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Aspects of computer modeling the processes of transport and cleaning from cuttings in horizontal well sections

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Аспекты компьютерного моделирования процессов транспорта и очистки от шлама горизонтальных участков скважин

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The relevance of the study is related to the need to form clear ideas about the factors of successful drilling operations and make a number of generalizations to existing methods for predicting the transport and cleaning of wells with a horizontal section, taking into account the features and patterns of drilling fluid flow in real drilling modes. The features of the spatial flow of a drilling fluid with solid particles mixture in the coaxial and eccentric areas of the well were studied; regularities of the developing steady flow of the mixture along the well were established; recommendations for the practice of applied calculations of the intensification of the cleaning wells process by hydraulic methods were substantiated. A well with a 12-meter horizontal eccentric section was chosen as the object of study, in which the flow was carried out under conditions that were really close to the actual drilling parameters. The universal key to understanding the features and identifying the regularities of the processes considered in the work were the methods of mechanics of inhomogeneous continuums for viscous homogeneous and heterogeneous mixtures, computational fluid dynamics (CFD) combined with the ideas of a complex physical-mathematical and numerical study of internal flows of rheologically complex viscous media. It was established that particles could significantly affect the structure of the averaged and pulsating flow of a droplet liquid, their settling led to the formation of an inhomogeneous anisotropic flow structure, the calculation of which required modern second-order turbulence models for Reynolds stresses. It was shown that in the bottom region of the annular space there was a zone with equivalent phase velocities, where the effects of a decrease in the intensity of molar transfer with an increase in the size of the sediment layer were manifested. Real drilling conditions were characterized by processes that accompany laminarization and stabilization of the mixture flow along the entire length of the well; near the boundary of the fixed layer of settled particles, a narrow layer of their suspended state was formed. Moreover, the bringing of cuttings particles from the reservoir surface, as well as their transition to a suspended state, was mainly determined by convective-diffusion mechanisms, the intensity of the pulsating small-scale movement of vortices with an anisotropic structure and the presence of local areas with "moderately high" flow velocities in contact with a curvilinear unstable to small disturbances section surface. The conditions for the formation of a stagnant zone, in which sedimentation and growth in the size of deposits were intense, were noted. A technology and algorithm for modeling the process of interaction of two-phase flows with the walls of an eccentric pipe was recommended for practice, based on demonstrations of CFD capabilities, as well as conclusions on improving the criteria relationships for determining the minimum drilling fluid flow rates, taking into account the correction of parameters characterizing the rheological features of the mixture, turbulence intensity, annulus geometry. space and connecting nodes.

Ключевые слова:
скважина, бурение, кольцевые потоки, эксцентричность, вращение, ядро, моделирование, гидродинамика, реология, неоднородность, турбулентность, замыкания, шлам, транспорт, седиментация, очистка.

Актуальность исследования связана с необходимостью формирования ясных представлений о факторах успешного выполнения буровых операций и внесения ряда обобщений в существующие методики прогноза транспорта и очистки скважин с горизонтальным участком с учетом особенностей и закономерностей течения бурового раствора в реальных режимах бурения. Исследованы особенности пространственного течения смеси бурового раствора с твердыми частицами в коаксиальной и эксцентричной областях скважины; установлены закономерности развивающегося установившегося течения смеси по скважине; обоснованы рекомендации в практику прикладных расчетов интенсификации процесса очистки скважин гидравлическими методами. В качестве объекта исследования выбрана скважина с 12-метровой горизонтальной эксцентричной секцией, в которой течение осуществляется в условиях, реально близких к фактическим параметрам бурения. Универсальным ключом к уяснению особенностей и выявлению закономерностей рассматриваемых в работе процессов выступают методы механики неоднородных сплошных сред для вязких гомогенных и гетерогенных смесей, вычислительной гидродинамики (CFD) объединенные идеями комплексного физико-математического и численного исследования внутренних течений реологически сложных вязких сред. Установлено, что частицы способны оказывать существенное влияние на структуру осредненного и пульсационного течения капельной жидкости, их осаждение приводит к формированию неоднородной анизотропной структуры течения, для расчета которой требуются современные модели турбулентности второго порядка для напряжений Рейнольдса. Показано, что в донной области межтрубного пространства имеется зона с эквивалентными скоростями фаз, где проявляются эффекты снижения интенсивности молярного переноса при росте размеров пласта отложений. Для условий реального бурения характерны процессы, сопровождающие ламинаризацию и стабилизацию течения смеси по всей длине скважины, вблизи границы неподвижного слоя осевших частиц наблюдается формирование узкого слоя их взвешенного состояния. Причем принос частиц шлама с поверхности пласта, а также их переход во взвешенное состояние в основном определяется конвективно-диффузионными механизмами, интенсивностью пульсационного мелкомасштабного движения вихрей с анизотропной структурой и наличием локальных областей с «умеренно высокими» скоростями потока, контактирующего с криволинейной неустойчивой к малым возмущениям поверхностью раздела. Отмечены условия формирования застойной зоны, в которой интенсивны седиментация и рост размеров отложений. Для внедрения в практику рекомендуются технология и алгоритм моделирования процесса взаимодействия двухфазных потоков со стенками эксцентричной трубы, основанные на демонстрации возможностей CFD, а также на заключении по совершенствованию критериальных связей определения минимальных скоростей течения бурового раствора с учетом коррекции параметров, характеризующих реологические особенности смеси, интенсивность турбулентности, геометрию межтрубного пространства и соединительных узлов.

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Introduction to the Problem of Cuttings Transport Modeling and Well Cleaning

Currently, horizontal wells are the most common type of oil and gas wells, drilling of which is complicated by the technological imperfections of cleaning curved wellbore from waste products. Cleaning control by monitoring the processes of cuttings transport, complicated by the interaction of the viscous mixture with the drill pipe walls, can reduce capital and operational costs for special equipment maintenance. And this is one of the major modern drilling challenges, which relies on computational technologies and mathematical modeling methods for hydrodynamics and coupled heat and mass transfer of heterogeneous media in internal systems. Moreover, in comparison with a relatively clear analysis of the mechanisms and drill product removal patterns along vertical well zones, and the establishment of corresponding features in directed sections requires a detailed study of the exchange processes of momentum, mass, and heat transfer, especially under conditions of extended well coverage. All of this raises the challenges of developing universal models to forecast the flow aspects of complex structured viscous mixtures in eccentric pipes within the computational fluid dynamics (CFD) methods. It includes the analysis of changes in local and integral flow properties, such as, the pressure drop, resistance, friction stress, vortex size and intensity of averaged, pulsating motion under the action of stable, transitional and laminar effects.

Due to the multiparametric, multidimensional, and multifactorial nature of the theoretical analysis, special attention should be paid to the issues of verifying the cleaning modeling results. In the context of CFD methods and models, researchers often refer to resource-intensive approaches that include the concept of discrete phase modeling (Lagrangian method), as well as more flexible second-order statistical turbulence models [1, 2] to account for the evolution of "fine" flow structure and the geometric arrangement of the medium particles [3, 4].

In such conditions, researchers face the urgent challenge to reduce computational time and resource consumption, as numerical modeling of hydrodynamics and mass transfer in rheologically complex mixtures, within the Euler-Euler and Euler-Lagrange approaches, increases the accuracy requirements for calculations in specific flow zones of heterogeneous mixtures in the eccentric annular space of wells and at the phase interaction boundaries [4, 5].

Lack of reliable experimental data on local momentum parameters and mass transfer processes in a mixture under actual drilling conditions (in situ), an essential tool for assessing the results reliability can be an integral analysis with a comprehensive forecast of well cleaning processes, framed within the Euler-Euler and Euler-Lagrange approaches. This would provide insight into the fundamental mechanisms that determine real drilling and the flow of rheologically complex mixtures in the eccentric annular zone, as well as formulate conditions for effective well cleaning.

The study aims at searching for the features of spatial flow of drilling mud mixtures with solid particles in the coaxial and eccentric areas of the well; to determine the patterns of the developing steady mixture flow along the well; and to provide recommendations for the practical calculation of intensifying the well cleaning process using hydraulic methods. The object of the study is a well with a 12-meter horizontal eccentric section, where the flow occurs under conditions close to the actual drilling parameters.

To understand the features and uncover the patterns of the processes considered in the work, the mechanics of heterogeneous continua for viscous homogeneous and heterogeneous mixtures, computational fluid dynamics (CFD) are used, combined with complex physical-mathematical and numerical internal flows study of rheologically complex viscous media. The research relevance is connected with clear insights into the factors affecting the effective drilling operations and the methodologies for forecasting well transport and cleaning, considering the features and trends of mixture flow in real drilling modes.

Brief overview of references

The interconnected thermodynamic processes occur in the elements of drilling equipment, the components of which are: heterogeneous mixture flow, mass transfer; heat transfer; rheophysical effects, which form at least five groups of variables (geometric; hydrogasdynamic; thermal; mass transfer, and physicochemical) It causes the problem of formulating a mathematical model in the form of differential equations system for the conservation laws of mass, momentum, energy of individual constituent phases (or its components), which use closure relations with phenomenological parameters about the the process and the medium. These parameters should be determined experimentally, which is quite challenging due to the multi-scale nature of the transfer processes in the well. Under such conditions, the concept of a complex theoretical and experimental study [3–5] on cleaning the operational areas of drilling equipment amidst a wide range of variations in the hydrogasdynamic and thermal diffusion parameters of the mixture within the well becomes particularly effective. It is clear that mathematical modeling methods within the software have proven to be essential in the studying cuttings transfer and transport in horizontal wells.

Bilgesu et al. [6] were among the first to apply the computational fluid dynamics apparatus within the Eulerian-Eulerian (EE) approach to analyse the influence on drilling of the transport mode specifics of a liquid mixture with cuttings, changes in the fluid properties in wells with an arbitrary borehole. These results encouraged researchers to analyze the details of nonlinear effects that accompany and complicate the mixture flow in pipes, for example, through the drill pipe rotation.

Therefore, Han et al. [7] also turned to the Eulerian approach to clarify the influence of coaxial pipe rotation on the cuttings transport in arbitrarily inclined wells. The need to assess the influence of changes in the solid phase particles structure on the cleaning intensification led Mme et al. [8] to undertake forecasts of cleaning within the Euler-Lagrange (EL) approach. However, within the range of studied parameter changes, the calculation results did not confirm the expected impact on cleaning intensification. This conclusion highlights that the actual drilling conditions are accompanied by nontrivial effects, the resultant value of which is highly sensitive to the specification of the force spectrum that define the hydrodynamics and mass transfer within a mixture with a complex structural composition, including the nature of both intra- and interphase interactions of its components.

The calculations by Xiao et al. [9] demostrated that effective wellbore cleaning requires a significant intensification of the convective-diffusion mechanisms involved in the momentum and mass transfer in the mixture, optimizing the operating parameters of flow and mass transfer processes. The study also emphasizes the impossibility to achieve complete cleaning of the cross-section without mechanical means. Furthermore, it is noted that modeling the mixtures flow in the annular well space, taking into account connections in real drilling conditions, demonstrates a significant accumulation of cuttings particles in these areas.

In the studies of Sun et al. [9, 10], Demiralp [11] it is shown that in modeling straight-swirling complex shear flows (for example, considering the coaxial drill pipe rotation [9,10], predicting turbulence [11]), the swirl mode is effective only at relatively low values of the velocity vector circumferential component. Its effectiveness is lost as it increases. Additionally, the evolution of the developing turbulent flow is successfully predicted by SST kω-turbulence model [1–5, 11], showing low-Reynolds zones of near-wall internal flows.

The results of studies by Ofei et al. [12–14] showed the flexibility of CFD models in forecasting various mixture transport modes, scenarios for cleaning the annular space with a correlation error of integral flow and mass transfer with corresponding experimental data ranging from 1 % to 12 %. Considering the current experience of applying CFD in solving hydrodynamic problems, Kamyab et al. [15] attempted to assess the capabilities of the EE approach in predicting the technology of coiled tubing drilling (CTD) under conditions when pipe rotation is impossible. They aimed to determine the minimum transport velocity (MTV) of the mixture necessary for effective well cleaning, assuming that the drilling fluid has the Newtonian fluid properties.

