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STUDY OF THE FLOW STRUCTURE AND HYDRAULIC PRESSURE LOSSES IN A WELL WITH A RETRIEVABLE CORE RECEIVER

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ABSTRACT

A mathematical model of the drilling mud flow in a removable rectilinear core barrel well is made up. The flow structure of in the well design elements was studied using numerical simulation. Pressure losses in the wellbore were analyzed. It was discovered that the main contribution to the pressure difference values is made by the annular channel between the borehole walls and the drill pipes, as well as the crown bit.

Key words: Drilling, Drilling Mud, Crown Bit, Rheological Parameters, Power-Law Model, Pressure Drop.

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1. INTRODUCTION

One of the methods to reduce the pressure drop in a well is the development of rock cutting tools that allow for not only drilling wells effectively but also for ensuring effective removal of sludge and low-pressure drops. Currently a substantial theoretical and experimental material for the drilling muds in the annular channels [1-2] is accumulated. Newtonian laminar flows in a concentric channel have a well-known analytical solution, which can be found in the classic textbook by L. D. Landau and E.M. Lifshitz [3]. A strict analytical solution is unknown for eccentric annular channels, but many approximate and asymptotic solutions have been proposed (Snyder, Gerald, Goldstein, 1965 [4]), including considering the rotation of the inner tube (Wannier, 1950). Besides, Newtonian currents have a sufficiently large number of different empirical correlations working in one or another range of parameters. The most common correlations can be found in the reference books (Kirillov, 1984 [5]) and (Idelchik, 1992 [6]).

The work by Volarovich and Gutkin (1949) [7], who proposed an approximation of an analytical solution to the pressure flow of a Bingham liquid in a concentric ring channel, was one of the very first papers on laminar flows in non-Newtonian fluids in annular channels.

Fredrickson obtained the first exact solutions of this problem for power and Bingham liquids in cooperation with Bird (1958) [8] and Laird (1957) [9]. In addition to the flows of power-law and Bingham fluids in a concentric annular channel in various approximations, the flows of other visco-plastic fluids were theoretically investigated: the Eyring fluid (Bird, 1965), the Rabinovich fluid (Rotem, 1962), the Eyring fluid (Nebrensk and Ulbrecht, 1968), the Casson fluid (Shulman, 1970), the Herschel-Bulkley fluid (Hanks, 1979) [10] and the Robertson-Stiff fluid (widely used to describe drilling fluids (Fordham et al., 1991)). Asymptotic solutions, considering the presence of eccentricity, were also proposed for some of these rheological models: Vaughn (1965) for the power-law fluids, Guckes (1975) [11] for the Bingham fluids, Haciislamoglu and Langlinais (1990) for the Herschel-Bulkley fluid, as well as for concentric channels in the presence of the inner tube rotation (Rivlin, 1956) [12].

Many papers on the numerical modeling of data flows appeared with the development of computer technology in parallel with the theoretical and experimental studies of currents in the annular channels. First of all, the following papers shall be mentioned: Locket (1992) - modeling of power-law and Bingham fluids flows; Hussain and Sharif (1998), [13] - modeling of power-law and Herschel-Bulkley fluids flow in an eccentric channel with partial blocking and considering the inner tube rotation; Mori, Nakamura, Horikawa (1987), [14] - modeling the viscoelastic fluid flow in a channel with eccentricity and the inner tube rotation.

Separately, it is worth highlighting a whole series of experimental and computational works by M.P. Escuider [15-17], who together with his colleagues devoted many papers to the study of laminar and turbulent flows of Newtonian and non-Newtonian media in annular channels with eccentricity and the inner tube rotation.

Despite the vast amount of theoretical, computational and experimental studies on the drilling mud flow in wells, the available materials cannot adequately provide the necessary information about all flow parameters in the required full range of parameters of the drill string and the rheological properties of the fluid. It is critical to have information on hydraulic resistance and flow structure in the well while drilling for valid and reliable control of the drilling process. This paper used computational fluid dynamics (CFD) methods based on the numerical solution of the spatial and nonstationary Navier-Stokes equations as applied to the complex rheology of real drilling muds [18-19] to solve these problems.

