}}{2}\right) \qquad (2.23)$$

In this case, we write the integral value (2.16) in the following form

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$$\frac{u(0,t)}{u_{0\max}} = [1 - 32\sum_{n=0}^{\infty}(-1)^n \frac{\sqrt[3]{\xi^2(2)EL}}{3\sqrt[3]{(2n+1)^7}\,\pi^3}(\cos A\sqrt{3}t - \sqrt{3}\sin A\sqrt{3t})e^{-\frac{\nu}{h^2}At}] \quad (2.24)$$

Here $A = \dfrac{\sqrt[3]{(2n+1)^{\frac{4}{3}}\pi^2}}{8\sqrt[3]{\xi^2(2)EL}}$

The solution (2.24) can be used to study the transition of an elastic adhesive fluid from a non-stationary state to a stationary state.

We now adopt the Oldroid model with two relaxation coefficients for elastic viscous fluid. In that case the relaxation function is visible, where $\delta(t)$ is Dirac's delta function.

$\bar{\eta}(s)$ is determined as follows $\dfrac{\eta\ (1+Bs\lambda_1)}{(1+s\lambda_1)} = \bar{\eta}(s)$

The installation of elastic adhesive fluid relaxation processes in the ring interval, excluding inertia, corresponds to the results of the work [64-69]. In flat channels, the root $s = -\dfrac{h^2}{\nu}\bar{s}$ in the Oldroid model is defined as follows:

$$-EL\bar{s} + \frac{(2n+1)^2}{4}\pi^2 EL\frac{1-\bar{s}ELB}{1-\bar{s}EL} = 0, \quad (2.25)$$

here as $EL = \dfrac{\nu\lambda_1}{h^2}$, (2.25) Equation (2.25) looks like this:

$$\bar{s}^2EL - \left(1 + \left(\frac{2n+1}{2}\right)^2\pi^2 BEL\right)\bar{s} + \left(\frac{2n+1}{2}\right)^2\pi^2 = 0 \quad (2.26).$$

Solution of this equation takes following form.

$$s_{1n,2n} = \frac{\left(1+\left(\frac{2n+1}{2}\right)^2\pi^2 BEL\right) \pm \sqrt{(1+\left(\frac{2n+1}{2}\right)^2\pi^2 BEL)^2 - (2n+1)^2\pi^2 EL}}{2EL}. \quad (2.27)$$

This equation has complex roots when it changes in the EL $0{,}6 < EL < 4$ field at $n = 0,\ B = \frac{1}{4}$. At $n = 0$ this field determined from following condition

$$\left[1 + \left(\frac{2n+1}{2}\right)^2 \pi^2 BEL\right]^2 - 4\left(\frac{2n+1}{2}\right)^2 \pi^2 EL < 0 \tag{2.28}$$

In all other $n = 0$, s_{1n}, s_{2n} values, the equation has real roots. From this $\cos x = 0$ root of the $\frac{\pi}{2}$ equation generates oscillations in the transition processes, the remaining $\frac{3\pi}{2}, \frac{5\pi}{2}, \ldots\ldots$ cases will only have real roots, therefore cannot generate vibrations. Thus $EL < 0{,}6$ at small values and at large $EL > 4$ values the flow obeys the law corresponding to the Newtonian fluid. Here is the following calculation formula for Oldroid made

$$u(y,t) = \frac{1}{2\eta}\left(-\frac{dp}{dx}\right)h^2\left[\left(1 - \frac{y^2}{h^2}\right) - 32\sum_{i=1}^{2}\sum_{n=1}^{\infty}\frac{(-1)^n(1 - EL\overline{s}_{in})^2}{(2n+1)^3\pi^3(1 - 2EL\overline{s}_{in} + BEL^2\overline{s}_{in}^2)} \times \right.$$
$$\left. \times\cos\left(\left(\frac{2n+1}{2}\right)\pi\frac{y}{h}\right)e^{-\frac{\nu}{h^2}\overline{s}_{in}t}\right] \tag{2.29}$$