Detailed theoretical and experimental studies to identify the changes in the pressure drop effect observed during the flow of various drilling fluids (assuming arbitrary rheology) at different flow rates, in the same configuration, performed by Sayindla et al. in [16], showed that generalizing modeling methods for changes in the rheological mixture properties allows for good correspondence between theoretical data and practice in pressure field forecast.

Additionally, it is important to mention the results of Heydari et al. [17], who assessed the closure of the governing motion equations using models with a scalar quantity of molar viscosity within the EE approach in CFD. They suggested the necessity of including second-order models for Reynolds stresses, such as RSS-k-ε, -ω, -L [1–5, 18, 19] type, in order to achieve more accurate predictions of the anisotropic structure characteristic in real drilling conditions and mixture transport in wells.

The analysis of data presented by Epelle and Gerodjorgis [20, 21] on the characteristics of cuttings transport and the patterns for intensifying the cleaning process shows that within the EE and EL approaches, the two-parameter standard k-ω model is effective in describing turbulence [19]. Moreover, both approaches have prediction errors for integral parameters in the range of up to 11 % when compared to corresponding experimental data.

The analysis of flow structure and the mixture composition calculation within the EL approach, with improved closure models to account for shape and structure changes of solid particles based on the Syamlal – Obrien [22] and Gidaspow [23] models, demonstrated that the assumption of spherical particle shape can significantly influence the modeling results, leading to a pressure drop in the working well section of up to 11 %.

In the studies by Akshik and Rajabi [24], and Ignatenko et al. [25], a successful attempt was made to adapt the EL approach for modeling transport processes in gas-liquid mixtures with solid particles, commonly used in drilling applications [24], as well as to consider coaxial rotation of the inner pipe [25]. The simulations indicated [25] that the swirling flow mode establishes conditions for vortex flow at low viscosities and rotation speeds, which contributes to a pressure drop and significantly affects the solid particles transport through the annular eccentric space.

Additionally, the analysis of the drilling fluids rheophysical properties highlight the results obtained by Pang et al. [26, 27] on non-Newtonian fluids of the Herschel-Bulkley type. Specifically, in [26], it was shown that a reduction in liquid viscosity significantly changes the cuttings particles concentration in the annular area. Similar results were observed in [27] when water was used as the working fluid. This analysis suggests that transitional processes have a substantial effect on cuttings flow, influenced by factors such as the non-linearity in the rheological properties of the medium, the structure and shape of particles, and the combined effects of coaxial and orbital drilling pipe rotations on the direct flow movement. All the aspects require accurate real drilling modeling and predictions related to the pipe twisting effects while clarifying the influence of orbital rotation effects. The highlighted challenge presents a prospect for numerical modeling of drilling processes. Therefore, the review of existing articles [3, 6–27] allows us to identify the following key points.

1. EE and EL approaches of the CFD method satisfactorily predict the well cleaning modes in horizontal sections, with average error ranges in integral parameters (such as correlations between theoretical and experimental pressure field values) of up to 12 %. However, the computational costs using the EL approach increase significantly due to the introduction of particle structure details and the SST k-ω turbulence model application for describing momentum transfer processes in low Reynolds number zones of the annular space.

2. To account for changes in the structure and shape of the mixture particles, Syamlal – Obrien [22] and Gidaspow [23] models are used. The models can most completely and accurately predict the flow mixture characteristics in the well quantitatively within the hydrodynamic mode and geometric configurations considered in the study.

3. It has been established that in the given formulations of the governing equations, their approximations, as well as assumptions about the mixture flow under the action of external and internal forces, the cuttings transport is very sensitive to the features, modes, details of the liquid phase flow, its rheology, and changes in the geometry of the well eccentric annular space.

Physical assumptions for mixture transport modeling in a well

We will assume that the drilling fluid behaves as a viscous droplet-like fluid with non-Newtonian rheology, fully capable of cuttings transport through the well eccentric space from the borehole to the surface. It is taken into account that its flow is complicated by factors such as particle sedimentation at the bottom section and the dense layer formation as a reservoir. The layer dimensions are highly dependent on the conditions and operating modes of drilling equipment, such as the effect of gravity, increased torque on the drill string with higher resistance, sticking of pipes, as well as challenges related to logging. It is assumed that the layer thickness is much less than the width of the annular area; the mixture flow in the upper part of the cross-section is influenced by the specifics of momentum and mass transfer in the bottom zone. Furthermore, we accept that a change in the well inclination angle is one of the major factors influencing the cuttings transport efficiency in the space configuration with the drill pipe eccentricity. The annular flow space exhibits asymmetry and significant narrowing under the drill pipe, which substantially complicates the particles transport through the annular space.

It is assumed that the rheological properties of the drilling fluid are described by the Herschel-Bulkley effective viscosity model, and their changes in response to deformation processes caused by flow dynamics can significantly effect well cleaning operations. It is also accepted that while drilling horizontal wells, the drill pipe may come into contact with the bottom part of the wall due to the pipe weight. Finally, we assume that the technology for constructing a numerical solution to the mathematical model will rely on the mechanics of heterogeneous continuous media, computational fluid dynamics methods, and theories of resistance, heat and mass transfer.

When predicting the mechanisms accompanying the flow of liquid and solid phases, the interactions occurring within and between phases in the momentum and mass transfer of the drilling fluid and solid particles in the eccentric annular well space, it is taken into consideration that the solid cuttings particles are chemically inert and spherical with a diameter d. The volume fraction occupied by the dispersed solid phase is characterized by $\alpha_p < O(10^1)$ values, and collisions between particles are neglected. The particle material density significantly exceeds the density of the carrier (liquid droplet) medium. We also assume that the established mixture flow mode is viscous-inertial and occurs under conditions of isothermal straight-line flow in the well.

In the given assumptions, aspects of computer modeling are related to characteristics of flow structure changes, minimum cuttings transport rate along the well length, and forecasting the conditions for uninterrupted operation of the technological equipment.

Mathematical model of fluid flow with cuttings particles in the well annular eccentric space

The flow of a dropping viscous fluid with complex rheology containing solid particles under isothermal steady laminar and turbulent modes in eccentric coaxial pipes, oriented horizontally and inclined in the action of gravity, is described by a system of differential equations that represent the mass (1) and momentum (2)–(4) conservation law, which have the general form [28–30]:

$$\frac{\partial(\alpha_q \rho_q)}{\partial t} + \nabla\cdot(\alpha_q \rho_q \vec{\upsilon}_q) = \sum_{p=1}^{N}(\dot{m}_{pq} - \dot{m}_{qp}) + S_q; \qquad (1)$$

$$\frac{\partial(\alpha_q \rho_q \vec{\upsilon}_q)}{\partial t} + \nabla\cdot(\alpha_q \rho_q \vec{\upsilon}_q \vec{\upsilon}_q) = -\alpha_q \nabla p + \nabla\cdot\bar{\bar{\tau}}_q + \alpha_q \rho_q \vec{g} + \sum_{p=1}^{N}(K_{pq}(\vec{\upsilon}_p - \vec{\upsilon}_q) + \dot{m}_{pq}\vec{\upsilon}_{pq} - \dot{m}_{qp}\vec{\upsilon}_{qp}) + (\vec{F}_q + \vec{F}_{lift,q} + \vec{F}_{Vm,q}), \qquad (2)$$

$$\bar{\bar{\tau}}_q = \alpha_q \mu_q (\nabla\vec{\upsilon}_q + \nabla\vec{\upsilon}_q^{T}) + \alpha_q(\zeta_q - \frac{2}{3}\mu_q)\nabla\cdot\vec{\upsilon}_q \bar{\bar{I}} \qquad (3)$$

$$\frac{\partial}{\partial t}(\alpha_s \rho_s \vec{\upsilon}_s) + \nabla\cdot(\alpha_s \rho_s \vec{\upsilon}_s \vec{\upsilon}_s) = -\alpha_s \nabla p - \nabla p_s + \nabla\cdot\bar{\bar{\tau}}_s + \alpha_s \rho_s \vec{g} + \sum_{l=1}^{N}(K_{ls}(\vec{\upsilon}_l - \vec{\upsilon}_s) + \dot{m}_{ls}\vec{\upsilon}_{ls} - \dot{m}_{sl}\vec{\upsilon}_{sl}) + (\vec{F}_s + \vec{F}_{lift,s} + \vec{F}_{VM,s}). \qquad (4)$$

In the equations (1)–(4) it is accepted that the indices q and s characterize the liquid and solid phases parameters, respectively; ρ – density; $\vec{\upsilon}$ – velocity vector; S_q – a source term that is absent in this statement; $\dot{m}_{qp}$ – the mass transfer intensity from p to q phase (in our case there is no transfer from the liquid to the solid phase, therefore $\dot{m}_{pq} = \dot{m}_{qp} = 0$); $\bar{\bar{\tau}}_q$ – stress tensor of the q phase; μ_q, ς_q – coefficients of shear and bulk viscosity of the q phase; p – pressure, K_{pq} – interfacial momentum exchange coefficient; $\vec{F}_s, \vec{F}_{lift,s}, \vec{F}_{VM,s}$ – respectively, the external force, the lift force, the virtual mass additional force of the solid phase particles (in our case, they are small and are neglected); p refers to the pressure used by all phases; p_s – the pressure of the solid phase particles; $K_{ls} = K_{sl}$ – the momentum exchange coefficient between the liquid and solid phases. It is evident that the dynamics are predominantly influenced by: viscous effects; pressure gradient forces; gravitational forces; and the resistance of interfacial processes.

According to the rheological equation (3) used to close equation (2) of the liquid phase with Newtonian rheology, it is assumed that in the case of a non-Newtonian viscoplastic system for the formulation of the Herschel-Bulkley model we have a combination of parameters (5):

$$\mu_{eff} = \mu_{eff}\left(\bar{\bar{\tau}}, \bar{\bar{S}}, T, P\right), \qquad (5)$$

where $\bar{\bar{\tau}}, \bar{\bar{S}}$ represent the stress and deformation rate tensors of the liquid phase, respectively. It should be noted that in heterogeneous media, μ_{eff} also depends on the concentration, shape and size of the particles. As specific formulations of non-Newtonian fluids rheology (the Herschel-Bulkley models for shear viscosity $\mu_q = \mu_{eff}$) we have (6):

$$\bar{\bar{\tau}} = \tau_0 + \kappa \bar{\bar{\dot{S}}}^{n}, \mu_{eff} \equiv \mu_f = (\tau_0 + \kappa \dot{\Gamma}^{n})\dot{\Gamma}^{-1}. \qquad (6)$$

Turbulence model and its features in the forecast of complex internal mixture flows

The results of preliminary studies (see, for example, [1–5, 18, 19, 31–35]) have shown that the two-parameter RANS models are quite reliable in forecast of the interconnected internal and interphase heat, mass, and momentum transfer processes in low Reynolds number zones of developing flows. These models serve as an effective base for multi-parameter Reynolds stress transfer models (RSS), such as SST–$k\omega$ [19], –kL [18, 35, 36], – $k\varepsilon$ [33], and – $k\tau$ [34]. The general (in index, brief, and symbolic form for Cartesian variables) representation of the RSS model (7) with a two-parameter hydrodynamic base (8), according to, for example, [35], takes the following form:

$$C_{ij} = D_{ij} + P_{ij} + R_{ij} + \varepsilon_{ij}; \qquad (7)$$

$$C_f = D_f + P_f + \varepsilon_f. \qquad (8)$$

Here the indices i, j ($i, j = \overline{1-3}$) respond to Reynolds stresses ($\overline{u_i' u_j'}$), f is a formal parameter of a base specific dissipative equation, that defines the reference to the differential transport equation, for example, for ω, ε or L. Other symbols characterize stress transfer mechanisms. $\overline{u_i' u_j'}$ (and the f feature) due to convection (C), diffusion (D), generation (P), redistribution (R), dissipation (ε), with detailed formulations available in references such as [35].