2. MATHEMATICAL MODEL

The mathematical model of the drilling mud flow is based on the RANS approach. It is believed that the Navier-Stokes equation can be described as a laminar or turbulent flow, but modern capabilities of existing computers are such that virtually all real achievements in calculating turbulent flows are associated with the use of semi-empirical turbulence models using the Reynolds approach. The essence of this approach is to solve the averaged Navier-Stokes equations:

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla\left(\rho \mathbf{v} \cdot \mathbf{v}\right) = -\nabla p + \nabla(\boldsymbol{\tau} - \rho \overline{\mathbf{v}' \cdot \mathbf{v}'}) + \mathbf{F}, \qquad \textbf{(7)}$$

where $\mathbf{v}$ is the time-averaged velocity field; $-\rho \overline{\mathbf{v}' \cdot \mathbf{v}'}$ is the Reynolds stress tensor.

When constructing two-parameter turbulence models, the Boussinesq hypothesis of isotropic turbulent viscosity is used to determine the components of the Reynolds stress tensor:

$$-\rho\overline{\mathbf{v}'\cdot\mathbf{v}'}=\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\left(\rho k+\mu_t\frac{\partial u_i}{\partial x_i}\right)\delta_{ij}, \quad \textbf{(8)}$$

where μ_t is turbulent viscosity; k is the kinetic energy of turbulent pulsations.

Using the Boussinesq concept allows for building many two-parameter semi-empirical models. This work uses the two-band two-parameter Menter SST model as the primary model for modeling turbulent flow.

The Menter model is written by superposing the k-ε and k-ω models, based on the fact that the k-ε models better describe the properties of free shear flows, in the k-ω model, they have an advantage in modeling near-wall flows. A smooth transition from the k-ω model in the near-wall region to the k-ε model far from solid walls is provided by introducing the empirical weight function F1.

The second important detail of the model is to change the standard connection between the k, ω, and turbulent viscosity. A modification of this connection consists in introducing the transition to the Bradshaw formula in the near-wall area. According to the Bradshaw's assumption, the shear stress in the boundary layer is proportional to the energy of turbulent pulsations.

Transport equations for k and ω:

$$\frac{\partial\rho k}{\partial t}+\nabla\left(\rho\mathbf{v}\cdot k\right)=\nabla\left((\mu+\sigma_k\mu_t)\cdot\nabla k\right)+\tilde{P}-\beta^*\rho\omega k, \quad \textbf{(9)}$$

$$\frac{\partial\rho\omega}{\partial t}+\nabla\left(\rho\mathbf{v}\cdot\omega\right)=\nabla\left((\mu+\sigma_\omega\mu_t)\cdot\nabla\omega\right)+\gamma\rho\frac{P}{\mu_t}-\beta\rho\omega^2+(1-F_1)\cdot(2\rho\sigma_{\omega 2}\frac{1}{\omega}\nabla k\cdot\nabla\omega). \quad \textbf{(10)}$$

A limiter is introduced in the turbulent energy generation term:

$$P=\tau^t{}_{ij}\frac{\partial u_i}{\partial x_j} \quad \tilde{P}=\min(P,20\cdot\beta^*\rho\omega k), \quad \textbf{(11)}$$

Weight function and its argument

$$F_1=\tanh(\arg_1{}^4)$$

$$\arg_1=\min(\max(\frac{k^{1/2}}{\beta^*\omega y},\frac{500\mu}{\rho\omega y^2});\frac{4\rho\sigma_{\omega 2}k}{CD_{k\omega}y^2}), \quad \textbf{(12)}$$

where the positive part of the cross diffusion terms in the transfer equation of ω:

$$CD_{k\omega}=\max(2\rho\sigma_{\omega 2}\frac{1}{\omega}\nabla k\cdot\nabla\omega;10^{-10}), \quad \textbf{(13)}$$

Expressions for the vortex viscosity with allowance for the Bradshaw hypothesis:

$$\mu_t=\frac{\rho a_1 k}{\max(a_1\omega;F_2\Omega)}, \quad \textbf{(14)}$$

where the vorticity magnitude is:

$$\Omega=\sqrt{2\Omega_{ij}\Omega_{ij}}, \quad \textbf{(15)}$$

The switching function F2 is defined similarly to F1:

$$F_2 = \tanh(\arg_2{}^2)$$
$$\arg_2 = \max(2\frac{k^{1/2}}{\beta^*\omega y}, \frac{500\mu}{\rho\omega y^2}) \quad \textbf{(16)}$$

The constants in the transfer equations are written by a superposition of the constants for the k-ω model (Wilcox) and the constants of the standard k-ε model.

