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ANALYSIS OF HERSCHEL-BULKELY FLUID FLOW IN ROTATING DRILL STRING

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The study analyzed the flow field of the Herschel-Bulkely fluid in drill string, intending to reveal the rotation effect of a drill string on the drilling fluid flow behavior and characteristics of friction pressure loss. The analysis was conducted using a Computational Fluid Dynamics (CFD) technique. Meanwhile, the influence of a helical flow field was explored, which is exerted by the rotation velocity of the drill string, axial velocity and fluid density variations. Also included is a comparative analysis between rotating and non-rotating flow of the Herschel-Bulkely fluid in drill string. When keeping other parameters constant, the friction pressure loss decreases with the growth of the rotation velocity, while the deviation percentage and deviation absolute value increase continuously. The result agrees with findings of relevant studies, with validity proved. On basis of the CFD results, a regressive model was established for analysis of friction pressure loss with rotation effect. Significant implications for drilling engineering are derived from the study. Deviation absolute value is able to guide drilling since the deviation absolute value can be too large to be neglected. Thus efficiency can be greatly increased in terms of drilling and equipment utilization, resulting in reduced cost.

Keywords: rotation effect, helical flow, friction pressure loss, drag reduction, Herschel-Bulkely model.

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1. Introduction

Rotating drilling has a long history and so far it is still a major way in drilling engineering. The rotation effect contributes greatly to the entire drilling operation, making drilling special and complicated. Study on rotation effect is closer and more applicable to the practical drilling operation. From the perspective of drilling hydraulics, the rotation effect of drill string exercises significant influence on flow both inside and outside the drill string. Undoubtedly, rotation effect deserves sufficient concern based on its importance. Extensive discussion has been carried out related to rotation effect of drill string during drilling for a long time. The general view holds that during the drilling process, drill string rotation would consume a large volume of energy during thousands- meter-long operation, which negatively affects cost control. However, as far as other scholars concerned, the rotation effect, to a large extent, maintains smooth of borehole and further reduces the risk of pipe-sticking. In recent years, with advanced drilling technology, drilling field has witnessed increasing amount of deviated and horizon wells [1-3]. Increasing attention has been paid to rotation effect with focus on hole-cleaning and cuttings transport. The importance of rotation effect to annular flow has been realized gradually [4-6], while little concern has been given on flow in the rotating drill string.

According to the existing theoretical system, the thousand-meter-long drill string has been supposed to be non-rotating regarding to the flow in the drill string. Under such circumstance, the flow can be simplified as one-dimensional axial flow, which shares the general flow theories and research methods utilized in general non-rotating pipe flow field. However, neglecting rotation effect, the supposition differs greatly from the real drilling conditions. With the rapid development of drilling technology and the accurate prediction requirements for Managed Pressure Drilling (MPD) [7-10], the original one-dimensional view cannot meet the demands of modern advanced drilling engineering. It is essential to develop more reasonable and accurate theories and models which are more consistent with the actual drilling conditions. However, the current level of modeling can not be able to draw the analytic solution for general turbulent flow [11, 12], not to mention the studies on 3-dimensional turbulent flow with rotation effect. Meanwhile, with respect to experiment, flow characteristics remains to be fully revealed due to the limit flow field data. To sum up, study on 3-dimensional flow with rotation effect in drill string is far more difficult than that on one-dimensional flow. With intention to conduct profound study, the most feasible method seems to be numerical simulation [13, 14].

Numerical simulation was applied to the turbulent flow in rotating drill string in this study. Based on simulation results, the rotating drill string is able to alter the flow field inside and further affect friction pressure loss in a significant way. Serving as an initial exploration for the flow features in rotating drill string, the study is characterized by its significant theoretical influence on relevant research field with models and conclusions derived.

2. Numerical method

2.1 Fluid model

Generally, drilling fluid is viewed as non-Newtonian fluid in drilling engineering. Aiming to facilitate engineering applications, Bingham model and power-law model, due to simple correlations and only 2 arguments, are usually considered in spite of their rough prediction. However, with intention to describe the rheology of the drilling fluid accurately, the Herschel-Bulkely model was adopted in this research, which falls into the category of 3-parameter model or modified power-law model. The formula is expressed as follows:

$$\tau = \tau_{HB} + k\gamma^n \quad (1)$$

where τ is shear stress, Pa;

τ_{HB} is yield stress, Pa;

k is consistency coefficient, Pa·s^n;

n is liquidity index, dimensionless;

γ is strain rate, s^{-1}.

As is known that τ_{HB} stands for the real lowest shear stress which is necessary for fluid to start moving. Thus, the 3-parameter model performs better than Bingham and power-law mode in terms of reasonability and accuracy [15,16]. Afterwards, a kind of oil base drilling fluid was applied, with the data derived from a rotating viscometer regressed to detail the parameters in Eq.(1). The formula with detail parameters is shown as follows:

$$\tau = 2.47449 + 0.12177\ \gamma^{0.74011} \quad (2)$$

2.2 Geometric model

In order to study characteristics of helical flow, simulation was carried out on the flow in a 15-meter-long drill string. The inner diameter of the drill string is 118.6 millimeters. The meshing scheme is hexahedral mesh elements mapped in the flow zone (fig.1). A higher density mesh near the wall has been adopted to capture the boundary flow. Boundary types were built up, namely velocity inlet, pressure outlet and rotary moving wall. Velocity specification method was set as component for the velocity inlet, with z axis being the symmetry axis of the rotating wall and slip excluded. To sum up, the wall roughness has been assumed to be hydraulic smooth.

