STEADY-STATE FLOW OF LIQUIDS IN CYLINDRICAL PIPES WITH A TRANSPARENT WALL

Бабажанова Юлдуз

Урганч давлат университети, ўқитувчи

Abstract: In this work, the steady-state flow of liquids in through-wall cylindrical pipes is studied. Changes in pressure and fluid consumption at different values of permeability coefficient were analyzed based on the derived formulas.

Key words: Non-Newtonian fluid, Newtonian fluid, fluid consumption, permeability coefficient, stationary flow, kinematic viscosity, cylindrical pipe.

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It is known that many scientific and practical studies have been devoted to the flow of elastic viscous liquids in channels and pipes by scientists of our country and abroad. These areas were developed by a number of authors, including Z.P. Shulman, B.M. Studied in Khusid works. J.F. Fayzullaev, K.Navro'zov in scientific research works, equations of nonlinear rheological state of memory fluids are summarized in the form of Maxwell's model. At present, foreign scientists A.I. Ageev, E.I. Mogilevskii, Zhaodong Ding, Rekha Bali, Nivedita Gupta, E.P. Valueva, L.L. Ferras, J.M. Scientific work is being carried out by Nobrega, Lorenzo Fusi, Kai Bao, Zohreh Sheidaei, R.P. Chobra and others.

Despite the fact that many studies have been conducted on the study of the motion of non-Newtonian fluids, concrete problems using the Shulman-Khusid model have not been sufficiently studied and applied. Taking this into account, in this work we will study the example of the flow of fluids in a stationary state for cylindrical pipes passing through the wall.

THE MAIN PART

The slow stationary flow of a non-Newtonian fluid in a cylindrical pipe with a throughwall is mathematically represented by the following system of equations:

$$\begin{cases} \frac{1}{\rho} \frac{\partial p_0(x)}{\partial x} = \nu \left(\frac{\partial^2 v_{0x}}{\partial r^2} + \frac{1}{r} \frac{\partial v_{0x}}{\partial r} \right), \\ \frac{\partial v_{0r}}{\partial r} + \frac{1}{r} v_{0r} + \frac{\partial v_{0x}}{\partial x} = 0. \end{cases}$$
(1)

In stationary flow, non-Newtonian fluids become Newtonian fluids. Accordingly, it is more convenient to apply this problem to Newtonian fluids.

The boundary conditions of the problem under consideration are defined as follows:

$$\begin{cases} r = R \ in \ \upsilon_{0r} = \frac{R\gamma *}{\eta} \left(p_0 - p_c \right), \ \upsilon_{0x} = 0, \\ r = 0 \ in \ \frac{\partial \upsilon_{0x}}{\partial r} = 0, \ \upsilon_{0r} = 0, \\ x = 0 \ in \ p_0 = p_0^0, \\ x = L \ in \ p_0 = p_0^L. \end{cases}$$
(2)

Here is liquid density; ρ – transverse and longitudinal coordinates; and – r,xtransverse and longitudinal velocities; \mathcal{D}_{0r} and \mathcal{D}_{0x} -kinematic viscosity coefficient; \vee – pressure inside the pipe; p_0 -pressure outside the pipe; p_c – and – pressures at the inlet p_0^0 Ba p_0^L – and outlet of the pipe, respectively; R – pipe radius; γ^* – permeability coefficient.

If we solve the first equation of the system of equations (1) using the boundary conditions (2), we have the longitudinal velocity formula along the axis as follows:

$$\nu_{0x}(x,r) = \frac{1}{4\eta} \left(-\frac{\partial p_0(x)}{\partial x} \right) \left(R^2 - r^2 \right).$$
(3)

By taking the found longitudinal speed into the second equation of (1), solving (2) based on the conditions, the formula for finding the transverse speed is obtained:

$$\nu_{0r}\left(x,r\right) = -\frac{r}{16\eta} \left(-\frac{\partial^2 p_0(x)}{\partial x^2}\right) \left(2R^2 - r^2\right). \tag{4}$$

In this case, the pressure and flow rate of fluids change along the longitudinal direction, and accordingly, other hydrodynamic quantities also change along the longitudinal coordinate. Therefore, all parameter solutions depend on the pressure and velocity of the fluid. We use the continuity equation and boundary conditions (2) to find these quantities. By multiplying the equation of continuity by , it is calculated and written in the transverse coordinate from 0 to R until it looks like this:

$$\frac{dQ(x)}{dx} = -2\pi \frac{\gamma^* R^2}{\eta} p_0(x).$$
⁽⁵⁾

Now if we multiply equation (3) by and integrate from 0 to R along the transverse coordinate, we get the following equation:

$$Q(x) = \frac{\pi R^4}{8\eta} \left(-\frac{\partial p_0(x)}{\partial x} \right).$$

From here the pressure change is found:

$$\frac{dp_0(x)}{dx} = -Z < \mathcal{G}_{0x}(x) > .$$
(6)

Here $Z = \frac{8\eta}{R^2}$, η is the coefficient of dynamic viscosity.

