A Numerical Study on Mud Cake Cleaning Using a Multi-Jet Rotating Tube

Dr. Mohamed N. Noui-Mehidi (PhD)
Petroleum Engineer Specialist
EXPEC Advanced Research Center, Saudi Aramco
Dhahran 31311, Saudi Arabia

Abstract

A numerical study of mud cake cleaning using rotating radial jets is presented. The fluid conveying tube has a rotating end equipped with jet nozzles along the circumference. The combination of the radial jets created by the nozzles and the tool rotation generate flow recirculations in the space between the outer tube and the borehole wall. These recirculations result in increasing the local shear rate on the borehole wall and therefore achieving better cleaning of the mud cake deposited on the wellbore wall. The study concerned solving the basic flow equations around the jet zone and revealed the effects of the jet intensity, the rotational speed and the returning axial flow on the flow distribution in the annulus. The numerical calculations revealed that the presence of flow recirculations resulted in higher velocity magnitude in the annulus leading to an increased shear rate on the wall.

Keywords: Wellbore cleaning – Mud Filtrate - Skin removal – Rotating jets

1. Introduction

Loss production resulting from clogging or plugging effects in the near wellbore region is still a major concern in research related to production operations. Mud filtrate invasion into permeable rocksthat occurs during drilling phases leads to unforeseen near wellbore damage that would need remediation (Chin, 1995; Chenevert and Dewan, 2001).The conventional treatment method concerns either the chemical means that strive to dissolve the material forming the cake in the near wellbore region, or the mechanical means by creating flows that impinge on the wellbore wall to remove the cake. Other nonconventional methods were used, such as high energy waves (Champion et al., 2003).

Mechanical treatment of mud cake filtrates are usually performed using coiled tubing — its efficiency is not always assured since the cleaning fluid injected with a conventional tube flows in the annular gap between the coiled tubing and the wellbore wall relies on the axial shear on the damaged wall. Other mechanical means, such as water jets, were used along with chemical agents, but both methods have shown limitations. In particular, axial water jets, if not applied correctly, can affect the performance of the well by producing excessive fines and creating water invaded zones (Al-Otaibi et al., 2004).Aslamand Alsalat (2000) have used a high-pressure water jet tool for mud cake cleaning. They showed that using rotating type jetting nozzles gave better results compared to stationary jets. The rotating jets assure better cleaning results of the mud cake in the whole circumference of the near wellbore region.

In the present study, the effects of the rotational speed of the jetting tool, the jets intensity and the resulting return axial flow are investigated. The flow system is solved by calculating the flow primitive variables in the gap between the rotating tool and the borehole wall.

2. Mathematical Formulation

The flow system representing the tube set-up with the radial jets is shown in Figure 1. The end of the liquid conveying tube is equipped with a rotating element that has jetting nozzles around the circumference, assuming that there is continuous jetting along the whole tool periphery. The rotating jet is directed radially towards to borehole wall as shown in Figure 1. In the flow properties analysis, only the gap between the outer tube and the borehole wall in considered and limited only to the rotating tool.

The outer diameter of the rotating tube has a radius R_i and the well borehole has a radiusR_0, the total length of the jet zone is H. The system is investigated in the horizontal section of a well that needs mud cake cleaning removal in the open hole section of the well, Figure 1. In the following numerical simulations, the flow analysis is performed around a region where the rotating jet is generated similarly to what is reported in Aslamand Alsalat (2000). The considered region is assumed to be distant from the end of the well, and therefore independent from the end zone conditions.

The flow system is governed by the equations describing a viscous incompressible axisymmetric Newtonian fluid of kinematic viscosity ν,defined in cylindrical coordinates and given by (Hwang and Yang, 2004):

$$\begin{aligned} &\nabla . U = 0 \\ &\frac{\partial U}{\partial t} + (U.\nabla)U = -\frac{1}{\rho}\nabla P + \nu \nabla^2 U + g \end{aligned} \qquad (1)$$

The problem consists in solving the primitive variables, where U is the fluid velocity, ρ the fluid density, P the pressure field, ν the fluid kinematic viscosity and g the gravity field. The velocity field U is decomposed in its components (u, w, v) given in the cylindrical coordinates directions (r, θ, z), respectively, Figure 1. The variables are made dimensionless using the scale d, $R_0\Omega$ and $d/R_0\Omega$ for length, speed and time, respectively, where Ω is the rotational speed of the rotating jet tool. There are three parameters that govern the flow properties in the present system, which are the rotational Reynolds number, defined by the rotating of the jetting tool, the jet Reynolds number, which describes the intensity of the radial jet generated at equal distant axial stations from the outer tube towards to the borehole walland the axial Reynolds number, which describes the axial return flow in the annular gap between the outer tube and the borehole wall.