Constants:

$$\phi = \phi_1 F_1 + \phi_2(1-F_1) \quad \phi = \{\sigma_k, \sigma_\omega, \gamma, \beta\}$$

A set of constants for the SST surface layer model:

$$\sigma_{k1} = 0.85 \quad \sigma_{\omega 1} = 0.5 \quad \beta_1 = 0.075 \quad \gamma = \frac{\beta_1}{\beta^*} - \frac{\sigma_{\omega 1}\kappa^2}{\sqrt{\beta^*}}$$

Set of constants for free shear layers:

$$\sigma_{k2} = 1.0 \quad \sigma_{\omega 2} = 0.856 \quad \beta_2 = 0.0828 \quad \gamma = \frac{\beta_2}{\beta^*} - \frac{\sigma_{\omega 2}\kappa^2}{\sqrt{\beta^*}}$$

Other constants used in the model:

$$\beta^* = 0.09 \quad \kappa = 0.41 \quad a_1 = 0.31.$$

Since in most cases the drilling fluid is a non-Newtonian one, a simplified approach is used to model non-Newtonian flows [7-8], in which the medium is treated as a nonlinear viscous liquid with the introduction of an effective fluid viscosity $\mu(\dot{\gamma})$ of the fluid, generally depending on the shear rate. In this case, the viscous stress tensor τ is defined as follows:

$$\tau = \mu D.$$

The components of the strain rate tensor $\mathbf{D}$ have the form of:

$$\mathbf{D}_{ij} = \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i},$$

the shear rate $\dot{\gamma}$ is the second invariant of the strain rate tensor:

$$\dot{\gamma} = \sqrt{\frac{1}{2}\mathbf{DD}}.$$

Depending on the mud rheology, the effective viscosity has the form of $\mu(\dot{\gamma}) = k$, for a Newtonian medium (k is the molecular viscosity of a liquid), $\mu(\dot{\gamma}) = k\dot{\gamma}^{n-1}$ for the Power-Law model, $\mu(\dot{\gamma}) = \frac{k\dot{\gamma} + \boldsymbol{\tau}_0}{\dot{\gamma}}$ for the Bingham plastic model, $\mu(\dot{\gamma}) = \frac{k\dot{\gamma}^n + \boldsymbol{\tau}_0}{\dot{\gamma}}$ for the Herschel-Bulkley model, where n and k are the rheological model components, $\boldsymbol{\tau}_0$ is the yield strength of viscoplastic fluid.

3. DESIGN CALCULATIONS

Computations were performed based on the complete hydraulic wells model, which considers the actual layout of the drilling and core barrels of the removable rectilinear core barrel well-NQ complex.

The geometry and computational grid for the crown bit are shown in Figures 1-2. The total granularity of the calculated grid was about 600,000 nodes.

Figure 1. Photo of the impregnated diamond crown bit by Terekalmaz JSC.