2.3 Mathematical model

The k - ε 2 equation model was applied as turbulent model. This model is composed of detailed k - ε models, namely Standard k - ε model, RNG k - ε model and Realizable k - ε model [17-20]. Based on analysis and comparison for the 3 models, the Realizable k - ε model is in accordance with physical property of the turbulent flow to the largest degree since, which relates the turbulent viscosity μ_t to the strain rate instead of a constant value. Due to C_μ, the situation can be avoided where a very large time average strain rate may lead to a negative normal strain in the Standard k - ε model [21]. Therefore the turbulent viscosity is related to curvature and rotation. The improvement for k - ε model is possible to provide a better description for the flow, which includes the rotating uniform shear flow, free flow containing jet flow and mixture flow, pipe flow, boundary flow and separation flow. Based on discussion above, Realizable k - ε model was finally applied in this research [22, 23].

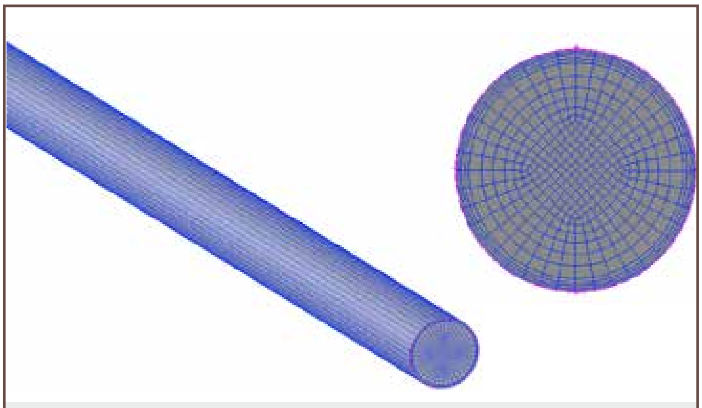


Fig.1. Geometric model in drill string

3. Analysis the flow in rotating drill string

The density of drilling fluid was set as 1000 kg/m^3, 1300 kg/m^3, 1600 kg/m^3, 1900 kg/m^3 and 2200 kg/m^3 respectively and the rheology model was calculated with Equation 2. The axial velocity was set as 2 m/s, 3 m/s, 4 m/s, 5 m/s and 6 m/s in accordance to the range of mud pump displacement. Rotation axis and rotation velocity in coordinate should be taken into account when setting drill string rotation. The rotation velocity was set as 3.14 rad/s, 6.28 rad/s, 9.42 rad/s, 12.56 rad/s, 15.7 rad/s and 18.84 rad/s.

Rotating around its own axis, drill string drives rotation of drilling fluid inside with viscosity force. In the meantime, the drilling fluid is also driven to flow along the pipe axis under the pressure of mud pump. Thus the flow field inside rotating drill string is centro-symmetric helical field. Resultant velocity contour is drawn on the cross section of the helical flow with the potential core in the middle, which shares similarity with the general non-rotating pipe flow (fig.2(a)) [24]. From the resultant velocity vector on the cross section of the helical flow, indication is derived that the vector is of circular movement around its axis (fig.2(b)). Helical vector near the rotating wall is composed of rotary component vector and axial component vector (fig.2(c)). Plane vector graph through the drill string axis is also the same with that of the general non-rotating pipe flow (fig.2(d)). Thus, the results show that the helical flow in rotating drill string involves all fluid particles in helical motion. Furthermore, the rotary vector and axial vector are free from mutual interference, following the principle of synthesis and decomposition.

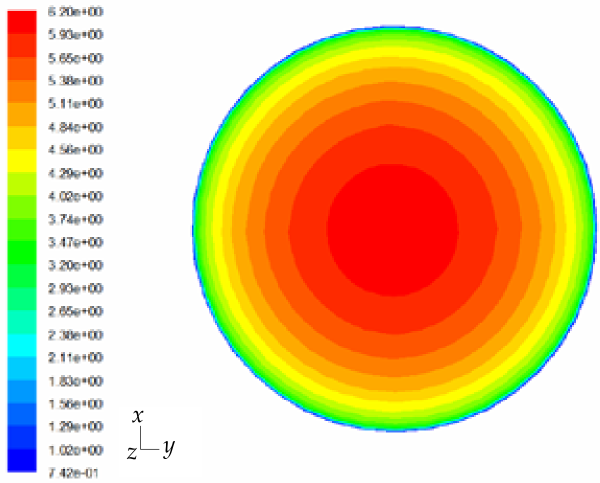
3.1. Impact of rotation velocity on helical flow

In this study, the profiles of different flow parameters are projections of a cross section inside drilling string on the plain. The cross section is 9 meters away form the inlet of the 15-meter-long drill string. The 0 point on abscissa axis marks the location where axis of drill string passes through.

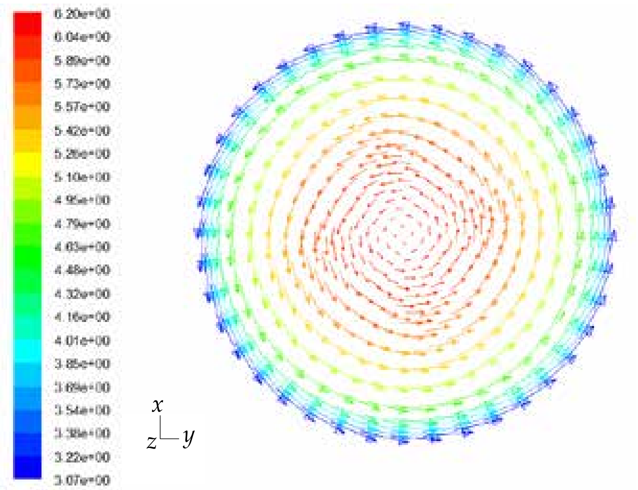
The axial velocity profile is shown to be more convex with the increase of rotation velocity (fig.3(a)), which is consistent with the flowing law. The area of potential core diminishes while its value increases. The result is based on the fact that periphery of the potential core has a tendency to break away under a larger rotation velocity and centrifugal force effect.

The tangential velocity profile distributes in the pattern of an inverted triangle (fig.3(b)). On the basis of correlation between linear velocity and angular velocity, the tangential velocity grows radially away from the 0 point of the abscissa axis. Tangential velocity reaches the maximum value near the rotating wall. The faster rotation velocity is, the bigger the overall tangential velocity profile is.