Using the above equations (5) and (6), the formulas for determining the pressure and fluid consumption in the pipe are obtained:

$$\frac{d^2 p_0(x)}{dx^2} - KZp_0(x) = 0,$$

$$\frac{d^2 < \mathcal{G}_{0x}(x) >}{dx^2} - KZ < \mathcal{G}_{0x}(x) >= 0.$$
Here
$$K = 2\frac{\gamma^*}{\eta}.$$
(7)

Solving the above equations (7) and (8) gives the following solutions:

$$p_{0}(x) = A_{1}e^{\sqrt{KZ}x} + A_{2}e^{-\sqrt{KZ}x},$$

$$< 9_{0x}(x) \ge -\sqrt{\frac{K}{Z}}(A_{1}e^{\sqrt{KZ}x} - A_{2}e^{-\sqrt{KZ}x}).$$
(10)

Now the values of coefficients A1 and A2 are determined from the boundary conditions (2) and written as follows:

$$A_{1} = -\frac{p_{0}^{0}e^{-\sqrt{-KZ}L} - p_{0}^{L}}{e^{\sqrt{KZ}L} - e^{-\sqrt{KZ}L}} ,$$
$$A_{2} = \frac{p_{0}^{0}e^{\sqrt{KZ}L} - p_{0}^{L}}{e^{\sqrt{KZ}L} - e^{-\sqrt{KZ}L}} .$$

Putting the found values of the coefficients in formulas (9) and (10), we pass to hyperbolic functions:

$$p_0(x) = \frac{p_0^0 sh\left(4\sqrt{\gamma^*} \frac{L-x}{R}\right)}{sh\left(4\sqrt{\gamma^*} \frac{L}{R}\right)} + \frac{p_0^L sh\left(4\sqrt{\gamma^*} \frac{x}{R}\right)}{sh\left(4\sqrt{\gamma^*} \frac{L}{R}\right)},$$
(11)

$$<\mathcal{G}_{0x}\left(x\right)>=\frac{R^{2}}{8\eta}\frac{4\sqrt{\gamma^{*}}L}{R}p_{0}^{0}\left(\frac{ch\left(4\sqrt{\gamma^{*}}\frac{L-x}{R}\right)}{sh\left(4\sqrt{\gamma^{*}}\frac{L}{R}\right)}-\frac{p_{0}^{L}ch\left(4\sqrt{\gamma^{*}}\frac{x}{R}\right)}{p_{0}^{0}sh\left(4\sqrt{\gamma^{*}}\frac{L}{R}\right)}\right).$$
 (12)

We perform numerical calculations using the received formulas (11) and (12). To do this, we derive the calculation formulas in dimensionless form:

$$\frac{p_0(x)}{p_0^0} = \frac{sh\left(4\sqrt{\gamma^*}\frac{L-x}{R}\right)}{sh\left(4\sqrt{\gamma^*}\frac{L}{R}\right)} + \frac{p_0^L}{p_0^0}\frac{sh\left(4\sqrt{\gamma^*}\frac{x}{R}\right)}{sh\left(4\sqrt{\gamma^*}\frac{L}{R}\right)},\tag{13}$$

$$\frac{Q(x)}{Q_{0}} = \frac{\langle \mathcal{G}_{0x}(x) \rangle}{\langle \mathcal{G}_{x}^{0}(x) \rangle} = \frac{p_{0}^{0} 4\sqrt{\gamma^{*}}}{p_{0}^{0} - p_{0}^{L}} \frac{L}{R} \left(\frac{ch\left(4\sqrt{\gamma^{*}}\frac{(L-x)}{R}\right)}{sh\left(4\sqrt{\gamma^{*}}\frac{L}{R}\right)} - \frac{p_{0}^{L}}{p_{0}^{0}}\frac{ch\left(4\sqrt{\gamma^{*}}\frac{x}{R}\right)}{sh\left(4\sqrt{\gamma^{*}}\frac{L}{R}\right)} \right).$$
(14)

The resulting formula (13) represents the change in pressure, and formula (14) represents the change in fluid consumption.

Analysis of results

We describe the quantities presented in a dimensionless form using graphs.



Figure 1. Pressure change at different values of permeability coefficient ($\gamma^* := 1-0,0001; 2-0,1; 3-0,2; 4-0,3; 5-0,5.$) $\frac{L}{R} = 5, p_0^L = 0.$

It can be seen from Figure 1 that the change in pressure significantly differs from the linear distribution law at increasing values of the permeability coefficient, that is, it changes from a linear law to a nonlinear law. As the value of the conductivity coefficient increases, the concavity of the curve increases. From this, it is possible to control the pressure change by changing the permeability coefficient.



Figure 2. Variation of fluid consumption at different values of permeability coefficient ($\gamma^* := 1-0,0001; 2-0,1; 3-0,2; 4-0,3; 5-0,5.$) $\frac{L}{R} = 5, p_0^L = 0.$

The change in fluid consumption is observed in the values of the increase in the coefficient of permeability, a several-fold increase in the initial cross-section of the pipe compared to a pipe without a wall. It was found that an increase in the coefficient of permeability leads to an increase in the fluid permeability of the cylindrical pipe. In particular, in the values of the permeability coefficient, it was found that its growth value is 3-4 times larger in the initial cross-section of the pipe compared to the wall-tight pipe.

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