It is noteworthy that when choosing appropriate turbulence model in the governing equations closure of the liquid phase dynamics, it should be taken into account that within the accepted assumptions of the geometric and hydrodynamic configuration and the heterogeneous mixture composition with a relatively high volume concentration of solid phase (up to 10 %), anisotropic effects will appear in the mixture flow structure. Under these conditions, it is reasonable to forecast the dynamics using the RSS turbulence model (within the ANSYS CFD package) with reference k, -ω, -ε, -L-bases modified to account for the movement mechanisms of the two-phase medium by the entrainment of solid cuttings particles by the carrier dropping liquid through interphase interaction forces as passive impurity particles.

Note that in the RSS model generalizations of two-phase flow in the present study it is assumed (similar to [36]) that the involvement of solid particles in the turbulent motion of the mixture occurs only through the influence of turbulent pulsations of the carrier liquid. Therefore, it is considered that the presence of particles contributes to a decrease in the kinetic energy of turbulent fluctuations. Correction is needed for the dissipative terms of the RSS model base, represented by the initial transfer equations, for example, for k, ω, L. Due to the inconvenience of the closing formulations of the model, they are omitted in this paper, with details available in sources such as [35].

Formulation of boundary conditions

The numerical integration of the governing equations system (1)–(6) and their closure relations (7), (8) is carried out using the following conditions. In the group of geometric conditions, details of the pipe configuration are specified: the longitudinal length (L), width and offset (b) of the core center relative to the longitudinal axis of the outer pipe. In the dynamics the inlet flow velocity (U_0), parameters of the "fine" structure (turbulence intensity (T_u), local properties of vortex – kinetic energy (k) and turbulence dissipation rate (ε), and scale (L) of energy-containing vortices, etc.) are defined. In the diffusion part the mixture composition (α_i) is specified. The thermophysics is determined by physical properties of the mixture: carrier medium (droplet, dispersed) density and particles material (solid, dispersed phase); α_p volume fraction of the solid phase; $\mu_f = \mu_f^0$, $\lambda_f = \lambda_f^0$ dynamic viscosity and thermal conductivity of the dispersed phase (liquid), respectively; as well as properties such as c_{pi} specific heat capacities of the phases, and other (mechanical, structural) quantities of the specific mixture.

It should be noted that to calculate the mixture composition, within the applied physical assumptions and EE/EL approaches, the spectrum of external forces is defined by the net effect of the interphace force, which is determined by the resistance force F_D. Moreover, as previously stated (for example, similar to [36–38]), it is assumed that at small α_p, the buoyant force can be neglected. In this case, the dynamics of the cuttings particles trajectories in the tube space can be calculated using equation (9) with the corresponding closure relations (10) in the form:

$$\frac{d\vec{u}_p}{dt} = F_D(\vec{u}_f - \vec{u}_p) + \frac{\vec{F}_{\text{тяж}}(\rho_p - \rho_f)}{\rho_p} + \vec{F}_\Sigma; \qquad (9)$$

$$F_D = \frac{18\mu_f}{\rho_p d_p^2}\frac{c_d \,\text{Re}}{24}, \quad \text{Re} = \frac{\rho_f d_p \left|\vec{u}_p - \vec{u}_f\right|}{\mu_f},$$

$$c_d = a_1 + \frac{a_2}{\text{Re}} + \frac{a_3}{\text{Re}^2}. \qquad (10)$$

Here the indices p, f refer to the particles of cuttings and liquid respectively; F_D is the hydrodynamic resistance force; F_{grav} is gravity; F_Σ – other possible external forces, for example, the Saffman/Magnuss/ buoyant forces, which are neglected within the stated assumptions.

The boundary conditions in the isothermal flow of a dispersed mixture are related to the following relationships of the required parameter at the B_i, where i = 1 (inlet), 2 (outer boundary of the annular zone), 3 (inner wall of the pipe), and 4 (outlet). At the inlet (B_1), homogeneous phase profiles (known for the process) along the cross-section and the phases are in equilibrium, at the outlet (B_4) – "soft" boundary conditions (flow continuity). At the walls of the coaxial space (B_2, B_3) for the dispersed (carrier) phase, no-slip conditions are formulated for all averaged and oscillatory response of the dropping liquid; for the cuttings particles slip conditions are applied.

Details of the numerical algorithm

Numerical integration of the equations describing hydrodynamics and mass transfer in the mixture (1)–(8) with the corresponding closure relationships (9), (10), is performed on operations that are: staggered grid construction of the computational domain for the considered problem; finite difference approximation of the differential equations, reducing the equations to the corresponding discrete analogy; a system of linear algebraic equations (SLAE) with the sought quantities for the dynamic and diffusion problem at the nodal points of the computational grid; solving the SLAE using an iteration method. These issues are detailed in previous publications (see, for example, [1–5, 35]). To achieve the required accuracy in integrating the equations, a corresponding smallness criterion is introduced between the solutions obtained in the last two iterations (m, $m+1$) for the corresponding spatial changes in the sought local parameters ($\text{F} = \{\vec{u}_f, \vec{u}_p, \overline{u_i' u_j'}, k, \varepsilon, \omega, L\}$) and their integral values (for example, $\text{F}_{wf} = \tau_{wf}$–), which corresponds to the type (11):

$$\max_{i,j,k}\left\{\frac{\left|\text{F}_{i,j,k}^{m+1} - \text{F}_{i,j,k}^{m}\right|}{\text{F}_{i,j,k}^{m+1}}\right\} \le \Delta_\text{F}, \Delta_\text{F} = O(10^{-2}), \% \qquad (11)$$

Also, the influence analysis of grid refinement on the accuracy of results allowed us to establish the optimal size of the difference grid. Calculations have shown that for the forecast of the viscous-inertial-gravitaty mixture flow with developed turbulence, a difference grid with a total nodes number of $1.5 \cdot 10^5$ is quite acceptable; the shape of this grid, for example, for an eccentricity e = 0.8, is presented in Fig. 1. Our experience indicates that when constructing the numerical solution for the problem, the density is quite satisfactory for the behavior trends of the algorithm, model, and calculation method in terms of the "cost – quality – accuracy" ratios when forecasting the well cleaning details from cuttings and its transport through the annular space at Re = $(0.08 \ldots 5) \cdot 10^5$. The pressure field calculation is performed using the standard SIMPLE procedure [39].

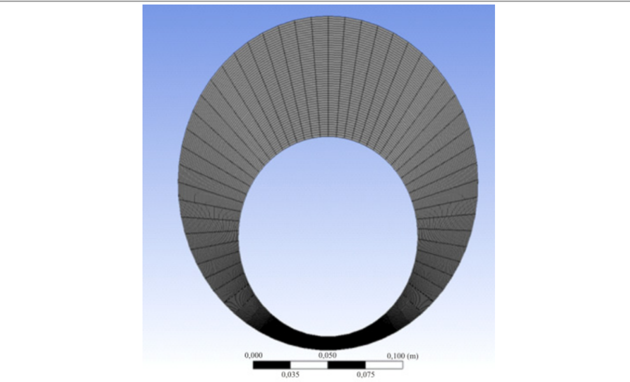

Fig. 1. Optimal view of the difference grid generated within the ANSYS CFD software for transport conditions and horizontal sections cleaning of eccentric pipes in real drilling

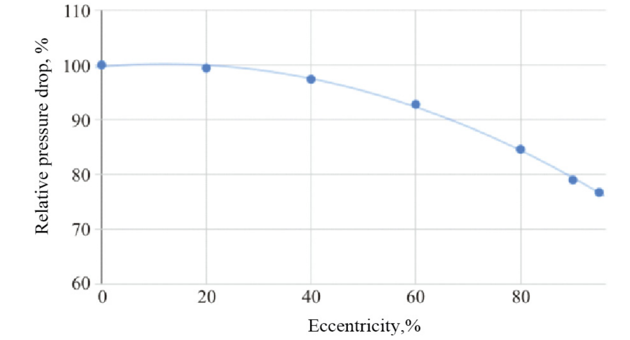

Fig. 2. Variation in dimensionless pressure drop ($\Delta p / \Delta p_0$, %) as a function of increasing core eccentricity $e = 2b/(D-d)$

Verification of the numerical results for the distribution of local and integral flow and mass transfer parameters in pipes was carried out with reference to relevant theoretical and experimental data fields of averaged and fluctuating velocities in homogeneous and heterogeneous internal flows in coaxial and eccentric pipes. This includes analytical data on the velocity field changes in laminar flow [40–42], as well as results of indirect accuracy analysis for the pressure drop calculation in eccentric pipes, performed using an engineering approach [43, 44] for turbulent flow conditions at Re = $(1 \ldots 8) \cdot 10^4$, in a pipe configuration with parameters: L = 10 m, R_2 = 0.1 m, R_1 = 0.06 m, μ = 0.001003 kg/ms. Comparison of the calculation results with engineering forecast data (within the criterion relationships for the pressure drop using software [43, 44]) indicate that a grid size of H = $(r \cdot \Theta \cdot x) \equiv (50 \cdot 60 \cdot 50)$ provides a pressure drop calculation accuracy with an error of (1–2) %, making further increase in the number of nodes unnecessary, especially from the perspective of numerical schemes efficiency, as well as the efficiency of the computational algorithm, and implementation costs. Fig. 2 presents the the dimensionless values distribution of the relative pressure drop ($\Delta p / \Delta p_0$, %) as a function of changes in eccentricity

(e, %), which confirms (see, for example, [42, 45–47]) the trend of decreasing pressure drop with increasing core eccentricity, while maintaining the conditions of physical similarity of flows with a flow rate Q = *idem*. It is noteworthy that the points in Fig. 2 correspond to the actual flow calculations in pipes at Re = 80,000. The curve represents the approximating line of the calculation results, Δp_0 corresponds to the pressure drop in the axisymmetric channel, $D = 2R_2$ is the diameter of the outer pipe, $d = 2R_1$ is the inner pipe diameter, and b is the offset of the pipe centers.

Considering the results within the approaches performed in [42–47], we note that detailed comparisons of $\Delta p/\Delta p_0$ distribution nature during drilling require considering the changes in the flow mode, rheology, physical properties of the liquid, as well as the parameters determining the geometry of the channel and their combinations (for example, R_2/R_1, etc.). The lack of reliable experimental data for the droplet liquid (water) flow always poses the challenge of verifying the obtained results based on their qualitative correspondence to similar processes.

Moreover, our experience in studying turbulent flow hydrodynamics of heterogeneous media in pipes with a complex cross-sectional shape [1–5] shows that the used RSS models of turbulence with k-ω/*L*- the reference base (in the ANSYS CFD PC) predict these processes with good accuracy. In addition, general estimates of the grid nesting showed that the required settling step in time, ensuring the stability of the numerical solution, is about 1–4 s. These data were obtained using an Intel i7-8700 CPU (with 12 cores, 3.2 GHz), which required about 15 days to simulate 10 s of mixture flow time, which is equivalent to one complete circulation of the flow through the examined geometry.