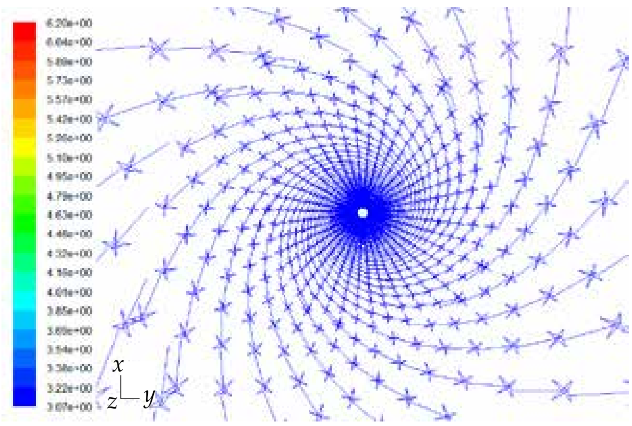
The turbulent kinetic energy profile reaches its maximum near the rotating wall (fig.3(c)). From the wall to the center of the cross section (the 0 point of the abscissa axis), the



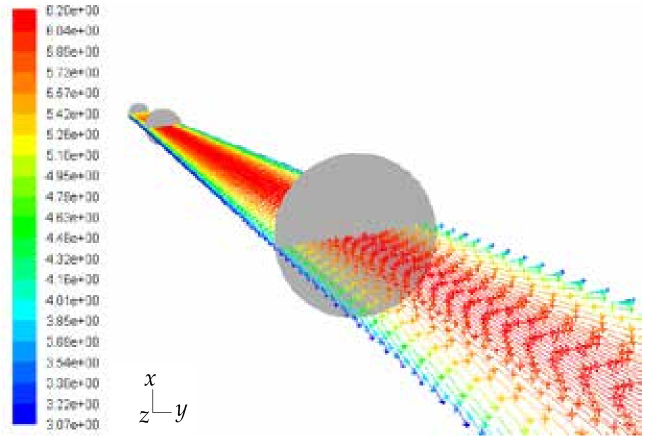
(a) Velocity contour on the cross section



(b) Velocity vectors on the cross section



(c) Velocity vectors near the rotating wall



(d) Velocity vectors in the axial plane

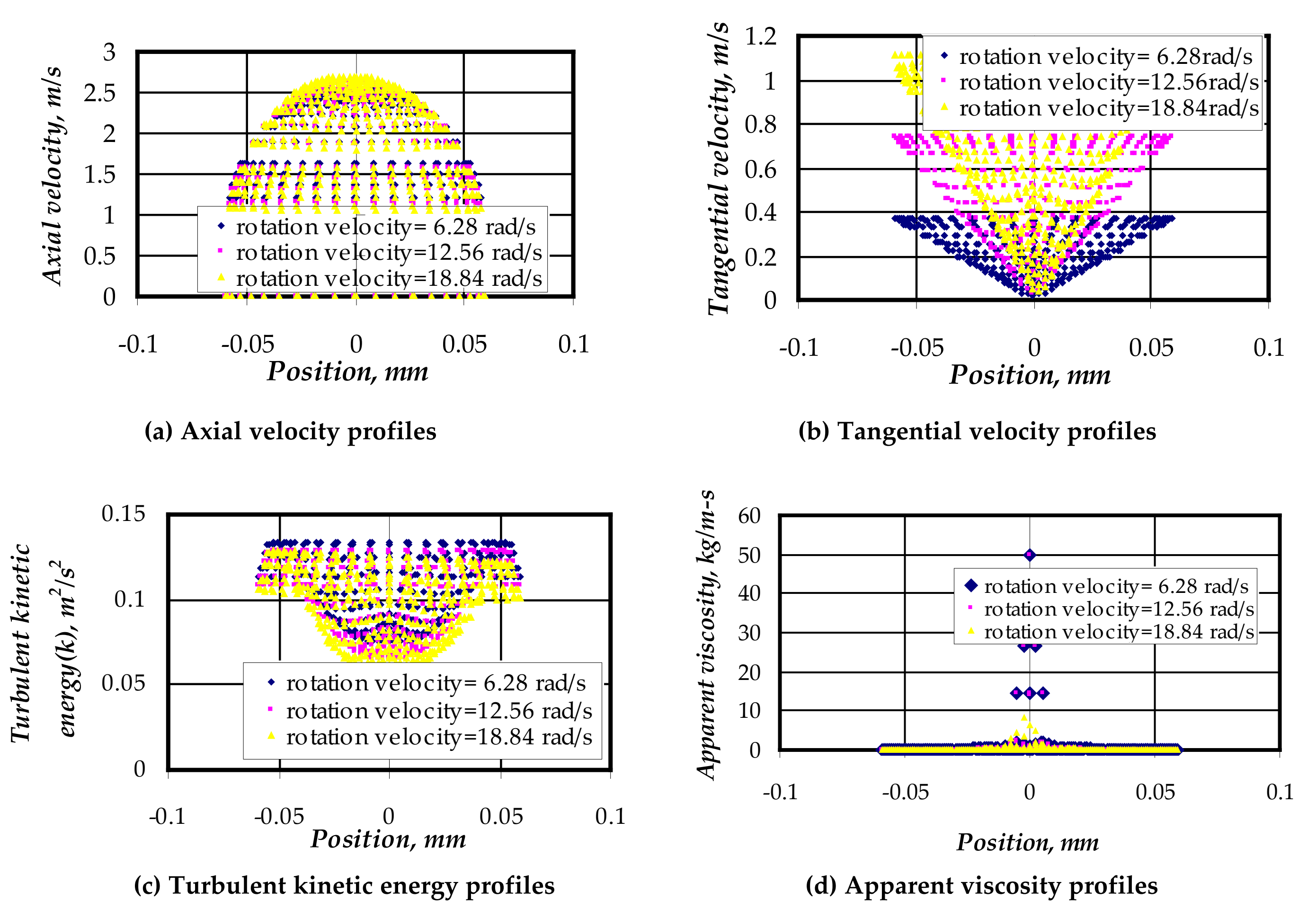
Fig.2. Helical flow velocity field in rotating drill string (m/s)