$$\frac{u(0,t)}{u_{0\max}} = \left[1 - 32\sum_{i=1}^{2}\sum_{n=1}^{\infty}\frac{(-1)^n(1 - EL\overline{s}_{in})^2}{(2n+1)^3\pi^3(1 - 2EL\overline{s}_{in} + BEL^2\overline{s}_{in}^2)} \times e^{-\frac{\nu}{h^2}\overline{s}_{in}t}\right] \tag{2.30}$$

here $u_{0\max} = \frac{h^2}{2\mu}\left(-\frac{dp}{dx}\right)$

Maxwell model, As a special case of the Oldroid model, at $\beta = 0$ the Oldroid model becomes the Maxwell model. The calculation formulas for the Maxwell model can be generated by putting a value of $\beta = 0$ in formulas (2.29) and (2.30).

Analysis of solutions and conclusions

One of the physical properties of elastic viscous fluid flow is that at the initial moment of momentum the velocity reaches its maximum value, then enters a phase of monotonous decrease and switches to a stationary flow. Vibrating changes in velocity, fluid flow, and other hydrodynamic quantities are observed in the flow. The process of transition from a non-stationary state to a stationary state in the movement of Newtonian viscous fluid in flat channels is manifested in the form of monotonous growth. We can observe this through Figure 1. As can be seen in the figure, the state of nonstationary fluid begins at zero value of motion and ends with the process of co-existence. This process corresponds to an approximate value of 1.5 without dimensionless time.

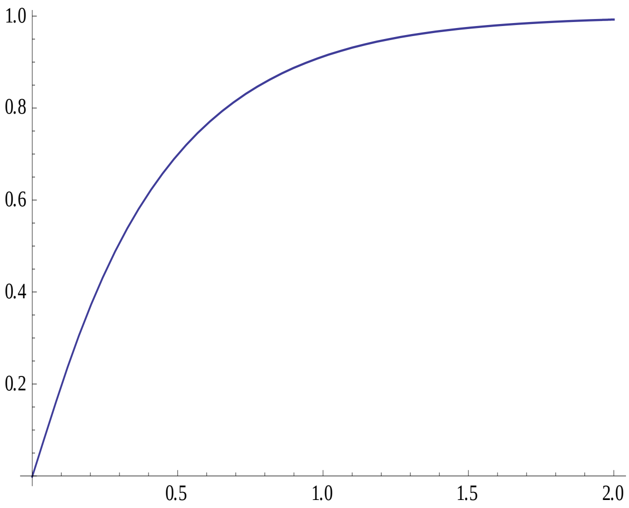
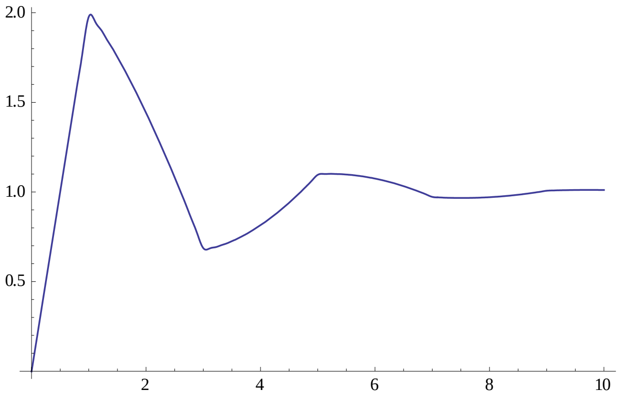


Figure 1.

The ratio of the maximum velocity of a nonstationary Newtonian adhesive fluid to the maximum velocity in the steady state time dependence.

