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# Research and Development of A Mathematical Model of a Polymer-Based Viscous Non Newtonian Fluid for Oil and Gas Wells Drilling

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**Abstract**

Analysis of the use of biopolymers in drilling and well stimulation for oil and gas production has been performed. Normal Newtonian fluid model, taken used as a sample, is considered a nonlinear viscous fluid. Models that are most common in oil and gas industry are considered. Laboratory studies of rheology of an aqueous solution with various concentrations of xanthan gum have been carried out. An analysis of experimental and numerical hydrodynamic studies in flexible pipes of coiled tubing units has been performed considering the rheology of drilling fluid. For the numerical simulation of the hydrodynamics of a non-Newtonian fluid authors apply an open integrable platform OpenFOAM.

***Keywords***: *Non newtonian fluid; Polymers; Drilling; Flushing.*

## 1. Introduction

Nowadays, use of polymer additives for technical fluids in the oil and gas industry is of interest. Polymer additives can affect the rheological properties of aqueous and hydrocarbon systems and form gels of various densities, viscosities and rheology. Such compositions are widely used due to their high cleaning, transporting and retention properties. Long chain polymers are also capable of reducing hydraulic resistance in turbulent flows. Also, polymer solutions prevent the penetration of liquid filtrate into the pores of the treated rocks [1-2].

Consider the use of biopolymers in drilling and well stimulation. The basis of technology for drilling oil and gas wells is cleaning the bottom of the wells with flushing fluid [3-4].

Development of drilling technology and increase in the share of hard-to-recover reserves are followed by the evolution of drilling fluids so as modern multicomponent and multifunctional systems appear [5-6]. The study [7] presents an overview of polymer drilling fluids and a classification of polymer reagents used in drilling fluids.

Therefore, the most suitable materials for drilling fluids and well stimulation include a weighting agent such as clay powder, starch, polyanionic cellulose of low and high viscosity, xanthan gum (biopolymer), etc.

Nowadays biopolymer and xanthan-based flushing solutions are widely known: Flo-Pro systems from M-I Drilling Fluids Co and ANCO-2000, from ANCOR Drilling Fluids. Xanthan gum is a polysaccharide that dissolves in water, it is produced by microorganisms Xanthomonas campestris [8].

Xanthan gum is used to regulate the rheological properties of water-based drilling fluids (both fresh and highly saline). It makes it possible to increase the viscosity even of low-concentrated solution, the gum provides its retaining and carrying characteristics. The recommended concentration of xanthan gum is 0.6 to 8 g/L.

## 2. Information review

In the classical formulation rheological properties of a viscous incompressible Newtonian fluid is described by a linear equation [9]:

$\tau = 2\mu S,$ (1)

where $\mu$ – dynamic (molecular) viscosity of a Newtonian fluid; $S \equiv S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$ – strain rate tensor; $u_i, u_j$ – Cartesian components of vector velocity.

Some fluids are characterized by nonlinear viscosity, plasticity, elasticity – they are called non-Newtonian fluids. These non-Newtonian fluids are thoroughly described by rheological theory. For one class of fluids that have similar properties, a generalized rheological model is presented. The simplified model of the studied fluid is described by the generalized Newtonian model, in which the fluid is considered a nonlinear viscous fluid with the effective viscosity [10 - 14]. Effective molecular viscosity depends on the rate of deformation of the fluid $\dot{\gamma} = \sqrt{2S.S}$.