very thin laminar boundary layer gradually moves apart and transforms into the turbulent flow. Shear effect is extremely strong since the tangential velocity near the wall is larger than that at any other location. Moreover, existence of axial flow also contributes to the high velocity gradient here. Therefore, the pulse tendency reaches to its strongest point near the wall outside the boundary layer. However, from the wall outside boundary layer to the center, turbulent kinetic energy becomes smaller as the axial velocity increases, while pulse tendency is not as strong as that near the wall. Furthermore, the whole turbulent kinetic energy gets smaller with increasing of rotation velocity. With respect to this point, the study believes that a strong dissipation for the vortex is induced by separation of the boundary layer and interferences of the axial flow and the rotation near the wall induce. Nevertheless, the large-scale vortex caused by rotating drill string will not be consumed completely. Random pulsation tendency in all directions will decrease with the help of the strong vortex. Thus, the helical flow will drive all fluid particles to form macroscopic rotation motion and weaken the effect of random pulsation tendency in all directions. As a result, the friction pressure loss will decrease certainly.

The apparent viscosity profile of Herschel-Bulkely fluid turns out to distribute in the pattern of a single-peak distribution on the cross section (fig.3(d)). However, apparent viscosity profile will be a horizon line according to a certain viscosity value if the drilling fluid is Newtonian fluid. The very high single peak is in the potential core which has the same axis of symmetry as the drill string. There is a huge drop when it is out of the potential core and then a very low apparent viscosity value until stretches to the boundary layer. Zooming in the low-value zone, a clear variation is achieved from center of the cross section to the boundary layer. Distribution of this part is conic with the lowest apparent viscosity in the boundary layer. In addition, when other parameters keep constant, the faster rotation velocity is, the larger strain rate of the fluid is especially in the potential core and the bigger decreasing amplitude of the single peak is. However, the decreasing trend tends to be gradual out of the single peak zone. The average apparent viscosity value is not accurate enough to represent the whole apparent viscosity profile on cross section due to the huge gap manifested between the maximum and minimum values. Therefore, the one-dimensional treatment is unreasonable for flow in the rotating drill string.

3.2. Impact of axial velocity on helical flow

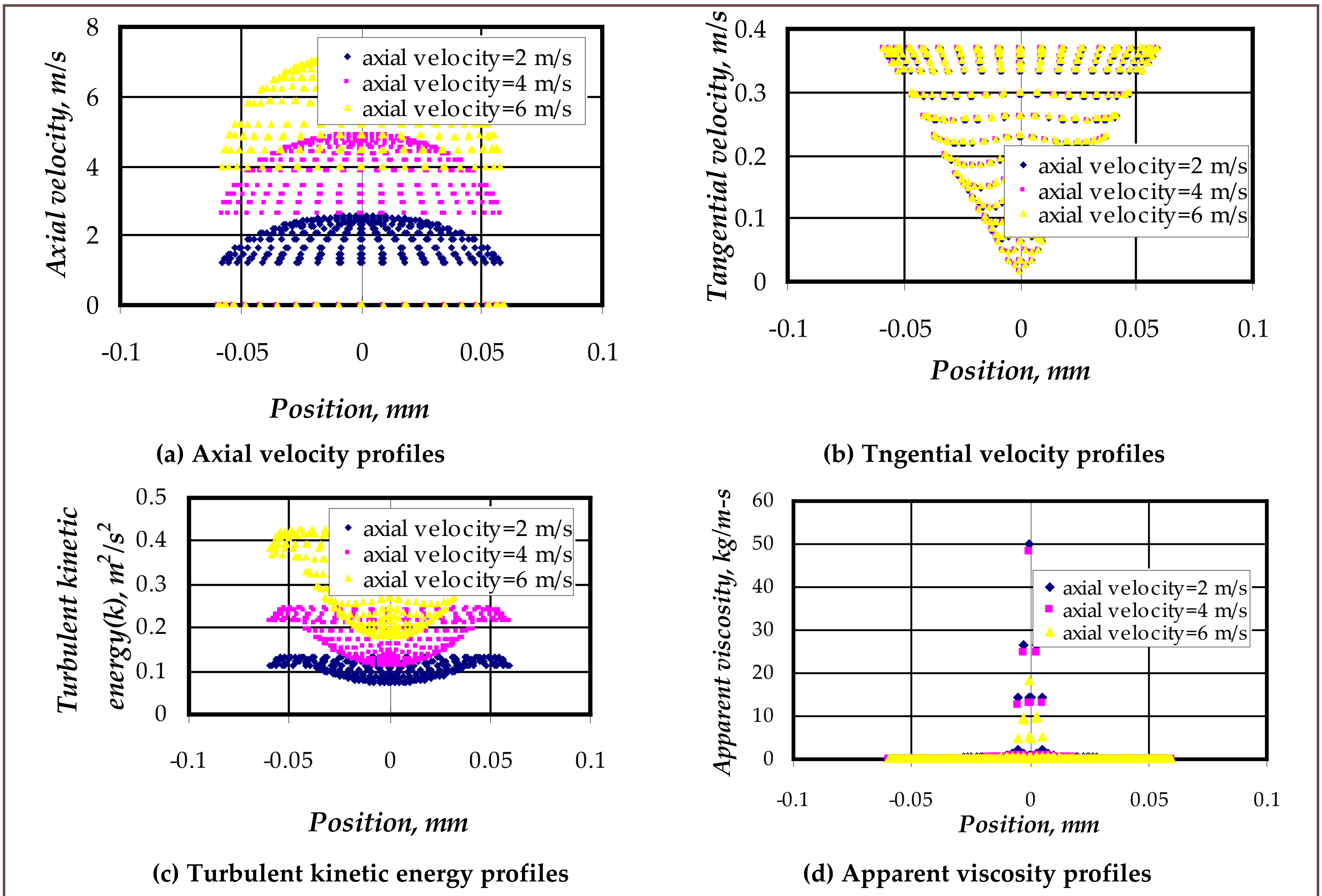
The impact of axial velocity variation on flow field inside the rotating drill string is the same with that on general non-rotating pipe flow. This point can find further illustration from the variation rules of parameter profiles along with alteration of axial velocity (fig.4(a)). Variation of axial velocity exerts no influence