Details of processes hydrodynamic similarity in wells, useful in applications

Given peculiarity of momentum, heat and mass transfer in the considered problem, significantly complicated by the multidimensional, multiparametric, and multifactorial effects of intra- and interphase exchange between the mixture components during their complex flow in an eccentric region, it is worth noting that for a systematic analysis of the features, establishing the patterns of flows, as well as issuing conclusions for practice, it is important to formulate the defining criteria of the similarity. These data will allow localizing areas of space with a non-trivial nature of changes in the mixture local/integral properties under well cleaning conditions. In the considered hydrodynamic and geometric configuration of the developing mixture flow, along with the criteria of Reynolds $\left(\mathrm{Re} = \frac{\rho_f^0 U_0 (R_2 - R_1)}{\mu_f}\right)$, Frouda $\left(Fr^2 = \frac{g(R_2 - R_1)}{U_0^2}\right)$, Prandtl $\left(\mathrm{Pr} = \frac{\mu_f c_f}{\lambda_f}\right)$, Schmidt $\left(Sm = \frac{\mu_f}{\rho_f^0 D_{mix}}\right)$, Bingham $\left(Bn = (\frac{\tau_0}{\kappa})(\frac{R_2 - R_1}{U_0})^n\right)$, where τ_0 is yield shear stress, there are dispersed flow criteria [28–32], such as Stokes (Stk $= \tau_r/\tau_{hd}$, where τ_r is particle dynamic relaxation time $\left(\tau_p = \frac{\rho_p^0 d^2}{18\mu_f}\right)$, τ_{hd} – characteristic hydrodynamic time of the process ($\tau_{hd} = L/U_0$)), particle weight fraction/loading $\left(\mathrm{M} = \frac{\rho_p^0 \alpha_b}{\rho_{fb}^0}\right)$ and the isobaric heat capacities ratio of solid particles and fluid $\left(\hat{C} = \frac{c_p}{c_f}\right)$.

Then, analyzing the real drilling modes and the corresponding mixture flows in the well, it should be taken into account that under conditions of Stk << 1, processes are possible when the cuttings particles will have velocities equal to the movement of the dispersed (droplet) liquid. Such a state is typical for conditions of dynamically equilibrium mixture flow, in which the phase velocities are assumed to be the same, and the dispersed flow itself can be described by a model of a single-phase medium with specific "effective" properties. Otherwise (Stk > 1), effects arise in the flow in which the particles are insensitive to changes in the properties of the dispersed medium due to the negligible effect of the liquid phase on the cuttings particles. Additionally, for mixture flow modeling, it is useful to take into account that at very high Stk values, calculations should be carried out using the frozen flow model [48]. The latter corresponds to the flow pattern of a dispersed medium with suspended particles in a single-phase flow, and with a change in the loading criterion (M), the intensity of the Stk criterion influence can change. Note that under non-isothermal flow conditions, the heat capacity criterion will account for the intensity of the differences between the characteristic times of thermal and dynamic relaxation of the dispersed phase.

Calculation results and their discussion

As physical assumptions, we present specific study of the features and regularities of the dispersed flow hydrodynamics and the transport of drilling products along the annular space. The results of numerical modeling correspond to the actual drilling process with a mass flow rate G = (23…24) kg/s of a rheologically complex mixture (Newtonian/non-Newtonian liquid), similar in properties to water. The given values of G correspond to an average liquid velocity of approximately $\bar{U}_f$ = m/s (or 373 g/min) and a solid phase particle velocity (sand) of approximately $\bar{U}_p$ = 1.596 kg/s. It should be noted that the values of G, $\bar{U}_f$, $\bar{U}_p$ are adequate for a sand volumetric fraction of about α_p = 1 % or drilling in a formation with 20 % porosity at a rate of 100 feet/hour, fully comply with drilling standards. It is assumed that the turbulent effects in the flow are sustained by a turbulence intensity of about T_u = 1…10 %. These values have been chosen to meet the extreme conditions of drilling, where the rate of penetration (ROP) is relatively high, but the flow velocity is still relatively low. Along with this, the hydrodynamic and geometric configurations of drilling are defined by the following parameters. For the pipe geometry, it is assumed: $x_k \equiv L$ = 10…15 m; R_2 = 0.1…0.2 m; R_1 = 0.06…0.12 m; e = 0.1…0.9. The thermophysical properties of the mixture are described by the following values: for the droplet liquid – ρ^0_f = 998.2 kg/m³, λ^0_f = 0.599 W/(m•°C); μ^0_f = 0.001003 kg/(m•s); c^0_f = 4.183 kJ/(kg•°C); for the dispersed phase (spherical sand particles) – ρ^0_p = 1650…2650 kg/m³; λ^0_p = 1.13…0.50 W/(m•°C); c^0_p = 2.09…0.3 kJ/(kg•°C); d_p = 5…6 мм.

The hydrodynamic part corresponds to the viscous-inertial-gravitational laminar and turbulent flow regimes in the range of changes in the Reynolds criterion: Re = (0.8…1)•103, (0.1…1)•105. Moreover, the changes detailing in the hydrodynamic and diffusion structures of the flow in the well is performed according to the data on the mixture entering the pipe at: $\bar{U}_f$ = 0.1 m/s (Re = 800); 1 (80000), as well as changes in such determining criteria as Cameron $\left(X^+ = \frac{1}{\mathrm{Re}}\frac{x}{L_0},\ L_0 = x_k \text{ или } \quad L_0 = R_2 - R_1\right)$, Schmidt (Sm), Prandtl (Pr), Froude (Fr), Bingham (Bn), Stokes (Stk), mass fraction (M), heat capacities (Ĉ), in the following range of numerical values: $X^+ \leq 0.5$ (laminar regime), 0.003 (turbulent regime); Sm = 0.038; Pr = 6.8; Fr ≤ 6.5 (laminar regime), 0.9 (turbulent regime); Bn = (0…5)•10^{-2}; Ĉ = 0.5…0.07; M = 2.654…1.65; Stk ≤ 0.053 (laminar regime), 0.53 (turbulent regime); $\frac{\rho_f^0}{\rho_p^0}$ = (0.605…0.376); α^0_p ≤ 1…10 %.

It should be noted that the calculations of mixture flow dynamics were performed using ANSYS CFD software package and applied the Euler-Euler approach. The results indicate that when the mixture passes through a well and the flow is loaded with particles, the following is observed: 1) a pressure drop for the given actual drilling conditions by a magnitude of 1047 pounds per square inch; 2) a continuous increase in the thickness of the cuttings particle layer about 2.6 %, which satisfactorily agrees with existing experiments [49]; 3) 100 % accumulation of cuttings in the eccentric space, following the analysis of the mass mixture flow rate at the pipe outlet; 4) an increase in annular and average mass velocities as a result from the reduction of the flow's effective cross-section due to cuttings accumulation, as well as the intensification of the convective-diffusive transfer mechanisms of mixture momentum and mass; 5) increased sedimentation of particles in the lower part of the well and destruction of the upper layer boundary. These features illustrate individual results of the calculations, presented in Fig. 3–7. In particular, the evolution of the dynamic average and pulsating flow structure along the pipe length is demonstrated by the axial component profiles calculations of the mixture velocity vector $u = (1 - \alpha_p)u_f + \alpha_p u_p$ when using the model with transport equations for Reynolds stresses (RSS-$k\omega$) (Fig. 3) and the coefficient of scalar molar viscosity forecasted by the two-parameter SST-$k\omega$-models (Fig. 4), for the turbulent flow regime at Re = 80,000, T_u = 5 %, R_1 = 0.2 m, R_2 = 0.12 m, e = 0.3, L = 10 m, M = 1.6, Stk = 0.5. The calculations show that the nature, dynamics, and intensity of particle sedimentation in the bottom part along the horizontal pipe section are affected by the parameters: M (flow load), gravity (Fr), and the Stokes criterion value. Thus, at small values (Stk ≤ 0.1), the formation in the flow characteristic conditions of equilibrium motion can be expected, when solid particles maintain an axial velocity close to that of a dispersed (droplet) medium. In this process, particles are intensively carried away by the flow, and the profiles of the averaged axial component retain the viscous-inertial-gravity flow structure with a slight asymmetry in the cross section. However, with increasing values of the Stokes criterion (Stk > 0.1), the effects of dynamic non-equilibrium in the phases become more pronounced. Under their influence, the gravitational force on particle transport is intensified, which promotes their deposition on the lower wall. These features can cause not only symmetry violations in the change of the averaged flow but also in the pulsating structure of the mixture flow, leading to turbulence anisotropy. To forecast these processes, it is advisable to refer to multiparametric RSS turbulence models [1–5, 35].

Data analysis (see Fig. 3, 4) of the axial component and turbulent viscosity in radial pipe sections with a step of Δx = 1 m shows that in the proximal part (x < 5…6 m) the nonlinear mechanisms of convective-diffusion transfer of momentum and mass are most pronounced. In this section, conditions are formed with the restructuring of the velocity field to the self-similar flow regime (Fig. 5). In particular, Fig. 5 shows the changes in the velocity vector axial component of a droplet liquid (water) during turbulent flow (Re = 80,000) in an extended annular eccentric pipe in specific sections identified by radius. Here, lines 1–5 correspond to sections/color: *1* (red) – A = $r/(b/e+R_1)$ = 0.95; 2 (blue) – A = 0.8; *3* (green) – A = 0.6; 4 (purple) – A = 0.4; 5 (pink) – (A = –0.95). The pipe configuration has the following parameters: R_2 = 0.1 m, R_1 = 0.06 m, eccentricity – e = 80 %, off-center distance between the outer and inner pipes – b = 0.032 m.

The results presented in Fig. 5 show that the flow development along the borehole is accompanied by the preservation of the single-phase flow features. It is evidenced by the change's nature in lines 1–5 and the presence of extremes in the axial velocity distribution. It is important to emphasize that the course of such effects has been experimentally confirmed (see, for example, [1, 2, 35, 50, 51]). Moreover, it is clear that momentum transfer processes stabilization is observed at lengths x > 6 m. In particular,

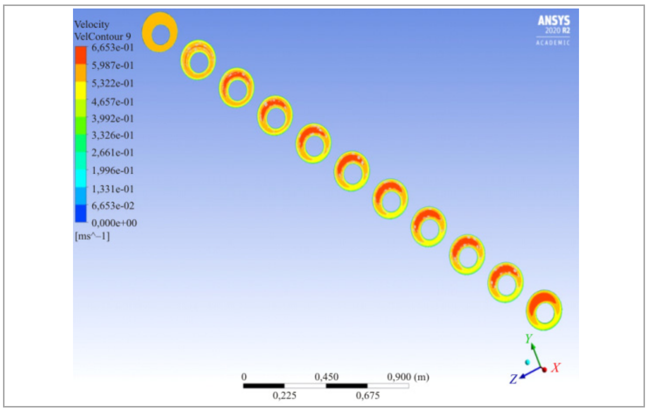

Fig. 3. Changes in the axial component of the velocity vector field during turbulent mixture flow in an eccentric pipe with a horizontal cross-section

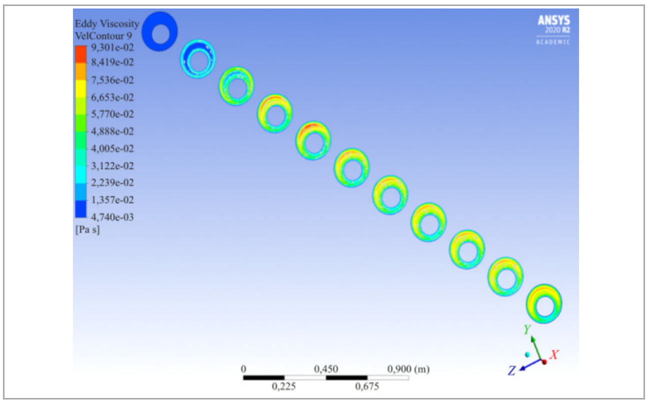

Fig. 4. Changes in molar viscosity (RANS approach, SST-$k\omega$ turbulence model) along the length of the eccentric pipe under the mixture flow conditions with parameters presented in Fig. 3

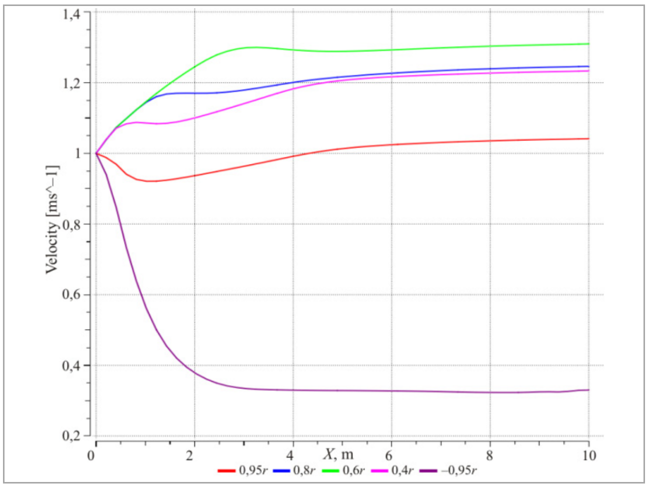

Fig. 5. Changes in the velocity vector axial component of a droplet liquid (water) during turbulent flow in an extended annular eccentric pipe at specific cross-sections distinguished by radius. Here, lines *1–5* correspond to sections/color: *1* (red) – A = $r/(b/e+R_1)$ = 0.95; 2 (blue) – A = 0.8; *3* (green) – A = 0.6; 4 (purple) – A = 0.4; 5 (pink) – (A = –0.95). The pipe configuration has the following parameters: R_2 = 0.1 m, R_1 = 0.06 m, eccentricity – e = 80 %, off-center distance between the outer and inner pipes – b = 0.032 m

in the central area of the live cross-section (lines 1–4), trends associated with the development of flow structure persist, characterized by a velocity field restructuring in the core (lines 2–4) and the wall-adjacent area of the boundary layer (lines 1 and 5).