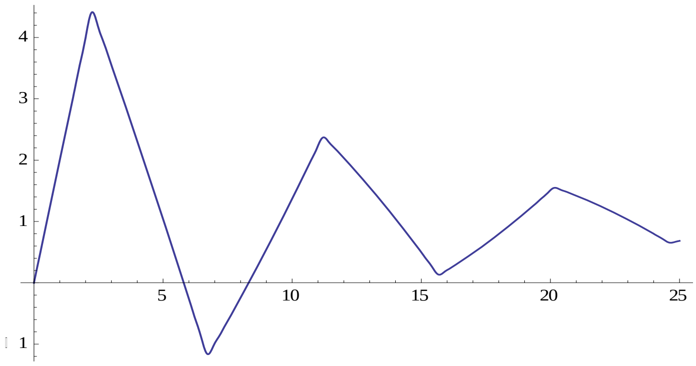
Information about this is given in many publications [13,21,27,28,34,53,55,57,61]. However, studies on the transition of elastic viscous fluids from a nonstationary stream to a stationary stream are insufficient. They are also available [34,59,60,66,67,69], the elastic adhesive fluid in some annular tubes is devoted to nostational problems of motion, which have been solved on the basis of the method of numerical finite separations. In this study, we solve the nonstationary motion of elastic viscous fluids in flat channels by analytical methods using Laplace-Carson transformations. Using formulas (2.29) and (2.30) given as a solution to the problem, first of all, we analyze the process of transition from a nonstationary motion of an elastic viscous fluid in a flat channel to a stationary state, given by the Maxwell model.



The time dependence of the ratio of the maximum velocity of the nonstationary elastic adhesive fluid to the maximum velocity in the steady state (when EL = 1 in the example of the Maxwell model).

Figure 2.

Figure 2 shows the time dependence of the ratio of the maximum value of the longitudinal velocity directed along the plane channel axis to the value of the stationary maximum velocity on the same axis of the process of transition of the elastic viscous fluid from the nostalgic state to the stationary state. As can be seen from the figure, the transition of an elastic viscous fluid from a non-stationary state to a stationary state is manifested in a wavy form, in contrast to a Newtonian fluid. The transition time would be several times greater than the Newtonian fluid transition time. Let us now examine such a case at large values of the coefficient of elasticity. Figures 3 and 4 show the process of transition of the coefficient of elasticity from the non-stationary state to the stationary state at the values of EL = 5 and EL = 10.



The time dependence of the ratio of the maximum velocity of the nonstationary elastic adhesive fluid to the maximum velocity in the steady state (when EL = 5 in the example of the Maxwell model).

3 - figure.

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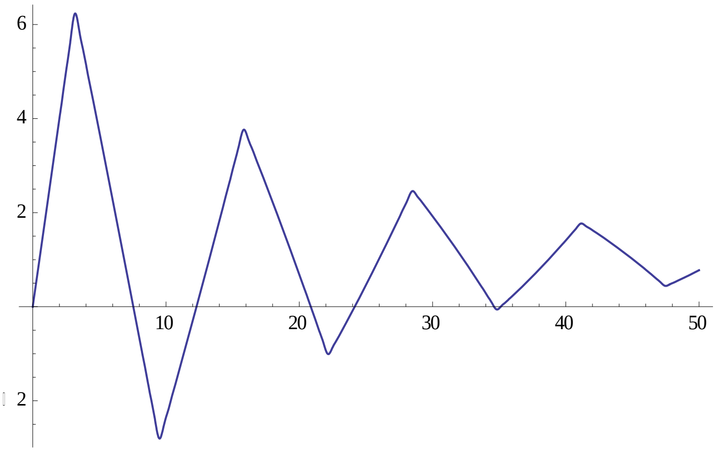
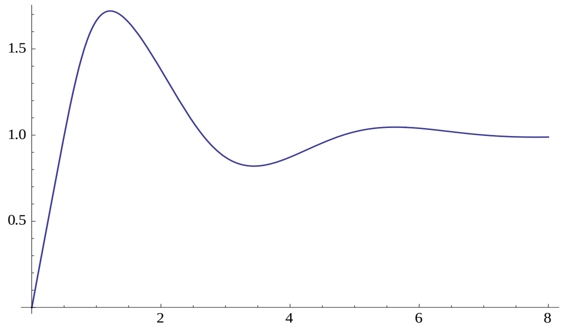


The time dependence of the ratio of the maximum velocity of the nonstationary elastic adhesive fluid to the maximum velocity in the steady state (when EL = 10 in the example of the Maxwell model).