(a) Axial velocity profiles (b) Tangential velocity profiles

(c) Turbulent kinetic energy profiles (d) Apparent viscosity profiles

Fig.3. Impact of rotation velocity on helical flow field (fluid density = 1000 kg/m³, axial velosity = 2 m/s)



(a) Axial velocity profiles (b) Tngential velocity profiles

(c) Turbulent kinetic energy profiles (d) Apparent viscosity profiles

Fig.4. Impact of axial velocity on helical flow field (fluid density = 1000 kg/m³, rotation velosity = 6.28 rad/s)

on tangential velocity (fig.4(b)), so all tangential velocity profiles coincide at different axial velocity. The apparent viscosity decreases with increasing of axial velocity, with variation obvious in potential core (fig.4(d)).

3.3. Impact of drilling fluid density on helical flow

Through comparative analysis, the density variation exerts no impact on axial and tangential velocity inside the drill string. Hence, the 2 kinds of component velocity profiles remain to be the same respectively with different density (fig.5(a) and (b)). However, a certain number of differences have been observed among turbulent kinetic energy profiles (fig.5(c)). As fluid density increases, the turbulent kinetic energy profiles become smaller in an overall way, with shapes invariant. That is to say, from respect of energy, the smaller density fluid particles are, the larger pulsation amplitude and turbulent kinetic energy they have are involved with constant flow velocity. The apparent viscosity decreases with increasing density, with conspicuous variation reflected in potential core (fig.5(d)).

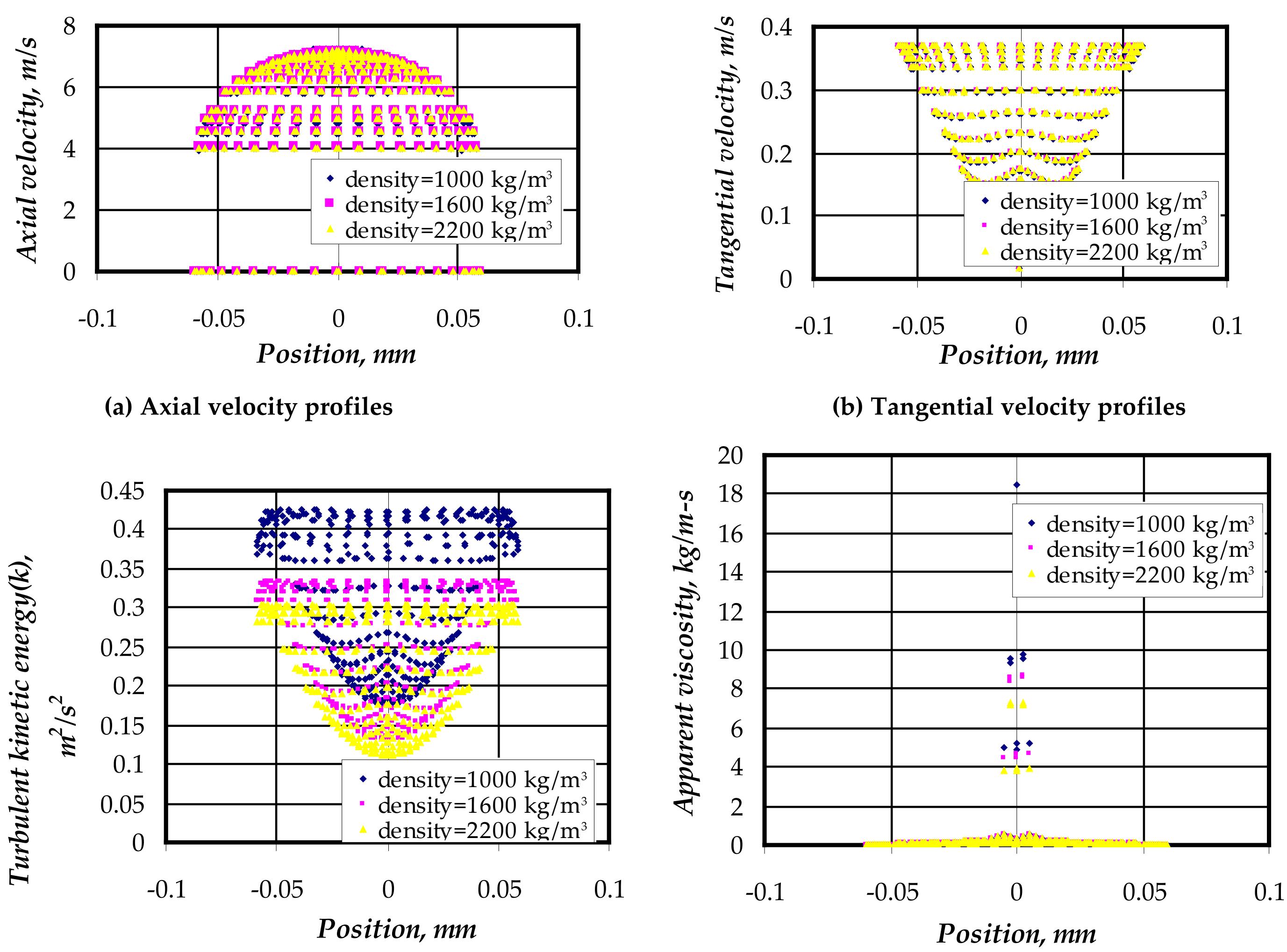
3.4. Friction pressure loss in rotating drill string

The characteristics of friction pressure loss in rotating drill string has been analyzed with different fluid densities taken into consideration, from the low density (1000 kg/m^3) to the high (2200 kg/m^3) (fig.6). The data points on the curves were acquired through simulating the flow in 15-meter-long rotating drill string with reference to Herschel-Bulkely mode of Equation 2. The friction pressure loss at 0 point of the abscissa indicates the friction pressure loss induced by flow with the same parameters above but in non-rotating drill string. Meanwhile, these data points are relatively corresponding to points in the friction pressure loss curves.