The generalized Newtonian model for a viscoplastic non-Newtonian fluid has the form:

$\tau = \mu_{eff}(\dot{\gamma}) \cdot \dot{\gamma}$ (2)

Models of fluid with a power-law rheological law, Bingman fluid and Herschel-Bulkley fluid are the most common in the oil and gas industry [5-6,10-17]. Effective viscosity is described by the following equations:

$\boldsymbol{\mu_{eff}(\dot{\gamma}) = k_v \dot{\gamma}^{n-1}}$– rate model; (3)

$\mu_{eff}(\dot{\gamma}) = \frac{k_v \dot{\gamma} + \tau_0}{\dot{\gamma}}$ – Bingman model; (4)

$\boldsymbol{\mu_{eff}(\dot{\gamma}) = \frac{k_v \dot{\gamma}^n + \tau_0}{\dot{\gamma}}}$ **–** Herschel-Bulkley model. (5)

where $k_\upsilon$ is a measure of the fluid consistency; *n* is the indicator of the non-Newtonian environment; $\tau_0$ is the ultimate shear stress (yield point).

Generalized information on the rheology and hydrodynamics of non-Newtonian fluids is presented in [14]. Laboratory studies of the rheological parameters of a drilling fluid with polymer additives for drilling permafrost are presented in [15]. The rheology of solutions is described by the Power-law and Bingham models.

A description of the new type of flushing fluid FLO-PRO is given in [16]. The results of laboratory and industrial studies of a biopolymer system for drilling inclined and horizontal boreholes of deep oil and gas wells are presented. An experience of long-time well drilling has shown that clay-free biopolymer solutions are effective for technical, economic and safety reasons.

In [17], experimental and computational studies of the effect of polymer additives on the resistance to the movement of liquids in pipelines are presented. It is noted that a small concentration of polymer additives to water and oil products impart new rheological properties to the fluid due to which the hydraulic resistance in turbulent flow is sharply reduced (Toms effect).

The results of numerical studies of the non-Newtonian models of a viscous fluid flow in a cylindric pipe, annular gaps, channels of hydraulic machines are presented in [13-14,18-19].

The aim of the work is to increase the efficiency of well drilling and intensify oil production by using biopolymer flushing solutions based on xanthan gum. The main tasks are considered: study of the rheological properties of an aqueous solution at various concentrations of xanthan gum; analysis - experimental and numerical hydrodynamic studies in flexible pipes of coiled tubing installations, taking into account the rheology of the drilling fluid.

## 3. Experimental studies of the rheological properties of the solution at various concentrations of xanthan gum

The current work is devoted to study of rheology of a water-based fluid mixed with xanthan gum biopolymer with a concentration of 1.2-12 g/L with a step of 1.2 g/L. The structure of the test solution is determined using a rotary viscometer. The initial data and results are presented in Table. 1. The magnitude of the shear stress is determined for eight values of the rotor speed of the viscometer - viscometer rotor speed (VRS, min$^{-1}$) and ten values of the concentration of xanthan gum (CXG, g/l). We have assumed that the rate of deformation of the fluid (shear rate) is identical to the rotor speed of the viscometer.

Table 1. Results of laboratory study of shear stress magnitude $\tau_0$, Pa

| VRS, $min^{-1}$ | Concentration of xanthan gum, g/L | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1.2 | 2.4 | 3.6 | 4.8 | 6 | 7.2 | 8.4 | 9.6 | 10.8 | 12 |
| 3 | 1 | 3 | 6 | 9 | 12 | 16 | 18 | 25 | 30 | 38 |
| 6 | 2 | 3 | 6 | 9 | 14 | 18 | 20 | 28 | 34 | 40 |
| 30 | 3 | 4 | 8 | 13 | 17 | 23 | 28 | 34 | 42 | 51 |
| 60 | 5 | 6 | 10 | 15 | 20 | 26 | 34 | 38 | 46 | 57 |
| 100 | 5 | 7 | 11 | 17 | 22 | 29 | 35 | 42 | 50 | 62 |
| 200 | 7 | 9 | 16 | 21 | 27 | 36 | 40 | 49 | 60 | 74 |
| 300 | 8 | 11 | 17 | 25 | 32 | 40 | 48 | 56 | 70 | 83 |
| 600 | 10 | 16 | 22 | 32 | 38 | 50 | 58 | 68 | 84 | 98 |

The rheological relation between the shear stress and the rotor speed of the viscometer are shown in Fig. 1. Results are shown for five concentrations of xanthan gum.