As can be seen from the figures, as the value of the coefficient

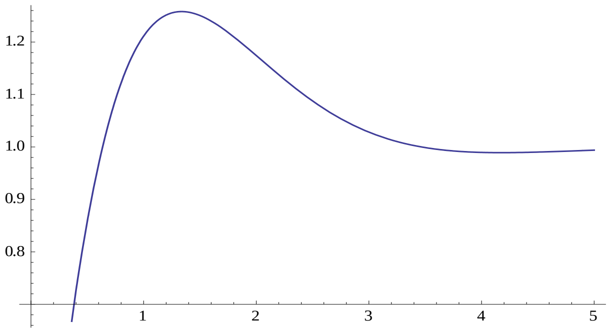
4 - figure.

of elasticity increases, the amplitude of the wave in the current and the time of transition from the nonstationary state to the stationary state increase. We now analyze the process of nonstationary motion of an elastic viscous fluid in a flat channel using the Oldroid model. The solutions to the problems found on the basis of this model are given in formulas (2.29) and (2.30).



Time dependence of the ratio of the maximum velocity of the nonstationary elastic adhesive fluid to the maximum velocity in the steady state (when EL = 1, B = 0.1 in the example of the Oldroid model).

Figure 5.



The time dependence of the ratio of the maximum velocity of the nonstationary elastic adhesive fluid to the maximum velocity in the steady state (when EL = 1 B = 0.5 in the example of the Oldroid model).

Figure 6.

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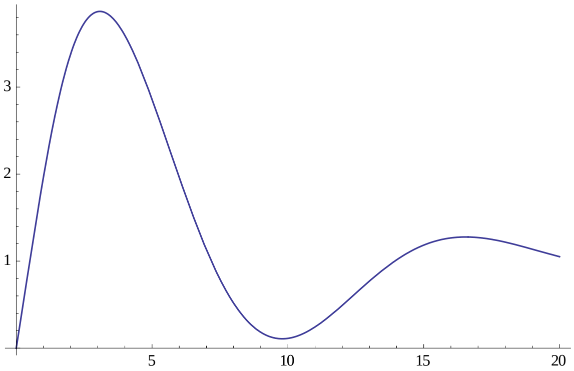
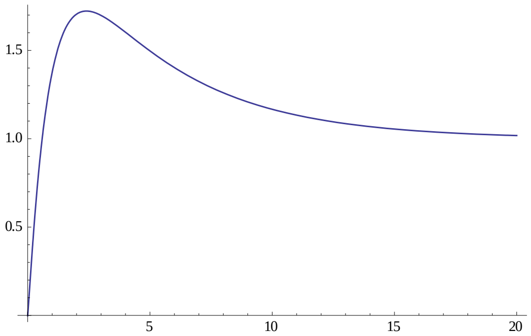


Figure 7.

The time dependence of the ratio of the maximum velocity of the nonstationary elastic adhesive fluid to the maximum velocity in the stationary state (when EL = 10, B = 0.1 in the example of the Oldroid model).



The time dependence of the ratio of the maximum velocity of the nonstationary elastic adhesive fluid to the maximum velocity in the steady state (when EL = 10 B-0.5 in the example of the Oldroid model).

Figure 8

The above mentioned figures show the process of transition from the nonstationary state to the stationary state of the maximum longitudinal velocity of edastic adhesive fluid in flat channels according to the Oldroid model at different values of elasticity and Oldroid coefficients. As can be seen from the figures, in the Oldroid model, all the processes of transition of the edastic adhesive fluid from the non-stationary state to the stationary state of the maximum longitudinal velocity are in the form of waves. This maximum value of the maximum longitudinal velocity oscillation amplitude occurs at values of constant coefficients EL = 10, B = 0.1. In this case, the deviation of the maximum longitudinal velocity oscillation amplitude from the value of the maximum longitudinal velocity of the fluid in the stationary state is increased by 3-4 times.

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