Based on analysis, the friction pressure loss grows as the fluid density and axial velocity increase, with other parameters constant. The result shares common feature with the case of general non-rotating pipe flow. When fluid density and axial velocity are constant, the friction pressure loss decreases following the increasing of drill string rotation velocity for every curve. The reason for this phenomenon can be interpreted with reference to relevant materials (explanation for fig.3(c)).

The friction pressure loss deviation percentage curves reveal the deviation of the friction pressure loss in two cases, namely rotation and non-rotation (fig. 6). The deviation percentage reaches about 5%-15% according to the simulation data. In addition, the deviation percentage almost rises linearly as the drill string rotation velocity increases, especially when the axial velocity is at a low level. Therefore, the increase of axial velocity elongates the rotation effect along the axial direction. Meanwhile, the proportion of friction pressure loss induced by the axial flow is increased, while that induced by rotation effect decreased.

Based on the numerical simulation results, a viewpoint was proposed that during drilling, the



(a) Axial velocity profiles

(b) Tangential velocity profiles

(c) Turbulent kinetic energy profiles

(d) Apparent viscosity profiles

Fig.5. Impact of fluid density on helical flow field (rotation velosity = 18.84 rad/s, axial velosity = 4 m/s)

rotation effect of the drill string plays a role of drag reduction for the flow inside. In previous studies, the direct numerical simulation technique was utilized to conduct analysis on fully developed turbulent flow in a rotating pipe by A.A.Feiz, M.Ould-Rouiss and G.Lauriat [25]. The findings agree with published studies and experiments related to numerical simulation. According to their conclusion, the friction factor decreases when increasing the rotation rate of the pipe, which shares consistency with the viewpoint proposed in this study. Thus, the validity is proved effectively for method and conclusions involved in this study.

Based on analysis and processing for a large amount of data, a regression model was established for friction pressure loss (Eq.3). The model reflects how friction pressure loss varies with variation of axial velocity, rotation velocity and fluid density.

$$\Delta P = A + \frac{B}{\exp\left(\frac{\omega}{206.2133} - \frac{\upsilon}{4.0896}\right)} \qquad (3)$$