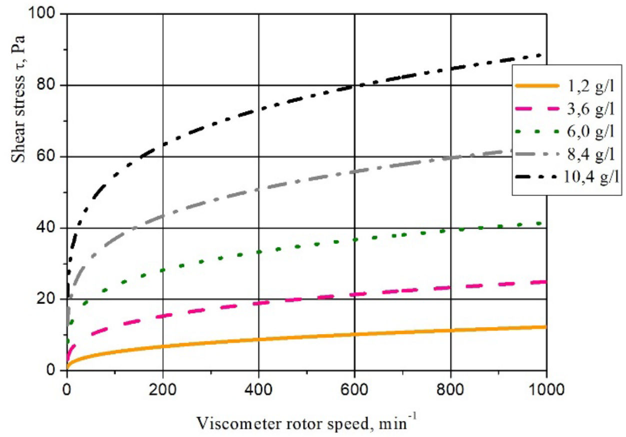


Fig. 1. Rheological characteristics of the studied process fluid

Processing laboratory studies of rheology. Determination of effective viscosity. The rheological lines on the Fig. 1 indicate that the studied liquids are described by the rate model $\tau(\gamma)=k_\upsilon \cdot \gamma^n$. The coefficients of the rheological model $k_\upsilon$ and n were defined by approximating laboratory data. The results are shown on the Fig. 2.

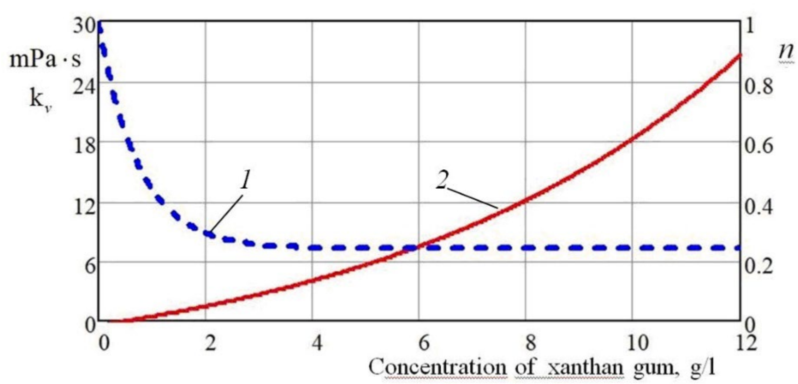


Fig. 2. The effect of the concentration of xanthan gum in water on the rheological characteristics of the rate-model fluid: 1 – $k_v$; 2 – $n$

At n=1 and $k_v$ = 1 mPa·s, the concentration of the gum is zero, i.e. the studied fluid is water. Using formula (3) the values of effective viscosity of the liquid can be defined. The effect of effective viscosity on the shear rate for five values of the concentration of xanthan gum in an aqueous solution are shown on the Fig. 3.

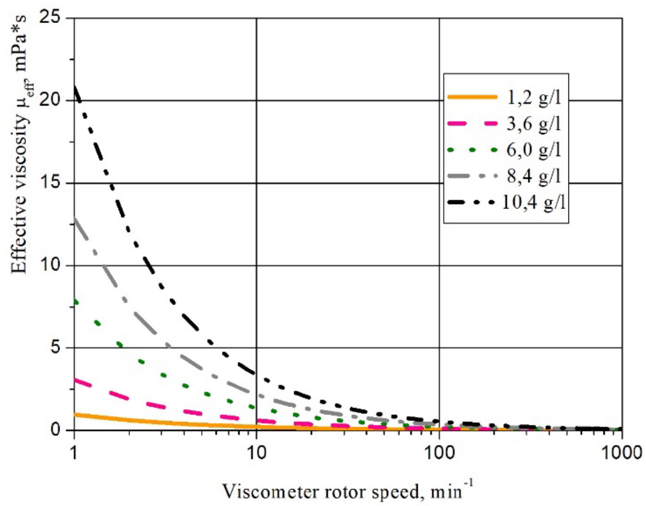


Fig. 3. The effect of rotor rotation speed of effective viscosity at various concentration of xanthan gum in water