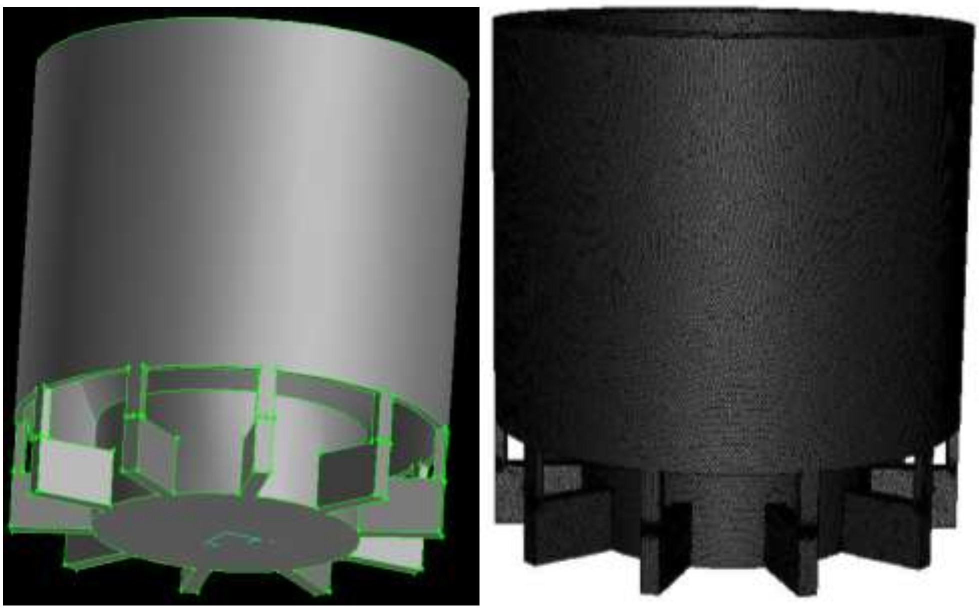

Figure 2. The geometry of the crown bit and a calculation grid fragment

The acrylic polymer solution with the following rheological parameters was taken as a model washing liquid: n = 0.35, k = 1.82 $MPa \cdot c^n$, density of 1,050 kg/m^3, well diameter of 0.0757 m, drilling pipe outer diameter of 0.069 m, fluid flow rate varied in the range from 40 to 70 l/min, and drill string rotational speed of 500 rpm.

The flow pattern in the main elements of the removable rectilinear core barrel-NQ well is shown in Figures 3-8.

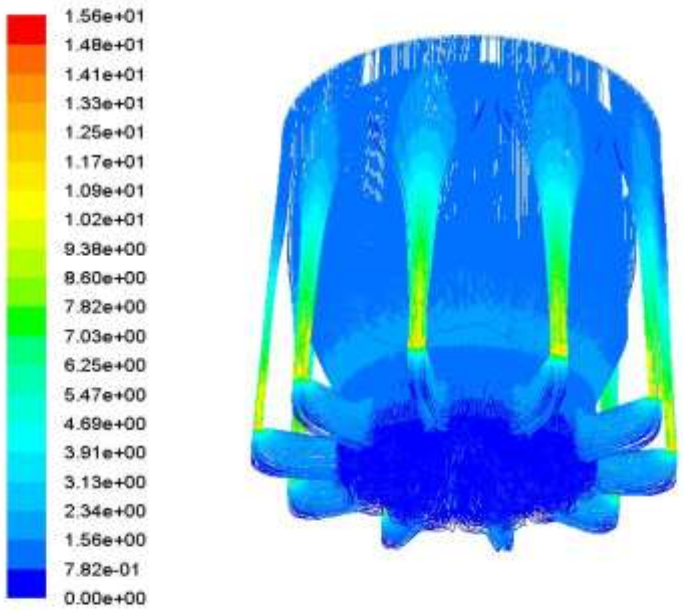

Figure 3. Visualization of the drilling fluid flows through the flushing channels of the crown bits, in m/s.

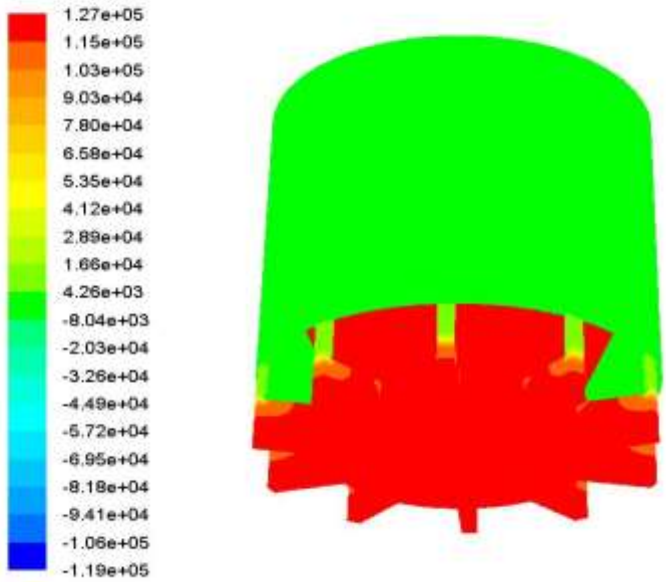

Figure 4. Static pressure on the crown bit walls, in Pa/m.

Pressure loss analysis in the crown bits shows that the principal losses at the drilling fluid flow are observed in the narrowing of the flushing channels of the crown bit (see Fig. 4). It is recommended to optimize the shape of the washing channels to reduce the pressure loss in the crown bits. This study is planned for the future.

Figures 5-7 show the rather complex structure of the flow in the core receiver channels. When the drilling fluid outflows from the round holes of the core receiver, an extensive flow recirculation zone is formed (see Fig. 6), which is a source of additional pressure loss.