where: $A = 28707.89338 - 18722.00646 e^{\frac{\rho}{2144.31783}}$

$B = -17577.94389 + 25431.54746 e^{\frac{\rho}{3473.73974}}$

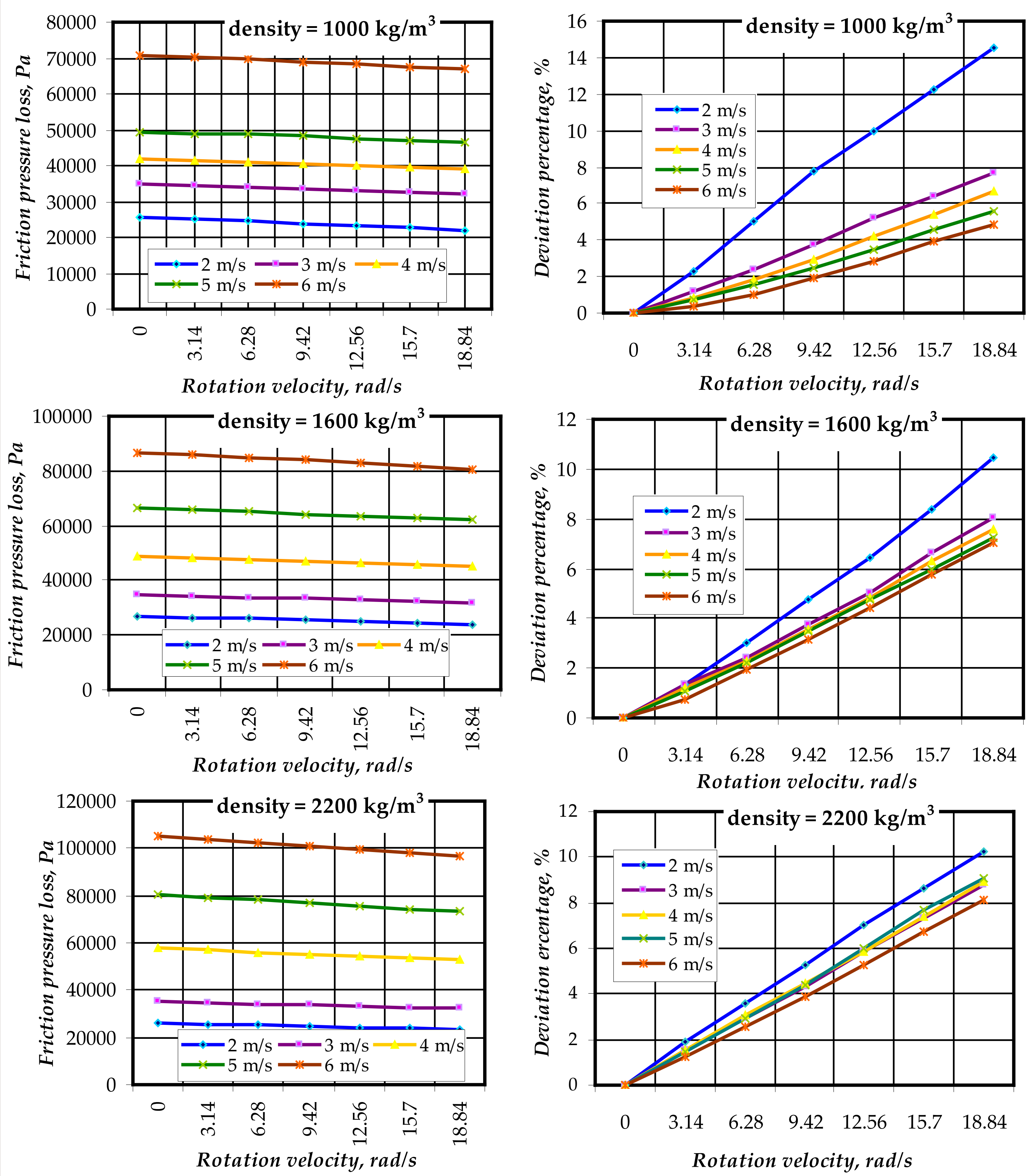


Fig.6. Friction pressure loss and deviation percentage in rotating drill string

ΔP is frictional pressure loss, Pa, ω is rotation velocity, rad/s, v is axial velocity, m/s, is fluid density, kg/m^3. On the basis of computationalρ fluid dynamics, this model can predict the friction pressure loss in rotating drill string and improve the accuracy of existing friction pressure loss models with rotation effect taken into account.

Based on the friction pressure loss in non-rotating pipe flow, the deviation absolute value curves of the friction pressure loss was obtained, with rotating drill string set as 6000 meters in length (fig.7). According to these figures, the deviation absolute values of friction pressure loss increase with rising of fluid density. For every curve, the deviation absolute value increases linearly on the whole when drill string rotation velocity increases with constant fluid density. The trend tends to be more apparent with high axial velocity. Deviation absolute value ranges from 1 MPa to 3.4 MPa, which is of great meaning to drilling (fig.7). With proper application, drag reduction exerts positive influence in reducing drilling cost and promoting efficiency.

Most calculations of the current drilling hydraulics have not taken the rotation effect of drill string into consideration. Therefore, during drilling design stage, without considering rotation effect, the friction pressure loss calculated from the models is inclined to be larger obviously than the actual situation. According to this value, pressure limit of the pump and high pressure pipeline at the surface are also designed to be larger obviously. Thus, more cost is involved in terms of operation and maintenance of mud pump and high pressure pipeline.

In addition, the drag reduction of the rotating drill string leads to reduced pressure of the surface mud pump accordingly. On the basis of the former design, when drilling deep, it is necessary to replace cylinder sleeves so as to expand the pump pressure or to replace drilling rig. However, drilling can be able to continue and the replacement can be carried out at a deeper depth owing to the drag reduction effect of the rotating drill string. Thus high efficiency is realized in terms of drilling and equipment utilization, with drilling cost reduced in the meantime.

A rough estimation was made based on the simulation results to evaluate the effect of drag reduction in rotating drill string. The drilling fluid density was assumed to be 1600 kg/m^3 with the axial velocity 5 m/s. In the meantime, the replacement of cylinder sleeves is supposed to happen at the depth of 6000 meters to expand the pump pressure. Friction pressure loss is about 26.635 MPa due to the former design without the drag reduction effect of the rotation drill string. However, with the same flow conditions and rotation effect taken into account, the friction pressure loss in rotating drill string is about 24.772 MPa at the depth of 6000 meters when rotation velocity is 18.84 rad/s. The drilling is able to be carried out to the depth of 6450 meters to achieve 26.635 MPa. Depth for replacing the cylinder sleeves is able to be altered to 6450 meters. Thus, the drilling efficiency and equipment utilization are greatly enhanced, with the drilling cost cut down significantly.