The area of a large maximum in a pipe flow section x = 2…4 m (line 3) indicates the completion of the stabilization

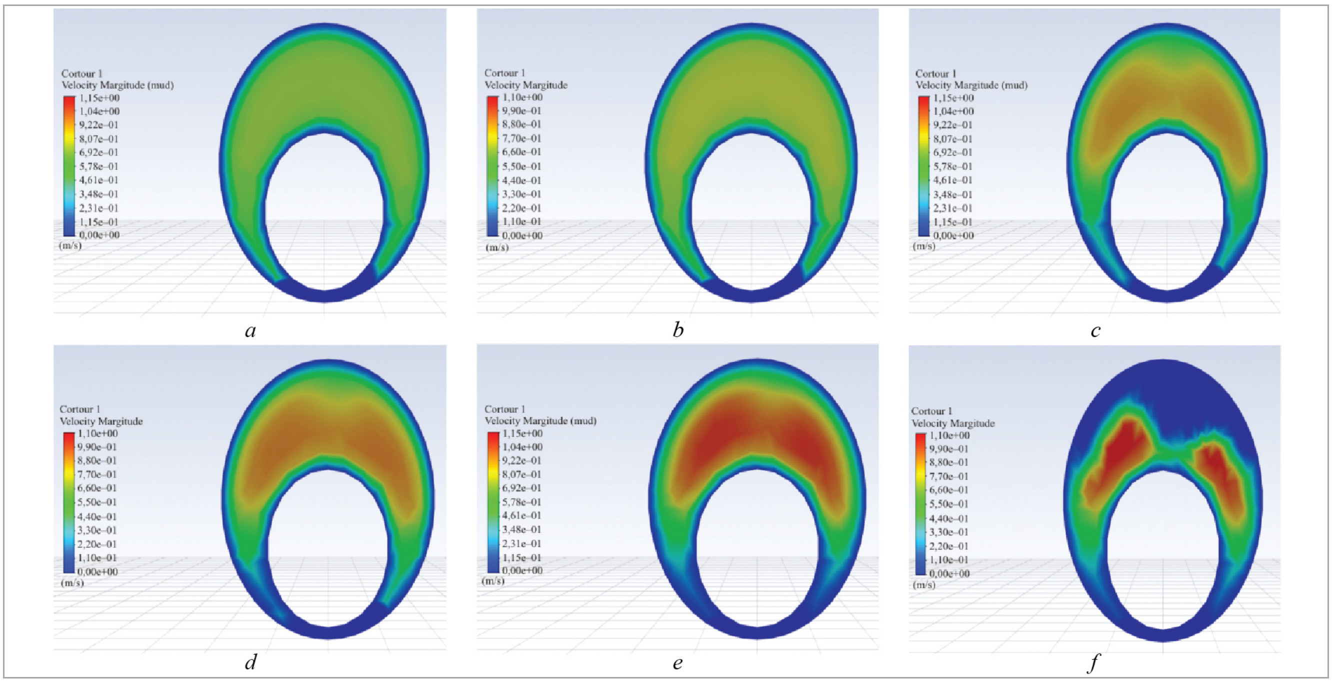

Fig. 6. Patterns of changes (a–e) in the axial component field of the velocity vector in cross-sections selected along the eccentric pipe length. Here the liquid corresponds to the figures: *a* – x = 1 m; *c* – 5 m; *e* – 15 m; sand to – *b* – x = 1 m; *d* – 5 m; *f* – 15 m

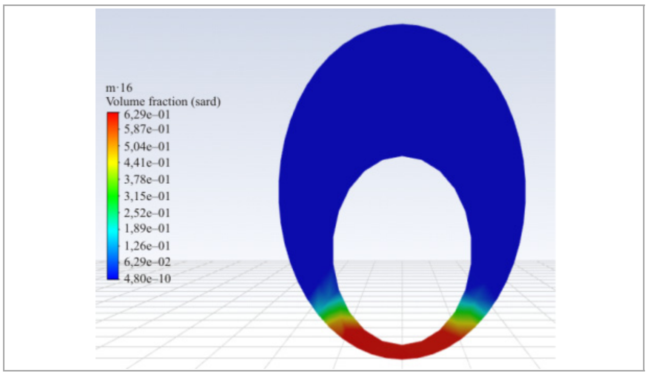

Fig. 7. Radial volume fraction distribution of solid particles (sand) in the outlet section of the eccentric pipe. The calculations correspond to the mixture flow under conditions similar to those presented in Fig. 4 for a pipe at $L = 10$ m, $e = 0.8$

process, after which the flow can be considered as self-similar. The conclusions about the mixture flow in real drilling conditions is valuable from a practical point of view, as it allows for the exclusion of disturbances affecting the mixture transport at the wellbore entrance and enables cleaning process management through engineering methods that take into account the peculiarities of transfer processes in radial planes. In general, the results in Fig. 3–5 show that the homogeneous nature of the mixture flow, even with a weak turbulence intensity (at $x < 3$ m, see Fig. 3, 4), leads to the generation of processes that intensify the flow in the upper part of the annular space cross-section. The increase in turbulent viscosity in the near-wall regions leads to intense flow mixing and is accompanied by a fuller profile of the axial velocity vector component in the liquid phase. It should be noted that as the flow is increasingly loaded with particles, as well as under the influence of gravity, the effect of the radial component of the velocity vector will become negligible. Flow conditions with a negative radial component will arise, intensifying the cuttings accumulation. Moreover, the viscous forces in the bottom part of the eccentric pipe will dominate over the inertial forces, leading to cross section blockage. The changes in the dynamic structure of the liquid and cuttings particles (sand) at specific cross-sections along the eccentric pipes length, presented in Fig. 6 (*a–e*), demonstrate these features. Note that the calculations were performed for the mixture turbulent flow regime (sand, water) at Re = 10^5, T_u = 1 %, R_1 = 0.2 m, R_2 = 0.12 m, e = 0.8, L = 15 m, M = 1.5, Stk = 0.389. The reference to a longer section of the horizontal wellbore is due to the need to clarify the features of solid particle flow under conditions complicated by disturbances in the carrying medium (due to low turbulence in the entry region) and the subsequent spatial restructuring of the averaged and pulsating flow under actual conditions in the pipe with specified parameters.

As follows from Fig. 6 (*a–f*), the stabilization zone of the axial mixture velocity along the length is significantly increased and exceeds the corresponding section for the dispersed (droplet liquid) phase (see Fig. 5 for comparison). Moreover, it is influenced not only by the features of changes in the local structure of the pulsating flow in the initial section (at $x < 5$ m) such parameters as Reynolds stresses, turbulent kinetic energy, pseudovorticity, integral scale of energy-containing vortices, etc., as well as effects related to particle dynamics. It is evident that in the proximal part of the pipe (at $x < 5$) trends towards increased particle inertia near the surface of the inner pipe are emerging. This phenomenon will contribute to the particles sedimentation in the well bottom area at the exit cross-sections (see fig. 6, *f*), thereby increasing the layer thickness. In particular, the data of radial changes in the volume fraction of the solid phase shown in fig. 7, corresponding to the flow conditions depicted in fig. 4, indicate that at the boundary of interaction between particles and the carrying phase, there exists an area for the suspended particles flow. The calculation suggests that when the carrier medium flows over the phase boundary (layer of stationary particles), hydrodynamic instabilities arise, which result in the dispersion of solid particles into the liquid phase.

It should be noted that currently the complex process features of phase interaction at the "layer – flow" interface are still poorly understood. These aspects are promising for clarifying the physical processes nature occurring at the unstable phase boundary and within the narrow zone characterized by high gradients of the interacting phases.

The process analysis in the mixture hydrodynamics within the examined pipes indicates that the influx of sediment particles from the layer surface and the particles transition into a suspended state are mainly determined by convective-diffusive mechanisms, the intensity of pulsating small-scale vortex motion with anisotropic structure, as well as "moderately high" flow velocities interacting with the curved impermeable phase boundary.

Conclusion

1. The study presents a numerical simulation of the liquid droplet mixture transport, similar in its rheological properties to water, along with solid particles (sand) under stationary developing turbulent flow conditions in coaxial eccentric pipes. The flow falls within the class of research on the complex shear flows hydrodynamics in wells with extended horizontal sections, in order to obtain results beneficial for developing recommendations for their effective cleaning under real drilling conditions. The mixture movement with suspended cuttings particles occurs in a turbulent regime, which can significantly influence the averaged and pulsating flow structure of the droplet liquid. It was found that the particles sedimentation under the influence of internal and external forces leads to the formation of a heterogeneous anisotropic flow structure, for which advanced turbulence models with Reynolds stress transport equations are required [1–5, 35]. Our practice shows that such models are more adaptable for processes involving mixtures with separation/addition effects at the phase boundary and the mixture interaction with the well walls.

2. The process of particle sedimentation is significantly influenced by the dispersed medium. Calculations show that in the near-wall and bottom regions of the annular space between the pipes, there is a zone with equivalent phase velocities, demonstrating effects of reduced molar transfer intensity with increasing deposit thickness. The turbulent migration of particles to the bottom is accompanied by a decrease in the transverse component values of the velocity vector and the localization around the drill pipe perimeter of two intensive particle movement zones. Under real drilling conditions, effects of flow laminarization are observed in the well bottom section, which intensifies the stabilization process of the mixture flow over lengths on the order of $x \approx 6$ m.

3. In the stationary layer vicinity of settled particles, a narrow layer of their suspended state is formed. Analysis indicates that the cuttings transport from the deposit surface and the particles transition into a suspended state are primarily determined by convective-diffusive mechanisms, the intensity of pulsating small-scale vortex motion with an anisotropic structure, as well as "moderately high" flow velocities interacting with the curvilinear surface that is unstable to minor disturbances. The study of the issue may be of particular interest in order to clarify the physical nature of the processes at phases interface.

4. Beyond the hydrodynamic stabilization section, tendencies are observed towards filling the velocity profile in the upper part of the cross-section, accompanied by relative acceleration (due to a decrease in viscous forces) and simultaneous deceleration of the flow in the bottom part of the annular section (due to an increase in viscous friction). In this process, the resulting effect of the interaction between inertial, viscous, and gravitational forces within the cross-section of the annular bottom well space leads to intensified conditions for the formation of a stagnant zone, where the processes of particle sedimentation and the growth of deposit thickness will be active. Consequently, over time, the reduction of cuttings accumulation in these areas by hydraulic means will become problematic, necessitating operations with mechanical methods, such as the pipe rotation for cuttings removal.