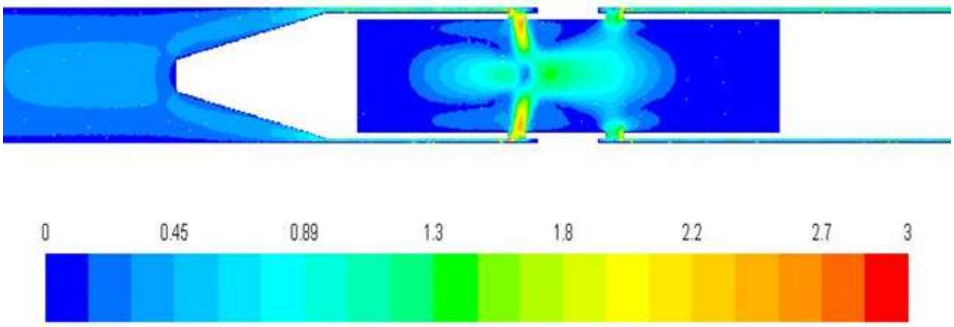

Figure 5. The speed module in the core catcher, in m/s

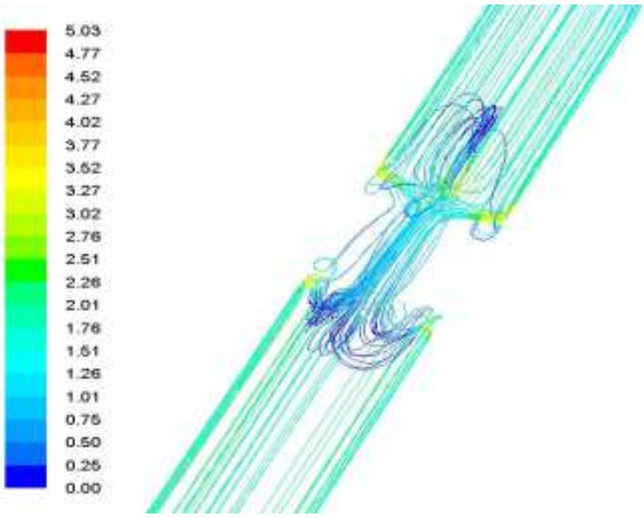

Figure 6. Visualization of the drilling fluid flow in the core catcher, in m/s.

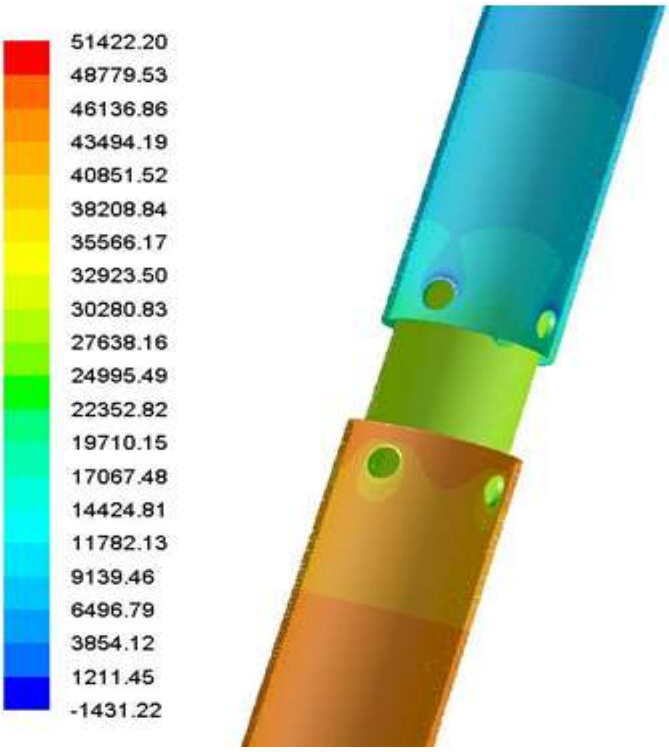

Figure 7. Static pressure on the core receiver walls, in Pa/m.

Figure 8 shows the velocity distribution and profile in the annular channel. As can be seen, the annular gap thickness in removable rectilinear core barrel well is minimal (3 mm). In this case, the effect of the angular velocity of the drill pipe rotation is insignificant. A flat section characteristic of non-Newtonian flows is observed on the velocity profile in the central part of the annular channel.