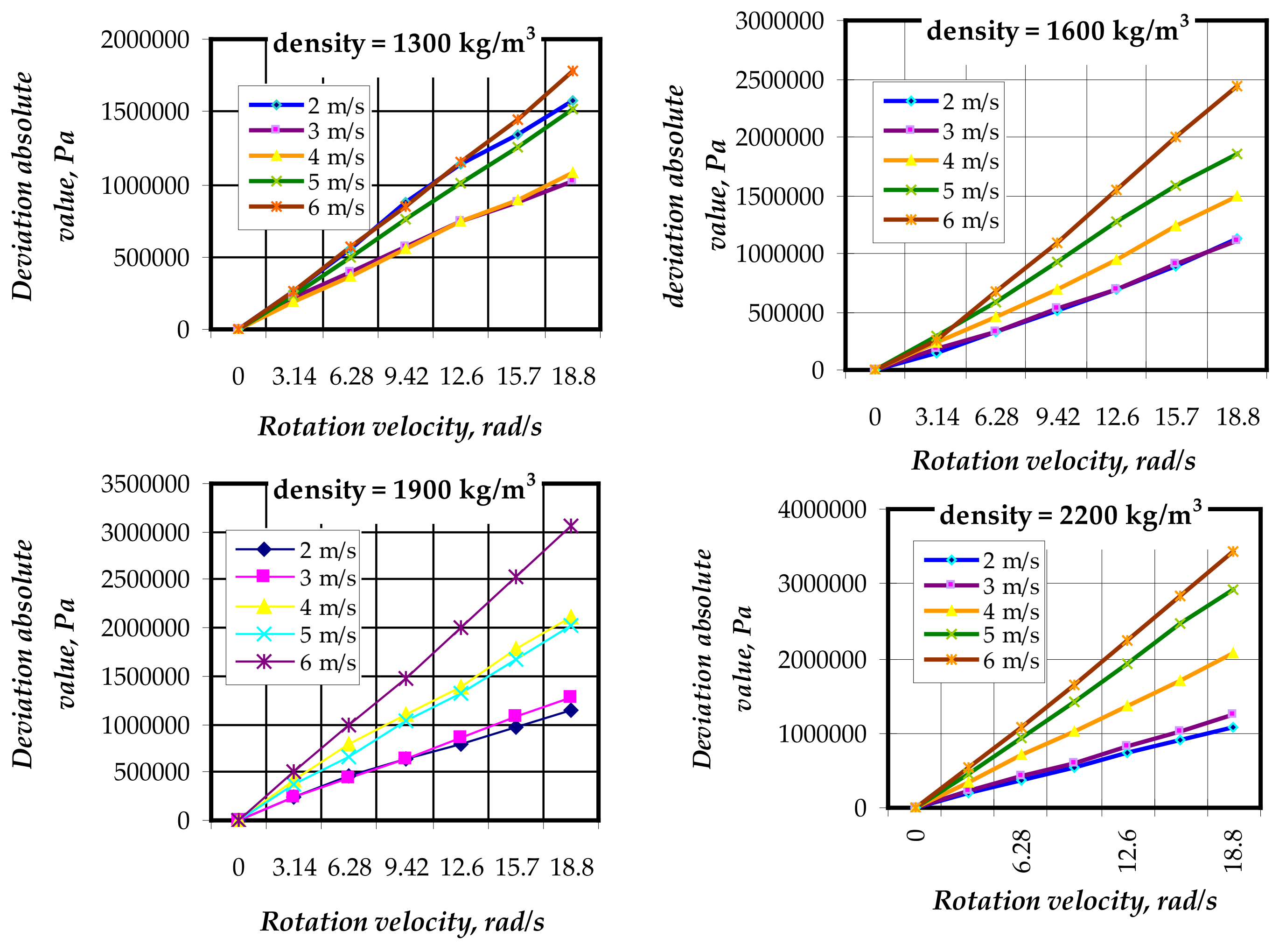


Fig.7. Friction pressure loss deviation absolute value in rotating drill string

4. Conclusions

In the study, a meaningful exploration was conducted for the flow in rotating drill string. The simulation results have been proved reasonable and valid with reference to other relevant reported studies. The flow field with rotation effect inside drill string is a helical field with a centro-symmetric composition, including rotating and axial flow. Tangential velocity increases with growth of the rotation velocity. Meanwhile, axial velocity profile becomes more convex and the resultant velocity grows overall accordingly. Axial velocity variation exercises no effect on tangential velocity, while effect fluid density variation has not been observed on all component velocities.

The variation of the apparent viscosity profile is special for the Herschel-Bulkely model which is closer to the real rheology property of drilling fluid. The profile appears a unique single peak distribution, and it decreases with the increase of the rotation velocity, axial velocity and the fluid density.

The variation of friction pressure loss in rotating drill string not only reaches consistency with that of general non-rotating pipe flow, but also presents other special rules. When other parameters are kept constant, the friction pressure loss will decrease with the growth of the rotation velocity. Compared with the case in non-rotating drill string, increase is reflected on deviation percentage and deviation absolute value. Furthermore, the deviation absolute value can be too large to be neglected. Making good use of this deviation absolute value to guide drilling design can greatly enhance efficiency of drilling and equipment utilization and decrease drilling cost. Finally a friction pressure loss model was established related to 3 parameters, namely axial velocity, rotation velocity and fluid density. The study also provides theoretical support for analysis on friction pressure loss with rotation effect in drill string, improving the drilling hydraulics theories.

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Анализ течения жидкости Гершеля–Балкли во вращающейся бурильной колонне

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Реферат

В статье, с целью определения влияния вращения бурильной колонны на свойства потока бурового раствора и характеристики гидравлических потерь на трение, дается анализ поля течения жидкости Гершеля–Балкли в бурильной колонне. Анализ проводился методом вычислительной гидродинамики (МВГ). При этом, главным образом было исследовано влияние на спиралевидное поле течения, возникающее под влиянием скорости вращения бурильной колонны, осевой скорости и колебаний плотности жидкости. Также представлен сравнительный анализ между вращающимся и не вращающимся потоком жидкости Гершеля–Балкли в бурильной колонне. Если остальные параметры остаются постоянными, то гидравлические потери на трение уменьшаются с увеличением скорости вращения. Результаты согласуются с результатами аналогичных исследований. На основе результатов МВГ была создана регрессионная модель для анализа гидравлических потерь на трение при вращении бурильной колонны. Получено, что абсолютная величина отклонения способна влиять на направление бурения. Таким образом, полученные результаты позволят повысить эффективность применяемого бурового оборудования.

Fırlanan qazma kəmərində Qerşel-Balkli mayesinin axınının təhlili

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Xülasə

Məqalədə, qazma kəmərinin fırlanmasının qazıma məhlulunun axını xassələrinə və sürtünmədə hidravlik itkilərin xüsusiyyətlərinə təsirini müəyyən etmək məqsədilə, qazma kəmərində Qerşel - Balkli mayesinin axını sahəsinin təhlili verilmişdir. Təhlil hidrodinamiki hesablama üsulu (HHÜ) ilə aparılmışdır. Əsasən, qazma kəmərinin fırlanma sürəti, oxboyu sürəti və mayenin sıxlığının dəyişməsinin spiralvari axın sahəsinə olan təsiri araşdırılmışdır. Həmçinin qazma kəmərində Qerşel-Balkli mayesinin fırlanan və fırlanmayan axınlarının müqayisəli təhlili təqdim edilir. Əgər başqa parametrlər dəyişməz qalırsa, onda fırlanma sürətinin artması ilə sürtünmədə olan hidravlik itki azalır. Alınan nəticələr müvafiq tədqiqatların nəticələrinə uyğun gəlir. HHÜ-in nəticələri əsasında fırlanma zamanı sürtünməyə hidravlik itkilərin təhlili üçün reqression model yaradılıb. İnhirafın mütləq kəmiyyəti çox böyük həddə olduğundan, qazmanın istiqamətinə təsir etmək qabiliyyətindədir. Beləliklə, alınan nətəcələr istifadə olunan avadanlıqların səmərəliliyinin artırılmasına imkan yaradır.