5. A detailed analysis of the calculations for a complex mixture flow in a well with an arbitrary generating borehole is primarily performed under the assumption of a Newtonian relationship between stress and strain rates in the mixture. However, most drilling fluids are classified as non-Newtonian liquids (such as Herschel-Bulkley type). Moreover, it should be noted that the mixture movement in the well annular space is a characteristic of a laminar regime, and only in rare cases it corresponds to a transitional regime (see, for example, [52]). It must be emphasized that while this study states that turbulence can improve the hydraulic cuttings transport, achieving turbulence during drilling with non-Newtonian fluids is not always possible.

6. As recommendations for the practical calculation of well cleaning from cuttings, an approach grounded in this research can be suggested, along with the technology and algorithm for modeling the interaction process of two-phase flows with the walls of an eccentric channel. This approach is based on the conclusions and demonstrations of the continuous electrodynamic (ED) method ability in forecasting the flows characteristics under consideration. The comparison of experimental data, based on a number of local and integral parameters, such as changes in flow structure and pressure drop along the well, confirm the high efficiency and validity of the methodology.

7. Furthermore, for addressing the technological challenges discussed in this paper, recommendations can be made for improving the criterion relationships used to determine the minimum flow velocities of the drilling fluid. The improvement should take into account the parameters correction that characterize the rheological mixture properties, the turbulence intensity, the geometry of the annular space, and the connectors, similar to the approaches presented in references [53–62].

References

1. Kharlamov S.N., Fatyanov D.S. Study of the structure of turbulent flow of natural raw materials in pipelines with a section of variable cross-section length of the confuser-diffuser type // Bulletin of Tomsk Polytechnic University. Georesources Engineering. - 2020. - Vol. 331, No. 8. - P. 53-67. DOI: 10.18799/24131830/2020/8/2768

2. Kharlamov S.N., Fatyanov D.S. Modeling of spatial flows of viscous media in a system of channels with sections of complex shapes // Bulletin of Tomsk Polytechnic University. Georesources Engineering. - 2021. - Vol. 332, No. 5. - P. 70–88. Doi: 10.18799/24131830/2021/5/3187

3. Kharlamov S.N., Janghorbani M., Filippov K.A. Mathematical modeling and methods for studying hydrodynamic cleaning of horizontal wells // Bulletin of Tomsk Polytechnic University. Georesources Engineering. - 2021. - Vol. 332, No. 8. - P. 53–73. DOI: 10.18799/24131830/2021/8/3305

4. Kharlamov S. N., Janghorbani M. Numerical modeling of flows of viscous mixtures of drill cuttings and crude oil flow in horizontal sections of wells with eccentric drill pipes // New challenges of fundamental and applied geology of oil and gas - XXI century: Proc. all-Russian scientific. conf. with the participation of foreign scientists, dedicated to the 150th anniversary of Academician of the USSR Academy of Sciences I.M. Gubkin and the 110th anniversary of Academician of the USSR Academy of Sciences and RAS A.A. Trofimuk / A. A. Trofimuk Institute of Petroleum Geology and Geophysics SB RAS; Novosibirsk State University. Section 2. Geology of oil and gas. Subsection 3. Oil and gas field geology. - Novosibirsk: IPC NSU, 2021. - 276 p. DOI 10.25205/978-5-4437-1248-2-221-224

5. Kharlamov S. N., Janghorbani M. Numerical study of viscous-inertial laminar swirling flow in a round pipe with an eccentric round core // Bulletin of Tomsk Polytechnic University. Georesources Engineering. - 2021. - Vol. 332, No. 11. - P. 7–21. DOI: 10.18799/24131830/2021/11/3423

6. Computational Fluid Dynamics (CFD) as a tool to study cutting transport in wellbores / HI Bilgesu, MW Ali, K. Aminian, S. Ameri // The Eastern Regional Meeting of the Society of Petroleum Engineers. – Lexington, Kentucky, USA, October, 2002. –27 p. doi: 10.2118/78716-ms

7. Solid–liquid hydrodynamics in a slim hole drilling annulus / SM Han, H. Young Kyu, W. Nam Sub, K. Young Ju // Journal of Petroleum Science and Engineering. – 2010. – Vol. 70, no. 3–4. – P. 308–319. DOI: 10.1016/J.PETROL.2009.12.002

8. Mme U., Pål Skalle. CFD calculations of cuttings transport through drilling annuli at various angles // International Journal of Petroleum Science and Technology. – 2012. – Vol. 6, No. 2. – P. 129–141.

9. Xiao-hua Z., Sun C., Tong H. Distribution features, transport mechanism and destruction of cuttings bed in horizontal well // Journal of Hydrodynamics. – 2013. – Vol. 25, No. 4. – P. 628–638. DOI: 10.1016/S1001-6058(11)60405-9
10. Effect of drillpipe rotation on cuttings transport using computational fluid dynamics (CFD) in complex structure wells / S. Xiaofeng, K. Wang, T. Yan, S. Shao, J. Jiao// Journal of Petroleum Exploration and Production Technology. – 2014. – Vol. 4, No. 3. – P. 255–261. DOI: 10.1007/s13202-014-0118-x
11. Demiralp Yasin. Effects Of Drill-pipe Whirling Motion on Cuttings Transport Performance for Horizontal Drilling. – MSc thesis, Louisiana State University, 2014. – 151 p.
12. Ofei TN, Irawan S, Pao W. CFD method for predicting annular pressure losses and cuttings concentration in eccentric horizontal wells // Journal of Petroleum Engineering. – 2014, No. 4. – P. 110–120. DOI: 10.1155/2014/486423
13. Ofei TN, Alhemyari SA Computational fluid dynamics simulation of the effect of drill pipe rotation on cuttings transport in horizontal wellbores using a Newtonian fluid // International Field Exploration and Development Conference (IFEDC 2015). – 2015. – P. 1–8. DOI: 10.1049/cp.2015.0582
14. Ofei TN Effect of yield power law fluid rheological properties on cuttings transport in eccentric horizontal narrow annulus // Journal of Fluids. – 2016. – Vol. 7, No. 3. – P. 116–124. DOI: 10.1155/2016/4931426
15. Kamyab Mohammadreza and Vamegh Rasouli. Experimental and numerical simulation of cuttings transportation in coiled tubing drilling // Journal of Natural Gas Science and Engineering. -2016. – Vol. 29. – P. 284–302. DOI: 10.1016/j.jngse.2015.11.022
16. Hole-cleaning performance comparison of oil-based and water-based drilling fluids / Sayindla Sneha, Bjørnar Lund, Jan David Ytrehus, Arild Saasen. // Journal of Petroleum Science and Engineering. – 2017. – Vol. 159. – P. 49–57. DOI: 10.1016/j.petrol.2017.08.069
17. Heydari Omid, Eghbal Sahraei, and Pål Skalle. Investigating the impact of drillpipe's rotation and eccentricity on cuttings transport phenomenon in various horizontal annuluses using computational fluid dynamics (CFD) // Journal of Petroleum Science and Engineering. – 2017. – Vol. 156. – P. 801–813. DOI: 10.1016/J.PETROL.2017.06.059
18. Kharlamov S.N., Kim V.Yu., Silvestrov S.I. Numerical modeling of a vortical investigation of heat transfer in fields of centrifugal mass forces in elements of the power equipment with a curvilinear wall // The 5th Proceedings of the International Forum on Strategic Technology (IFOST. University of Ulsan, October, 13–15, 2010), University of Ulsan: Ulsan, South Korea, 2010. – P. 105–109.
19. Menter FR Two-equation eddy-viscosity turbulence models for engineering applications // AIAA Journal. – 1994. – Vol. 32, No. 8. – P. 1598–1605.
20. Epelle Emmanuel I., Dimitrios I. Gerogiorgis. Transient and steady state analysis of drill cuttings transport phenomena under turbulent conditions // Chemical Engineering Research and Design. – 2018. – Vol. 131. – P. 520–544. DOI: 10.1016/j.cherd.2017.11.023
21. Epelle Emmanuel I., Dimitrios I. Gerogiorgis. CFD modeling and simulation of drill cuttings transport efficiency in annular bends: effect of particle sphericity // Journal of Petroleum Science and Engineering. – 2018. – Vol. 170. – P. 992–1004. DOI: 10.1016/j.petrol.2018.06.041
22. Syamlal Madhava, O'Brien TJ The derivation of a drag coefficient formula from velocity-voidage correlations // Technical Note, US Department of Energy, Office of Fossil Energy, NETL, Morgantown, WV., 1987. – P. 1– 11.
23. Gidaspow D. Multiphase flow and fluidization: continuum and kinetic theory descriptions. – Academic press: San Diego, 1994. – 467 p.
24. Akhshik Siamak, and Majid Rajabi. CFD-DEM modeling of cuttings transport in underbalanced drilling considering aerated mud effects and downhole conditions // Journal of Petroleum Science and Engineering. – 2018. – Vol. 160. – P. 229–246. DOI: 10.1016/J.PETROL.2017.05.012
25. Steady-state cuttings transport simulation in horizontal borehole annulus/ Y. Ignatenko, O. Bocharov, A. Gavrilov, R. May // 37th International Conference on Ocean, Offshore Mechanics and Arctic Engineering. American Society of Mechanical Engineers. Digital Collection. – 2018. – No. 51296 (V008T11A051). – P. 12.
26. Numerical prediction of flow behavior of cuttings carried by Herschel-Bulkley fluids in horizontal well using kinetic theory of granular flow / Pang Boxue, Shuyan Wang, Guodong Liu, Xiaoxue Jiang, Huilin Lu, Zhenjie Li. // Powder Technology. – 2018. – Vol. 329. – P. 386–398. DOI: 10.1016/J.POWTEC.2018.01.065
27. Effect of orbital motion of drill pipe on the transport of non-Newtonian fluid-cuttings mixture in horizontal drilling annulus / Pang Boxue, Shuyan Wang, Xiaoxue Jiang, Huilin Lu // Journal of Petroleum Science and Engineering. – 2019. – Vol. 174. – P. 201–215. DOI: 10.1016/J.PETROL.2018.11.009
28. Nigmatulin R.I. Dynamics of multiphase media. – M.: Nauka, 1987. – T. 1. – 464 p.
29. Yeoh GH and Tu J. Computational Techniques for Multi-Phase Flows. – Elsevier Ltd, Inc., 2010. – 210 p.
30. Crowe CT Review - numerical models for dulite gas-particle flows // ASME Journal of Fluids Engineering. – 1982. – Vol. 104 (Sept.). – P. 297–303.
31. Kharlamov SN, Kudelin NS, Dedeyev PO Hydrodynamic, heat and acoustic processes modeling in transport of rheologically complex viscous media technology in pipelines // XVIII International Scientific Symposium in Honor of Academician MA Usov: PGON2014 IOP Publishing IOP Conference Series: Earth and Environmental Science 21. – Tomsk, 2014. – P. 1–6.
32. Prospects of RANS models with effects multiparameter at modeling of complex non-isothermal flows of viscous media in devices with any configuration of surface / SN Kharlamov, V.Yu.Kim, SI Silvestrov, RA Alginov, SA Pavlov // Proc. of the 6th International Forum on Strategic Technology. – Heilongjiang, Harbin, China, 2011. – Vol. 2. – P. 787–791. DOI: 10.1109/IFOST.2011.6021139
33. Launder BE On the computation of convective heat transfer in complex turbulent flows // Journal of Heat Transfer. – 1988. – Vol. 110. – P. 1112–1128.
34. Chien WL, Lien FS, Leschziner MA Computational Modeling of Turbulent Flow in Turbomachine Passage with Low-Re Two-equation Models // Computational Fluid Dynamics. – 1994. – P. 517–524.
35. Bubenchikov A.M., Kharlamov S.N. Mathematical models of non-uniform anisotropic turbulence in internal flows. – Tomsk: Tomsk State University, 2001. – 448 p.
36. Miloshevich H. Modeling of two-phased turbulent flows in jets with burning particles and phase transition in them // Proceedings of the 4th European CFD conference, Athens, Greece. – 1998. – Vol.1, pt. 1. – P. 175–179.
37. Di Giacinto, Sabetta, Piva. Effects of bilateral interaction in gas flows with a loose set of particles // Theoretical foundations of engineering calculations. - 1982. - V. 104, No. 3. - P. 122-131.
38. Morsi SA, Alexander AJ An Investigation of Particle Trajectories in Two-Phase Flow Systems // Journal of Fluid Mechanics. – 1972. – Vol. 55, No. 2. – P. 193–208.
39. Patankar SV, Spalding DB A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows // International Journal of the Heat and Mass Transfer. – 1972. – Vol. 15. – P. 1787–1806.
40. Happel J., Brenner H. Low Reynolds number hydrodynamics with special applications to particular media. – New Jersey, Prentige-Hall, 1965. – 553 p.
41. Piercy NAV, Hooper MS, Winney HF Viscous flow through pipes with cores // Journal of science. – 1933. – Vol. 15. – P. 647–676.
42. Shishenko R.I., Esman B.I., Kondratenko P.I. Hydraulics of drilling fluids. – M.: Nedra, 1976. – 294 p.
43. Boyun G., Liu G. Applied drilling circulation systems: hydraulics, calculations and models. – Gulf Professional Publishing, Burlington, 2011. – 272 p.
44. Pressure drop in piping elements. Software-Factory Schmitz, Schifferstadt, Germany [Electronic resource]. – URL: http://www.druckverlust.de/Online-Rechner (date of access: 01.12.2022).
45. Effects of drill string eccentricity on frictional pressure losses in annuli / D. Vahid, Y. Ma, Z. Li, T. Geng, M. Yu // Journal of Petroleum Science and Engineering. – 2020. – Vol. 187, No. 106853. – P. 1–12. DOI: 10.1016/J.PETROL.2019.106853
46. Podryabinkin EV, Rudyak VY Modeling of turbulent annular flows of hershel-bulkley fluids with eccentricity and inner cylinder rotation // Journal of Engineering Thermophysics.– 2014. –Vol. 23(2). – P. 137–147. DOI: 10.1134/S1810232814020064
47. Accurate predictions of velocity profiles and frictional pressure losses in annular YPL-fluid flow / Hashemian Yahya, Mengjiao Yu, Stefan Miska, Siamack Shirazi, Ramadan Ahmed // Journal of Canadian Petroleum Technology. – 2014. – Vol. 53, No. 6. – P. 355–363. DOI: 10.2118/173181-PA
48. Turbulent flows of gas suspensions / A.A. Shraiber, L.B. Gavin, V.A. Naumov [et al.]. – Kyiv: Naukova Dumka, 1987. – 240 p.
49. Simulation of transient cuttings transportation and ECD in wellbore drilling / SS Costa, S. Stuckenbruck, SA Fontoura, AL Martins // Europec/EAGE Conference and Exhibition. – 2008. – Jun 9 (OnePetro). – 11 p.m. DOI: 10.2118/113893-MS
50. Grutzner H. Beitrage zur theoretischen und experuncntellen Untersuchung der Turbulenz. – Akademic-Verlag Berlin, 1976. – 135 p.
51. Barbin Jones. Turbulent flow in the initial section of a smooth pipe // Technical Mechanics. - 1963. - No. 1. - P. 34–41.
52. Busch Alexander. On particle transport and turbulence in wellbore flows of non-Newtonian fluids-Findings from acuttings transport process analysis by means of computational fluid dynamics, rheometry and dimensional analysis. PhD Dissertation. – Norwegian University of Science and Technology, 2020. – 187 p.
53. Kharlamov S.N., Dzhanghorbani M.Procedures and tools for monitoring the processes and mechanisms of sludge transport during hydraulic cleaning of horizontal wells // Bulletin of Tomsk Polytechnic University. Georesources Engineering. - 2020. - Vol. 331, No. 12. - P. 22-40. DOI: 10.18799/24131830/2020/12/2936
54. Kharlamov S.N., Dzhanghorbani M.Cuttings transport processes during cleaning of wells with arbitrary orientation of drill pipes containing an eccentrically located round core with a movable wall: problems, results, prospects (review) // Bulletin of Tomsk Polytechnic University. Georesources engineering. - 2020. - Vol. 331, No. 7. - P. 131-149. doi: 10.18799/24131830/2020/7/2725
55. Kharlamov SN, Alginov RA Engineering approaches' progress in calculation of inhomogeneous turbulence in pipelines // Society of Petroleum Engineers – SPE Russian Oil and Gas Technical Conference and Exhibition. – Moscow, Russia, 2010. – Vol. 2. – P. 798–805.
56. Gavignet Alain A., Ian J. Sobey. Model aids cuttings transport prediction // Journal of Petroleum Technology. – 1989. – Vol. 41, No. 9. – P. 916–921.
57. Nguyen Desmond, Rahman SS A three-layer hydraulic program for effective cuttings transport and hole cleaning in highly deviated and horizontal wells // SPE/IADC Asia Pacific Drilling Technology. Society of Petroleum Engineers. – 1996. – P. 1–15. DOI: 10.2118/36383-MS
58. Esch T., Menter FR Heat transfer predictions based on two-equation turbulence models with advanced wall treatment // Turbulence, Heat and Mass Transfer. – 2003. – No. 4. – P. 633–640.
59. Assessment of numerical methods for estimating the wall shear stress in turbulent Herschel–Bulkley slurries in circular pipes / D. Mehta, AKT Radhakrishnan, JB van Lier, FHLR Clemens // Journal of Hydraulic Research. – 2021. – Vol. 59, No. 2. – P. 196–213. DOI: 10.1080/00221686.2020.1744751