Results of the study show that increase of the rotor speed of the viscometer (shear rate) is followed by decrease of viscosity for all concentrations of xanthan gum. These solutions are pseudoplastic fluids. The effect of effective viscosity on the concentration of xanthan gum shows that at low shear rates, the viscosity of the solution has a minimum at a concentration of 1.2 g/L. Further increase of xanthan gum concentration is followed by increase the viscosity of the solution. The results of rheology studies are used to determine the flow regime in pipes and predict the hydraulic resistance coefficients.

## 4. Experimental studies of flushing solution supply through a flexible coiled tubing pipe

In this work there has been studied pumping of a xanthan gum (XG) in water solution through a flexible pipe of a coiled tubing installation. The studies have been carried out at 11 operating modes of the pumping unit (Q-fluid flow through the pipe in L/min). Also, as a result of the experiment, the type of pumped liquid changed. The concentration of xanthan gum biopolymer varied from 1.2 g/L to 12 g/L. As a result of the tests, the required fluid injection pressure was determined. Coiled tubing pipe outlet pressure is equal to atmospheric pressure. Therefore, it is assumed that the injection pressure is equal to the hydraulic losses along the length of a pipe. Table 3 shows the test results: the effect of concentrations of xanthan gum, the flow of the pumping unit and the pressure loss in atmospheres when pumping liquid through a 38.1 mm pipe with a wall thickness of 3.2 mm and a pipe length of 5620 m.

Tab. 3. Pressure loss in a flexible pipe at different modes of pumping liquid with different concentration of xanthan gum, atm

| Fluid flow *Q*, L/min | Concentration of xanthan gum , g/L | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1.2 | 2.4 | 3.6 | 4.8 | 6 | 7.2 | 8.4 | 9.6 | 10.8 | 12 |
| 50 | 29.4 | 40.1 | 63 | 90.5 | 114.4 | 147.7 | 174.3 | 205.4 | 250.1 | 300 |
| 80 | 33.1 | 40.9 | 75.4 | 106.7 | 132.4 | 169.8 | 200.4 | 231.8 | 281.8 | 336.3 |
| 100 | 39.2 | 45.7 | 61.6 | 116.2 | 142.8 | 182.6 | 215.3 | 246.8 | 299.8 | 356.6 |
| 120 | 46.7 | 52.1 | 68.4 | 92.6 | 152.6 | 194.4 | 229.1 | 260.7 | 316.3 | 375.3 |
| 150 | 60.4 | 64.3 | 79.9 | 104.5 | 122.9 | 154.7 | 248.4 | 280 | 339.2 | 401 |
| 180 | 77.1 | 79.4 | 93.3 | 118.2 | 135.5 | 167.6 | 196.3 | 217.7 | 360.5 | 424.9 |
| 200 | 89.9 | 91 | 103.3 | 128.3 | 145 | 177.2 | 206.5 | 226.2 | 273.4 | 440.1 |
| 230 | 111.6 | 110.9 | 119.9 | 145.1 | 160.7 | 193.1 | 223.2 | 240.5 | 288.2 | 337.1 |
| 250 | 127.8 | 125.9 | 132.8 | 157.3 | 172.3 | 204.8 | 235.2 | 251.1 | 299.1 | 347.7 |
| 280 | 154.7 | 150.7 | 155.4 | 177.4 | 191.3 | 223.9 | 255.1 | 268.6 | 317.1 | 365.2 |
| 300 | 174.4 | 169 | 171.9 | 191.9 | 205 | 237.7 | 269.4 | 281.3 | 330.1 | 377.9 |

## 5. Results and discussion

According to hydraulics laws [10], the pressure loss in a cylindrical pipe for a viscous fluid is determined by the equation:

$$\Delta P = \lambda\left(\frac{L}{D}\right)\frac{\rho V^2}{2} \qquad (8)$$

where λ is the hydraulic resistance coefficient; D is the hydraulic diameter of the pipe; L is the pipe; V is the average velocity of the fluid in the pipe; ρ is the density of the liquid.

