How the radius of the screw insert core influences the flow behavior of the polymer solution

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Abstract. In this paper the authors studied the 3-dimensional flow behavior of the polymer solution in the screw barrel. Numerical simulation was performed in the COMSOL Multiphysics® suite. An aqueous solution of polyacrylamide was regarded as a specific liquid. Demonstrated that, with a decrease in the gap between the outer tube and the screw insert core, the profile of the axial component of the velocity vector is aligned over the entire barrel cross-section, except for the region adjacent to the screw ribs.

Currently, it is difficult to achieve an exact analytical solution to the problem of the non-Newtonian flow in a screw barrel [1]. Known are only analytical solutions of the problem of the isothermal flow of ordinary Newtonian fluid in the barrel of a single-screw extruder [2]. In addition, most of the solutions to such problems were obtained with assumptions concerning the small curvature of the screw ribs and the consideration of the flow region in the rectangular form [3]. Moreover, the rotation of the screw insert means the rotation of the outer wall [4, 5, 6]. Generally, there are publications in which the power law is used to describe the rheological behavior of a polymer solution [7]. The disadvantage of this model is the infinite viscosity at zero shear rate. This paper uses the Cross-model [8, 9, 10], which takes into account the asymptotic values of the effective viscosity in threshold cases.

A consideration was given to the 3-D stationary laminar flow of a 0.5% aqueous solution of polyacrylamide in a round pipe with a CCW screw insert (Fig. 1). Mathematical modeling was performed considering that gravity is negligible. Due to this assumption, the distributions of hydrodynamic characteristics in two regions bounded by the screw insert ribs (Fig. 1) are identical. Therefore, one of these regions is regarded as the study area (area - i) further in the text.

The numerical solution was performed using the COMSOL Multiphysics® suite. The Navier-Stokes equations are taken as the basic equations:

\[ \rho (\nabla \dot{V} - \dot{V}) = \nabla \cdot (p \mathbf{I} + \eta (\nabla \dot{V} + (\nabla \dot{V})^T)) \]  \hspace{1cm} (1)\\
\n\n\n\[ \nabla \cdot \dot{V} = 0 \]  \hspace{1cm} (2)

where \( p \) is the pressure, Pa; \( \mathbf{I} \) is the unit tensor; \( \eta \) is the effective viscosity, Pa·s; \( \rho \) is the liquid density, kg/m³; \( \dot{V} = \{v_x, v_y, v_z\} \) is the velocity vector.
Fig. 1 Transversal (b) and longitudinal (a) section of the barrel: \( L_0 \) is the length of the rectilinear portion; \( L \) is the pitch of the screw barrel (the length of the barrel part corresponding to the 360-degree rotation of the screw ribs); \( r_1 \) is the radius of the inner pipe; \( r_2 \) is the radius of the outer pipe; \( \#1, \#2 \) are the identical fluid flow regions, limited by the outer and inner pipes and screw ribs; \( h \) is the thickness of the ribs.

The following conditions are taken as threshold conditions:

1) a developed velocity profile in the coaxial barrel is specified on the pipe inlet

\[
v_i = 2U_a \left( 1 - \left( \frac{r}{r_2} \right)^2 \right) \log \left( \frac{r_1}{r_2} \right) - \left( 1 - \left( \frac{r}{r_2} \right)^2 \right) \frac{\log \left( r_1/r_2 \right)}{1 + \left( \frac{r}{r_2} \right)^2} \log \left( \frac{r_1}{r_2} \right) + \left( 1 - \left( \frac{r}{r_2} \right)^2 \right) \frac{\log \left( r_1/r_2 \right)}{1 + \left( \frac{r}{r_2} \right)^2} = 0, \quad v_r = 0, \quad v_\varphi = 0. \tag{3}
\]

where \( U_a \) is the mean flow velocity.

2) the conditions for adhesion of the liquid are satisfied on the barrel walls and on the surface of the screw insert ribs;

3) the condition of equality of zero pressure is given at the pipe outlet.

For describing the rheological behavior of the aqueous solution of 0.5% polyacrylamide, the authors used the Cross-model [11] with the following parameters: \( \eta_0 = 1.08 \text{ (Pa}\cdot\text{s}), \eta_\infty = 0.0023 \text{ (Pa}\cdot\text{s}) \) are the asymptotic values of the effective viscosity at \( \dot{\gamma} \rightarrow 0 \) and \( \dot{\gamma} \rightarrow \infty \), respectively; \( \lambda_c = 5 \text{ (s)} \) is the characteristic time; \( n = 0.8 \) is a coefficient that determines the viscosity reduction rate; \( \dot{\gamma} \) is the shear rate, 1/s. The density of the aqueous solution of 0.5% polyacrylamide is believed to be \( \rho = 999 \text{ kg/m}^3 \).

Numerical results are presented for a stationary flow of 0.5% polyacrylamide in a barrel with the three types of screw inserts. The geometry of the screw inserts: \( L/D_2 = 3 \), \( r_1 = 0.013 \text{ (m)} \), \( r_2 = 0.0195 \text{ (m)} \), \( h = 0.004 \text{ (m)} \). The diameter of the outer pipe \( D_2 = 0.039 \text{ (m)} \), the length of the upstream section \( L_0 = 1.5 \cdot D_2 \), the length of the screw insert along the z-axis is equal to \( L_e = 7.5 \cdot D_2 \).

As can be seen from Fig. 2, a steady-state velocity behavior is formed on the initial hydrodynamic portion of the barrel containing the screw insert. Here \( A_i \ (i = 45...360) \) are the planes spaced apart from \( A_0 \) at the distance corresponding to the rotation of the screw insert by \( i \) degrees. \( A_0 \) is the cross-section of the barrel from which the screw insert starts [12].

\[ A_0 \]
Fig. 2 Curves of the dimensionless axial component of the velocity vector in various runs of the barrel with screw insert around the circumference with radius $r = r_3$ and $U_a = 0.05$ (m/s): 1 – $A_{35}$, 2 – $A_{30}$, 3 – $A_{35}$, 4 – $A_{30}$, 5 – $A_{360}$, 6 – $A_{360}$ (dashed black line), 7 – $A_{15}$

The velocity trends shown in Figure 3 are built around the circumference with radius $r_3 = (r_1 + r_2)/2$ (Fig. 3). The results obtained illustrate that the length of the initial hydrodynamic run does not exceed the distance limited by the plane $A_{360}$, i.e. $L_1 = 3D_2$. In this event, the velocity trend is getting packed and tends to the line showing a constant velocity throughout the barrel cross-section with a decrease in the gap between the coaxial cylinders (Fig. 4).

Fig. 3 The fluid flow region in the barrel cross-section: $r_3 = (r_1 + r_2)/2$, $\beta$ is the current angle value, $\alpha$ is the sector size

Fig. 4 Trends of the dimensionless axial component of the velocity vector in the cross-section $A_{360}$ around the circumference with radius $r_3$

Conclusion

Numerical results show that the initial hydrodynamic portion in the screw insert barrel for the aqueous solution of 0.5% polyacrylamide is limited by the distance $L_1 = 3D_2$. The gap between the outer pipe and the radius of the screw insert core was found to be less in order to ensure the same residence time of the polymer solution flow throughout the barrel cross-section.

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