60. Chuklov A.S., Salnikova O.L., Chernykh V.I. Assessment of the influence of geological and physical characteristics of deposits with a complex geological structure on the conditions of hydrocarbon inflow // Subsoil Use. - 2022. - Vol. 22, No. 1. - P. 9–14. DOI: 10.15593/2712-8008/2022.1.2
61. Oney E., van Oort E. Modeling the effects of drill string eccentricity, pipe rotation and annular blockage on cuttings transport in deviated wells // Journal of Natural Gas Science and Engineering. – 2020. – T. 79, No. 103221. – P. 101–112. Doi: 10.1016/j.jngse.2020.103221
62. Hicham F., Hadjadj A., Haddad A., Ofei TN Numerical study of parameters affecting pressure drop of power-law fluid in horizontal annulus for laminar and turbulent flows // Journal of Petroleum Exploration and Production Technology. – 2019. – Vol. 9, No. 4. – P. 3091–3101. DOI: 10.1007/s13202-019-0706-x

Библиографический список

1. Харламов С.Н., Фатьянов Д.С. Исследование структуры турбулентного потока природного сырья в трубопроводах с секцией переменного по длине поперечного сечения конфузорно-диффузорного типа // Известия Томского политехнического университета. Инжиниринг георесурсов. – 2020 . – Т. 331, № 8. – С. 53–67. DOI: 10.18799/24131830/2020/8/2768
2. Харламов С.Н., Фатьянов Д.С. Моделирование пространственных течений вязких сред в системе каналов с участками соединений сложной формы // Известия Томского политехнического университета. Инжиниринг георесурсов. – 2021. – Т. 332, № 5. – С. 70–88. Doi: 10.18799/24131830/2021/5/3187
3. Харламов С.Н., Джангхорбани М., Филиппов К.А. Математическое моделирование и методы исследования гидродинамической очистки горизонтальных скважин // Известия Томского политехнического университета. Инжиниринг георесурсов. – 2021. – Т. 332, № 8. – С. 53–73. DOI: 10.18799/24131830/2021/8/3305
4. Харламов С. Н., Джангхорбани М. Численное моделирование течений вязких смесей бурового шлама и потока сырой нефти на горизонтальных участках скважин с эксцентричными бурильными трубами // Новые вызовы фундаментальной и прикладной геологии нефти и газа – XXI век: материалы всерос. науч. конф. с участием иностранных ученых, посвященную 150-летию акад. АН СССР И.М. Губкина и 110-летию акад. АН СССР и РАН А.А. Трофимука / Институт нефтегазовой геологии и геофизики им. А. А. Трофимука СО РАН; Новосибирский государственный университет. Секция 2. Геология нефти и газа. Подсекция 3. Нефтегазопромысловая геология. – Новосибирск: ИПЦ НГУ, 2021. – 276 с. DOI 10.25205/978-5-4437-1248-2-221-224
5. Харламов С. Н., Джангхорбани М. Численное исследование вязкостно-инерционного ламинарного закрученного течения в круглой трубе с эксцентричным круглым ядром // Известия Томского политехнического университета. Инжиниринг георесурсов. – 2021. – Т. 332, № 11. – С. 7–21. DOI: 10.18799/24131830/2021/11/3423
6. Computational Fluid Dynamics (CFD) as a tool to study cutting transport in wellbores / H.I. Bilgesu, M.W. Ali, K. Aminian, S. Ameri // The Eastern Regional Meeting of the Society of Petroleum Engineers. – Lexington, Kentucky, USA, October, 2002. –27 p. doi: 10.2118/78716-ms
7. Solid–liquid hydrodynamics in a slim hole drilling annulus / S.M. Han, H. Young Kyu, W. Nam Sub, K. Young Ju // Journal of Petroleum Science and Engineering. – 2010. – Vol. 70, № 3–4. – P. 308–319. DOI: 10.1016/J.PETROL.2009.12.002
8. Mme U., Pål Skalle. CFD calculations of cuttings transport through drilling annuli at various angles // International Journal of Petroleum Science and Technology. – 2012. – Vol. 6, № 2. – P. 129–141.
9. Xiao-hua Z., Sun C., Tong H. Distribution features, transport mechanism and destruction of cuttings bed in horizontal well // Journal of Hydrodynamics. – 2013. – Vol. 25, № 4. – P. 628–638. DOI: 10.1016/S1001-6058(11)60405-9
10. Effect of drillpipe rotation on cuttings transport using computational fluid dynamics (CFD) in complex structure wells / S. Xiaofeng, K. Wang, T. Yan, S. Shao, J. Jiao // Journal of Petroleum Exploration and Production Technology. – 2014. – Vol. 4, № 3. – P. 255–261. DOI: 10.1007/s13202-014-0118-x
11. Demiralp Yasin. Effects Of Drill-pipe Whirling Motion on Cuttings Transport Performance for Horizontal Drilling. – MSc thesis, Louisiana State University, 2014. – 151 p.
12. Ofei T.N., Irawan S, Pao W. CFD method for predicting annular pressure losses and cuttings concentration in eccentric horizontal wells // Journal of Petroleum Engineering. – 2014, № 4. – P. 110–120. DOI: 10.1155/2014/486423
13. Ofei T.N., Alhemyari S.A. Computational fluid dynamics simulation of the effect of drill pipe rotation on cuttings transport in horizontal wellbores using a Newtonian fluid // International Field Exploration and Development Conference (IFEDC 2015). – 2015. – P. 1–8. DOI: 10.1049/cp.2015.0582
14. Ofei T.N. Effect of yield power law fluid rheological properties on cuttings transport in eccentric horizontal narrow annulus // Journal of Fluids. – 2016. – Vol. 7, № 3. – P. 116–124. DOI: 10.1155/2016/4931426
15. Kamyab Mohammadreza and Vamegh Rasouli. Experimental and numerical simulation of cuttings transportation in coiled tubing drilling // Journal of Natural Gas Science and Engineering. -2016. – Vol. 29. – P. 284–302. DOI: 10.1016/j.jngse.2015.11.022
16. Hole-cleaning performance comparison of oil-based and water-based drilling fluids / Sayindla Sneha, Bjørnar Lund, Jan David Ytrehus, Arild Saasen. // Journal of Petroleum Science and Engineering. – 2017. – Vol. 159. – P. 49–57. DOI: 10.1016/j.petrol.2017.08.069
17. Heydari Omid, Eghbal Sahraei, and Pål Skalle. Investigating the impact of drillpipe's rotation and eccentricity on cuttings transport phenomenon in various horizontal annuluses using computational fluid dynamics (CFD) // Journal of Petroleum Science and Engineering. – 2017. – Vol. 156. – P. 801–813. DOI: 10.1016/J.PETROL.2017.06.059
18. Kharlamov S.N., Kim V.Yu., Silvestrov S.I. Numerical modeling of a vortical investigation of heat transfer in fields of centrifugal mass forces in elements of the power equipment with a curvilinear wall // The 5th Proceedings of the International Forum on Strategic Technology (IFOST. University of Ulsan, October, 13–15, 2010), University of Ulsan: Ulsan, South Korea, 2010. – P. 105–109.
19. Menter F.R. Two-equation eddy-viscosity turbulence models for engineering applications // AIAA Journal. – 1994. – Vol. 32, № 8. – P. 1598–1605.
20. Epelle Emmanuel I., Dimitrios I. Gerogiorgis. Transient and steady state analysis of drill cuttings transport phenomena under turbulent conditions // Chemical Engineering Research and Design. – 2018. – Vol. 131. – P. 520–544. DOI: 10.1016/j.cherd.2017.11.023
21. Epelle Emmanuel I., Dimitrios I. Gerogiorgis. CFD modelling and simulation of drill cuttings transport efficiency in annular bends: effect of particle sphericity // Journal of Petroleum Science and Engineering. – 2018. – Vol. 170. – P. 992–1004. DOI: 10.1016/j.petrol.2018.06.041
22. Syamlal Madhava, O'Brien T.J. The derivation of a drag coefficient formula from velocity-voidage correlations // Technical Note, US Department of energy, Office of Fossil Energy, NETL, Morgantown, WV., 1987. – P. 1–11.
23. Gidaspow D. Multiphase flow and fluidization: continuum and kinetic theory descriptions. – Academic press: Sand Diego, 1994. – 467 p.
24. Akhshik Siamak, and Majid Rajabi. CFD-DEM modeling of cuttings transport in underbalanced drilling considering aerated mud effects and downhole conditions // Journal of Petroleum Science and Engineering. – 2018. – Vol. 160. – P. 229–246. DOI: 10.1016/J.PETROL.2017.05.012
25. Steady-state cuttings transport simulation in horizontal borehole annulus/ Y. Ignatenko, O. Bocharov, A. Gavrilov, R. May // 37th International Conference on Ocean, Offshore Mechanics and Arctic Engineering. American Society of Mechanical Engineers. Digital Collection. – 2018. – № 51296 (V008T11A051). – P. 12.
26. Numerical prediction of flow behavior of cuttings carried by Herschel-Bulkley fluids in horizontal well using kinetic theory of granular flow / Pang Boxue, Shuyan Wang, Guodong Liu, Xiaoxue Jiang, Huilin Lu, Zhenjie Li. // Powder Technology. – 2018. – Vol. 329. – P. 386–398. DOI: 10.1016/J.POWTEC.2018.01.065