While pipe length L and diameter D are constants, fluid velocity V may vary and depends on the operating mode of the pump unit, i.e. $V = f(Q)$. Pressure losses are known from the experiment and depend on the operating mode of the pump and the type of pumped liquid - $\Delta P = f(Q, k_v, n)$. Based on the results of experimental studies, we calculate the coefficient of hydraulic losses λ according to the formula:

$$\lambda(\mathrm{Q}, \mathrm{k}_v, n) = \frac{2D\cdot\Delta P(\mathrm{Q}, \mathrm{k}_v, n)}{L\rho\cdot V(Q)^2}. \qquad (9)$$

Effect of the resistance coefficient on the flow rate of the pumped liquid is shown on the Fig. 4.

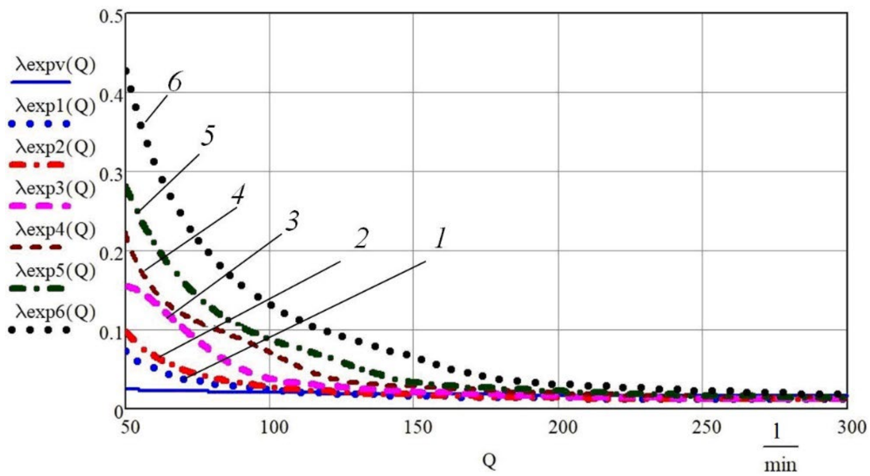


Fig. 4. Effect of the resistance coefficient in the pipe on the operating mode of the pumping unit at the concentration of xanthan gum in water: 1 - 1.2 g/L; 2 - 2.4 g/L; 3 - 3.6 g/L; 4 - 4.8 g/L; 5 - 6 g/L; 6 - 8.4 g/L.

According to the hydraulic law, the drag coefficient is represented as a function of the Reynolds criteria. Non-Newtonian fluids are described by generalized Reynolds criteria. For a fluid described by the rate rheological model, the Metznel-Reed Reynolds criteria expression is normally used [10, 12]:

$$Re^* = \frac{D^n V^{2-n}\rho}{\frac{k_v}{8}\left(\frac{6n+2}{n}\right)^n},$$

where $k_v$– measure of a fluid consistency; $n$– non-Newtonian area indicator.

Results of recalculation of the experimental data for determination of $\lambda = f(Re^*)$ are presented on the Fig.5. Analysis of the experimental data of the drag coefficient in a coiled tubing pipe for a non-Newtonian fluid shows that increase of the biopolymer concentration in water provides the laminar mode of the fluid flow. The pressure loss coefficient decreases as the concentration raises up.