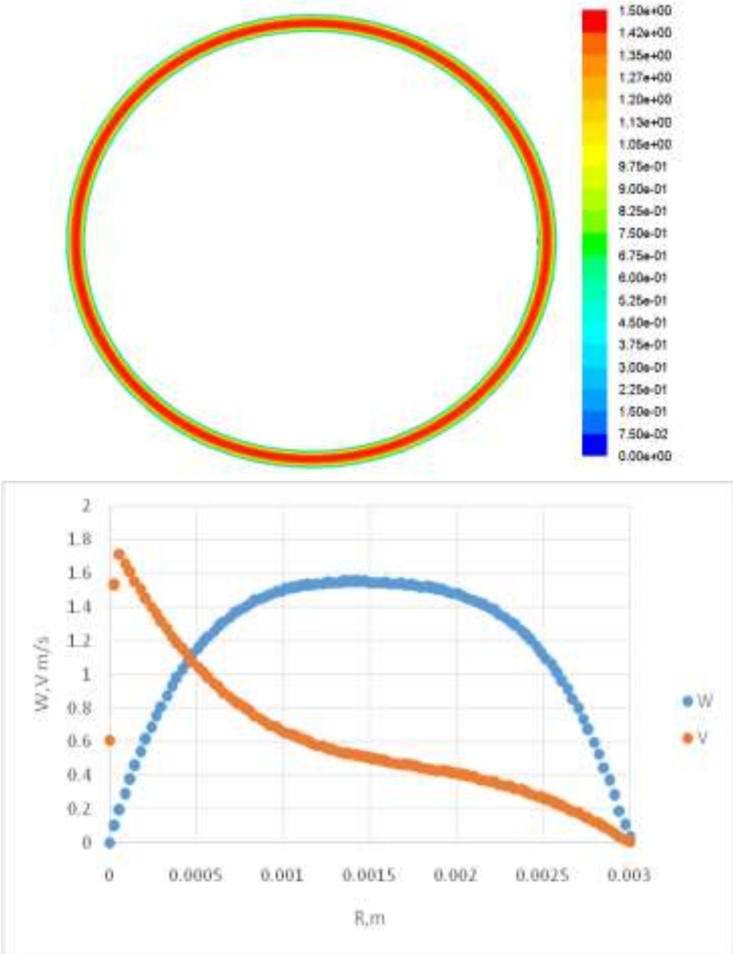

Figure 8. Isolines and axial and tangential velocity components profiles in the annular gap, in m/s.

Table 1 shows the calculation of the pressure drop at various flow rates obtained for the removable rectilinear core barrel well-NQ complex in numerical simulation. It is seen that the main pressure loss occurs when the drilling fluid moves in the annular space. This is a specific feature of drilling with removable rectilinear core barrel well complexes, in which the annular channel width is 3 mm. The remaining elements of the complex make a significantly smaller contribution to the total pressure loss in removable rectilinear core barrel well.

Table 1 The pressure drop in the various elements of the removable rectilinear core barrel well and the annular space layout at different flow rates, Pa.

Drilling complex element	Flush flow rate, l/min			
	40	50	60	70
Core catcher	25172.4	31980.1	40397.6	50085.5
Crown bit	37825.3	51710.6	69766.9	89986.1
Reamer shell	5105.9	5788.3	6511.4	7348.1
Drill pipe	6829.4	6859.8	7115.2	7618.2
Annular channel	678915.9	834483	1002072	1170245

4. CONCLUSIONS

The authors developed a mathematical model and a method for calculating the flushing fluids flow in removable rectilinear core barrel wells. Theoretical models and modern numerical methods of mathematical modeling were used to develop a methodology for calculating hydraulic losses in removable rectilinear core barrel drilling wells with non-Newtonian fluids. The theoretical approach is based on the computational fluid dynamics methods. The mathematical model is based on the solution of three-dimensional non-stationary Navier-Stokes equations consisting of mass conservation equation or motion equations and the equations of motion or momentum conservation principle. A widely known approach, in which the medium is treated as a non-linear viscous liquid with the introduction of an effective fluid viscosity, which in general depends on the shear rate, was used to model non-Newtonian flows.

The calculation method adapts to the complex spatial geometry of real wells, considers the drilling process conditions (flow pattern, drilling mud flow rate, drill pipe rotation speed, eccentricity, etc.), and real mud properties (density, rheology).