27. Effect of orbital motion of drill pipe on the transport of non-Newtonian fluid-cuttings mixture in horizontal drilling annulus / Pang Boxue, Shuyan Wang, Xiaoxue Jiang, Huilin Lu // Journal of Petroleum Science and Engineering. – 2019. – Vol. 174. – P. 201–215. DOI: 10.1016/J.PETROL.2018.11.009
28. Нигматулин Р.И. Динамика многофазных сред. – М.: Наука, 1987. – Т. 1. – 464 с.
29. Yeoh G.H. and Tu J. Computational Techniques for Multi-Phase Flows. – Elsevier Ltd, Inc., 2010. – 210 p.
30. Crowe C.T. Review- numerical models for dulite gas-particle flows // ASME Journal of Fluids Engineering. – 1982. – Vol. 104 (Sept.). – P. 297–303.
31. Kharlamov S.N., Kudelin N.S., Dedeyev P.O. Hydrodynamic, heat and acoustic processes modelling in tranport of rheologically complex viscous media technology in pipelines // XVIII International Scientific Symposium in Honour of Academician M.A. Usov: PGON2014 IOP Publishing IOP Conference Series: Earth and Environmental Science 21. – Tomsk, 2014. – P. 1–6.
32. Prospects of RANS models with effects multiparameter at modeling of complex non-isothermal flows of viscous media in devices with any configuration of surface / S.N. Kharlamov, V.Yu.Kim, S.I. Silvestrov, R.A. Alginov, S.A. Pavlov // Proc. of the 6th International Forum on Strategic Technology. – Heilongjiang, Harbin, China, 2011. – Vol. 2. – P. 787–791. DOI: 10.1109/IFOST.2011.6021139
33. Launder B.E. On the computation of convective heat transfer in complex turbulent flows // Journal of Heat Transfer. – 1988. – Vol. 110. – P. 1112–1128.
34. Chien W.L., Lien F.S., Leschziner M.A. Computational Modelling of Turbulent Flow in Turbomachine Passage with Low-Re Two-equation Models // Computational Fluid Dynamics. – 1994. – P. 517–524.
35. Бубенчиков А.М., Харламов С.Н. Математические модели неоднородной анизотропной турбулентности во внутренних течениях. – Томск: Томский государственный университет, 2001. – 448 с.
36. Miloshevich H. Modelling of two-phased turbulent flows in jets with burning particles and phase transition in them // Proceedings of the 4th European CFD conference, Athens, Greece. – 1998. – Vol.1, pt. 1. – P. 175–179.
37. Ди Джачинто, Сабетта, Пива. Эффекты двустороннего взаимодействия в газовых потоках с неплотным множеством частиц // Теоретические основы инженерных расчетов. – 1982. – Т. 104, № 3. – С. 122–131.
38. Morsi S.A., Alexander A.J. An Investigation of Particle Trajectories in Two-Phase Flow Systems // Journal of Fluid Mechanics. – 1972. – Vol. 55, № 2. – P. 193–208.
39. Patankar S.V., Spalding D.B. A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows // International Journal of the Heat and Mass Transfer. – 1972. – Vol. 15. – P. 1787–1806.
40. Happel J., Brenner H. Low Reynolds number hydrodynamics with special applications to particular media. – New Jersey, Prentige-Hall, 1965. – 553 p.
41. Piercy N.A.V., Hooper M.S., Winney H.F. Viscous flow through pipes with cores // Journal of science. – 1933. – Vol. 15. – P. 647–676.

42. Шишенко Р.И., Есьман Б.И., Кондратенко П.И. Гидравлика промывочных жидкостей. – М.: Недра, 1976. – 294 с.
43. Boyun G., Liu G. Applied drilling circulation systems: hydraulics, calculations and models. – Gulf Professional Publishing, Burlington, 2011. – 272 p.
44. Pressure drop in piping elements. Software-Factory Schmitz, Schifferstadt, Germany [Электронный ресурс]. – URL: http://www.druckverlust.de/Online-Rechner (дата обращения: 01.12.2022).
45. Effects of drill string eccentricity on frictional pressure losses in annuli / D. Vahid, Y. Ma, Z. Li, T. Geng, M. Yu // Journal of Petroleum Science and Engineering. – 2020. – Vol. 187, № 106853. – P. 1–12. DOI: 10.1016/J.PETROL.2019.106853
46. Podryabinkin E.V., Rudyak V.Y Modeling of turbulent annular flows of hershel-bulkley fluids with eccentricity and inner cylinder rotation // Journal of Engineering Thermophysics. – 2014. –Vol. 23(2). – P. 137–147. DOI: 10.1134/S1810232814020064
47. Accurate predictions of velocity profiles and frictional pressure losses in annular YPL-fluid flow / Hashemian Yahya, Mengjiao Yu, Stefan Miska, Siamack Shirazi, Ramadan Ahmed // Journal of Canadian Petroleum Technology. – 2014. – Vol. 53, № 6. – P. 355–363. DOI: 10.2118/173181-PA
48. Турбулентные течения газовзвеси / А.А. Шрайбер, Л.Б. Гавин, В.А. Наумов [и др.]. – Киев: Наукова думка, 1987. – 240 с.
49. Simulation of transient cuttings transportation and ECD in wellbore drilling / S.S. Costa, S. Stuckenbruck, S.A. Fontoura, A.L. Martins // Europec/EAGE Conference and Exhibition. – 2008. – Jun 9 (OnePetro). – 11 p. DOI: 10.2118/113893-MS
50. Grutzner H. Beitrage zur theoretischen und experuncntellen Untersuchung der Turbulenz. – Akademic-Verlag Berlin, 1976. – 135 p.
51. Барбин Джоунс. Турбулентное течение на начальном участке гладкой трубы // Техническая механика. – 1963. – № 1. – С. 34–41.
52. Busch Alexander. On particle transport and turbulence in wellbore flows of non-Newtonian fluids-Findings from acuttings transport process analysis by means of computational fluid dynamics, rheometry and dimensional analysis. PhD Dissertation. – Norwegian University of Science and Technology, 2020. – 187 p.
53. Харламов С.Н., Джангхорбани М. Процедуры и инструментарий мониторинга процессов и механизмов транспорта шлама при гидравлической очистке горизонтальных скважин // Известия Томского политехнического университета. Инжиниринг георесурсов. – 2020. – Т. 331, № 12. – С. 22–40. DOI: 10.18799/24131830/2020/12/2936
54. Харламов С.Н., Джангхорбани М. Процессы транспорта шлама при очистке скважин с произвольной ориентацией буровых труб, содержащих эксцентрично расположенное круглое ядро с подвижной стенкой: проблемы, результаты, перспективы (обзор) // Известия Томского политехнического университета. Инжиниринг георесурсов. – 2020. – Т. 331, № 7. – С. 131–149. doi: 10.18799/24131830/2020/7/2725
55. Kharlamov S.N., Alginov R.A. Engineering approaches' progress in calculation of inhomogeneous turbulence in pipelines // Society of Petroleum Engineers – SPE Russian Oil and Gas Technical Conference and Exhibition. – Moscow, Russia, 2010. – Vol. 2. – P. 798–805.
56. Gavignet Alain A., Ian J. Sobey. Model aids cuttings transport prediction // Journal of Petroleum Technology. – 1989. – Vol. 41, № 9. – P. 916–921.
57. Nguyen Desmond, Rahman S.S. A three-layer hydraulic program for effective cuttings transport and hole cleaning in highly deviated and horizontal wells // SPE/IADC Asia Pacific Drilling Technology. Society of Petroleum Engineers. – 1996. – P. 1–15. DOI: 10.2118/36383-MS
58. Esch T., Menter F.R. Heat transfer predictions based on two-equation turbulence models with advanced wall treatment // Turbulence, Heat and Mass Transfer. – 2003. – № 4. – P. 633–640.
59. Assessment of numerical methods for estimating the wall shear stress in turbulent Herschel–Bulkley slurries in circular pipes / D. Mehta, A.K.T. Radhakrishnan, J.B. van Lier, F.H.L.R. Clemens // Journal of Hydraulic Research. – 2021. – Vol. 59, № 2. – P. 196–213. DOI: 10.1080/00221686.2020.1744751
60. Чухлов А.С., Сальникова О.Л., Черных В.И. Оценка влияния геолого-физических характеристик залежей со сложным геологическим строением на условия притока углеводородов // Недропользование. – 2022. – Т. 22, № 1. – С. 9–14. DOI: 10.15593/2712-8008/2022.1.2
61. Oney E., van Oort E. Modeling the effects of drill string eccentricity, pipe rotation and annular blockage on cuttings transport in deviated wells // Journal of Natural Gas Science and Engineering. – 2020. – Т. 79, № 103221. – Р. 101–112. Doi: 10.1016/j.jngse.2020.103221
62. Hicham F., Hadjadj A., Haddad A., Ofei T.N. Numerical study of parameters affecting pressure drop of power-law fluid in horizontal annulus for laminar and turbulent flows // Journal of Petroleum Exploration and Production Technology. – 2019. – Vol. 9, № 4. – P. 3091–3101. DOI: 10.1007/s13202-019-0706-x

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