For mathematical modeling (MM) of a turbulent flow of an incompressible viscous fluid, a system of continuity and Navier-Stokes equations is used [9, 13]:

$$\begin{cases} \frac{\partial\rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = 0; \\ \frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) + \frac{\partial}{\partial x_j}(\rho u_i' u_j') = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + f_i, \end{cases} \qquad (6)$$

where *i, j* = 1 ... 3 - summation over the same indices; $x_1$, $x_2$, $x_3$ - coordinate axes; $u_1$, $u_2$, $u_3$ - time-averaged velocities; $u_1', u_2', u_3'$ - pulsation components of velocities; *fi* - expresses the effect of mass forces.

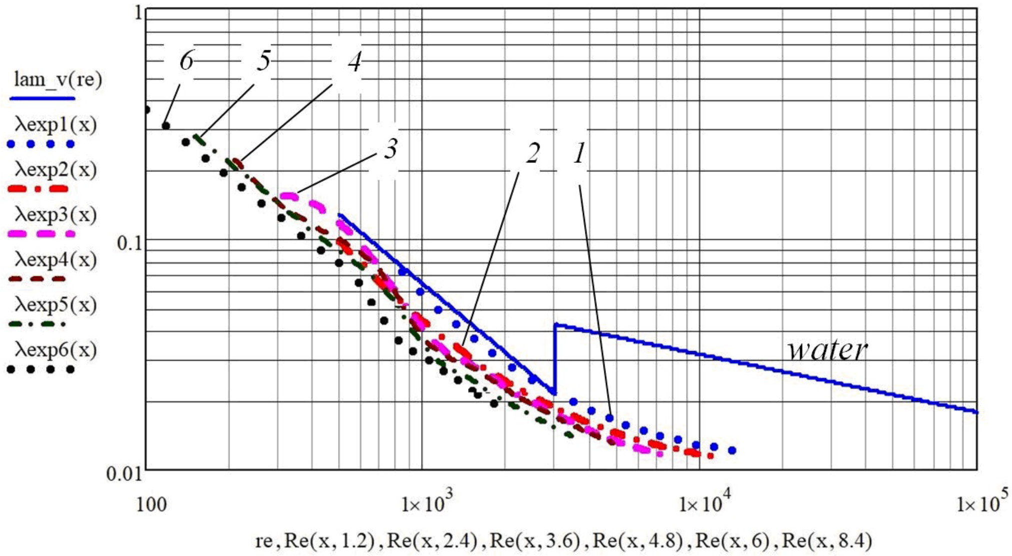


Fig. 5. Changing of the resistance coefficient $\lambda = f(Re^*)$at various concentration of xanthan gum in water: *1* – 1,2 g/L; *2* – 2,4 g/L; *3*– 3,6 g/L; *4* – 4,8 g/L; *5* – 6 g/L; *6* – 8,4 g/L.

To close the system of equations (6), the two-parameter Menter SST model is used [20]. Menter's model is written by a superposition of the *k-ε* and *k-ω* models, based on the fact that the *k-ε* type models describe the properties of free landslide flow better and the k-ω model they have an advantage when modeling near-wall flow. A smooth transition from the k-ω model in the near-wall region to the k-ε model for zones far from solid walls is provided by introducing weight empirical functions [20, 13].

To confirm the reliability of coefficient calculation of the rate rheological model of a non-Newtonian fluid, a numerical simulation of a three-dimensional viscous flow was carried out using OpenFOAM software system [21]. The system is based on a set of libraries that provide tools for solving systems of partial differential equations in both space and time. The working language of the code is C ++. In terms of this language, most of the mathematical differential and tensor operators in the program code (before translation into the executable file) equations can be presented in a readable form, and the discretization and solution method for each operator can be selected by the user during the calculation.

The calculated area is taken to be the volume of liquid filling the inner space of a flexible pipe 1 m long and 38 mm in diameter.