The flow structure of in the well design elements was studied using numerical simulation. Pressure losses in the wellbore were analyzed. It was discovered that the main contribution to the pressure difference values is made by the annular channel between the borehole walls and the drill pipes, as well as the crown bit.

In the future, it is planned to use this data for the design and manufacture of a new rock cutting tool for drilling wells.

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REFERENCES

[1] Gnoevoy, A.V., Klimov, D.M. and Chesnokov, V.M. Fundamentals of the Bingham Media Theory. Moscow: FIZMATLIT, 2004.

[2] Wilkinson, W.L. Non-Newtonian fluids. Hydrodynamics, mixing and heat transfer. Moscow: Mir, 1964.

[3] Landau, L.D. and Lifshitz, E.M. Theoretical Physics: Textbook. In 10 volumes. Vol. VI. Hydrodynamics. Moscow: Nauka, 1986.

[4] Snyder, W.T. and Gerald, A. Analysis of Fully Developed Laminar Flow in an Eccentric Annular. *A.I.Ch.E. Journal*, 11(3), 1965, pp. 462-467.

[5] Kirillov, P.L. Handbook of Thermohydraulic Calculations. Moscow: Energoatomizdat, 1984.

[6] Idelchik, I.E. Handbook of Hydraulic Resistance. Moscow: Mechanical Engineering, 1992.

[7] Volarovich, M.P. and Gutkin, A.M. Bingham Viscous Liquids Flow Between Two Parallel Walls and in the Annular Space. *Journal of Applied Physics*, XVI(3), 1949, pp. 321-328.

[8] Fredrickson, A.G. and Bird R.B. Non-Newtonian flow in annuli. *Ind. Eng. Chem*., 50, 1958, pp. 347-352.

[9] Laird, W.M. Slurry and Suspension Transport. Basic Flow Studies on Bingham Plastic Fluids. *Ind. Eng. Chem*., 49(1), 1957, pp. 138-141.

[10] Hanks, R.W. The Axial Laminar Flow of Yield-Pseudoplastic Fluids in a Concentric Annulus. *Ind. Eng. Chem.*, 18(3), 1979, 488-493.

[11] Guckes, T.L. Laminar Flow of Non-Newtonian Fluids in an Eccentric Annulus. *J. Eng. Ind.*, 1975, pp. 498-506.

[12] Rivlin, R.S. Solution of Some Problems in the Exact Theory of Viscoelasticity. *J. Rat. Mech. Anal.*, 5(1), 1956, pp. 179-188.

[13] Hussein, Q.E. and Sharif. M.A.R. Viscoplastic Fluid Flow in Irregular Eccentric Annuli. *J. Energy Res. Tech.*, 120, 1997, pp. 201-207.

[14] Mori, N., Eguchi, T., Nakamura, K. and Horikawa, A. Pressure Flow of Non-Newtonian Fluids between Eccentric Cylinders with the Inner Cylinder Rotating. *Journal of the Textile Machinery Society of Japan*, 33(2), 1987, pp. 46-53.

[15] Escudier, M.P., Gouldson, I.W., Oliveira, P.J. and Pinho, F.T. Effects of Inner Cylinder Rotation on Laminar Flow of a Newtonian Fluid through an Eccentric Annulus. *International Journal of Heat and Fluid Flow*, 21, 2000, pp. 92-103.

[16] Escudier, M.P., Oliveira, P.J., Pinho, F.T. and Smith, S. The Fully Developed Laminar Flow of Non-Newtonian Fluids through Annuli: Comparison of Numerical Calculations with Experiments. *Experiments in Fluids*, 33, 2002, pp.101-111.

[17] Nouri, J.M. and Umur, H. Flow of Newtonian and Non-Newtonian Fluids in Concentric and Eccentric Annuli. Cambridge: Cambridge University Press, 1993.

[18] Neverov, A.L., Minakov, A.V., Zhigarev, V.A. and Karataev D.D. Improving the Efficiency of Constructing Deep Wells Complexes with Removable Core Receiver. *Journal of Mining Science*, 6, 2016, pp. 75-85.

[19] Zhigarev, V.A., Neverov, A.L., Guzei, D.V. and Pryazhnikov, M.I. Studying Laminar Flows of Power-Law Fluids in the Annular Channel with Eccentricity. *IOP Conf. Series: Journal of Physics: Conf. Series*, 899, 2017.