A mesh of computational domain was created by the block method, a computational mesh with hexahedral cells and a wall layer was constructed to ensure the value y + ≤2 [21-22].

The velocity vector in m/s was set as a boundary condition in the inlet section. The calculation was carried out for the operating range of the pump Q: 50 - 300 L/min. At the exit from the computational domain, the static pressure was set equal to P/ρ = 101.325 $m^2/s^2$.

A comparison of the experimental and calculated pressure losses along the length of the pipe is shown in Fig. 6. The numerical results are recalculated for the operating conditions of the coiled tubing. Consistence of the experimental data is observed for aqueous solutions with xanthan gum concentration up to 6 g/L.

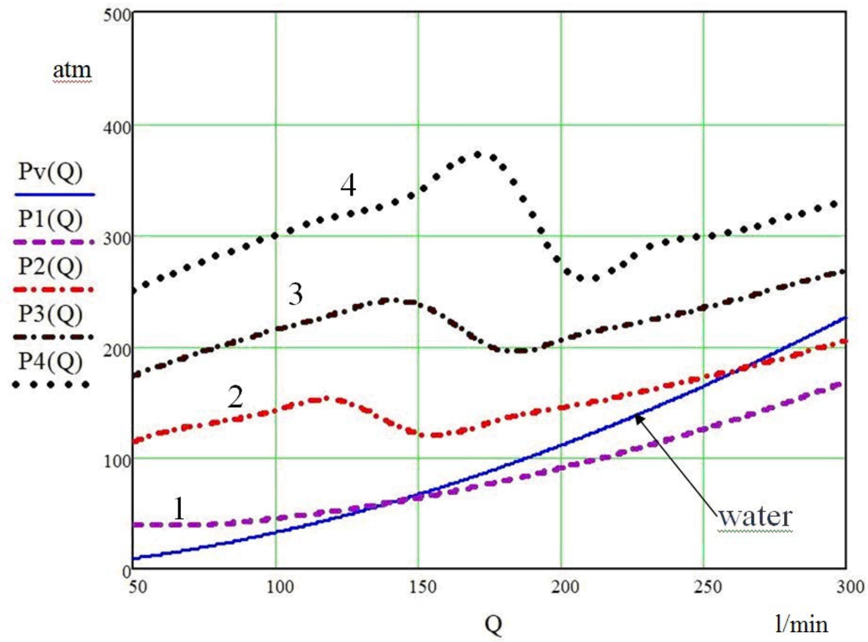


Fig. 6. Comparison of the experimental and calculation pressure loss along the pipe length. Concentration of xanthan gum:1 – 2,4 g/L; 2 – 6g/L; 3 – 8,4 g/L; 4 – 12 g/L. Δ – calculation points received by the *OpenFOAM*

## 6. Conclusions

Research of polymer additives in process fluids have shown that solution based on biopolymer additives is considered a non-Newtonian fluid. A structure of viscous non-Newtonian rate model fluid based on xanthan gum in a coiled tubing coiled tubing has been studied.

The basic equations of the mathematical model of stationary motion of a generalized Newtonian fluid do not differ from the classical model of a Newtonian fluid. In turbulent flows, the molecular viscosity of a non-Newtonian medium depends on the fluctuating shear rate. Therefore, when describing a turbulent flow, it is necessary to operate with the averaged value of the effective molecular viscosity.

Modeling a three-dimensional viscous flow of a non-Newtonian viscous fluid shows an adequate similarity between the experimental and calculated data, which indicates the correct choice of the mathematical model, the turbulence model and the correctness of determining the coefficients of the power-law model of the fluid and.

The research results make it possible to predict the value of the drag coefficient and pressure loss when pumping a viscous non-Newtonian fluid through a flexible coiled tubing pipe.

To improve the accuracy of design work, it is necessary to carry out preliminary laboratory studies of the rheological parameters of the test fluid (drilling fluids, water-oil mixtures, solutions with polymers.

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