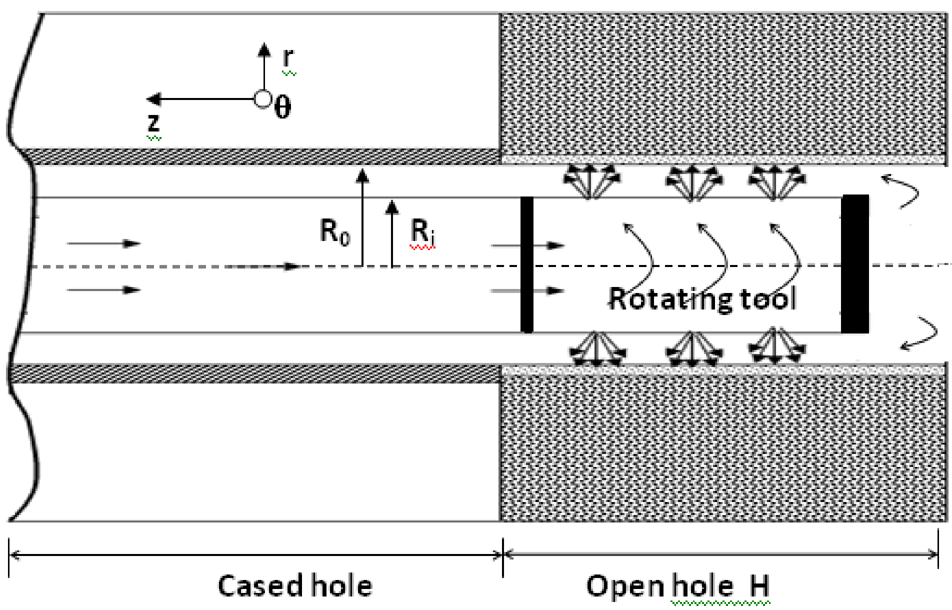


Fig. 1.Schematics of the set-up arrangement.

The axial flow is the result of the accumulated fluid at the bottom of the well, which recirculates back in the annulus. These numbers can be defined by: $\mathrm{Re}_{rot} = \frac{\Omega R_0 d}{\nu}$ where Ω is the rotational speed of the jetting tool, d the gap width between the tool and the wellbore wall, and ν the kinematic viscosity of the fluid.

The jet intensity is represented by $\mathrm{Re}_j = \frac{V_{jet}\, e}{\nu}$, describing thejet radial flow intensity, where V_{jet} is the jet velocityat the exit of the nozzle and e is the opening of the nozzle corresponding to a circular orifice and $\mathrm{Re}_{ax} = \frac{V_{ax}\, d}{\nu}$, describes the axial return flow where V_{ax} is the return axial flow in the annulus.

A finite-difference method is used in integrating the governing equations. This mathematical formulation was previously used by several authors in treating flow with different type of instabilities (Ohmura et al., 1994, Noui-Mehidi et al., 2002).The non-dimensional equations are discretized on a rectangular mesh grid and no-slip boundary conditions are applied at the walls while a constant flow flux is imposed at both inlet and outlet of the system. The numerical domain is discretized using staggered mesh grid, where the pressure is defined at the centers of the numerical cells to avoid the appearance of oscillatory solutions (Fletcher, 1970). The numerical calculations are performed using the concept of the Simplified Marker and Cell (SMAC) method developed by Amsden and Harlow (1970), and which is a type of operator-splitting method that separates the solutions of velocity and pressure fields with an iterative procedure. At each time step,Δt, the momentum equations are solved for a temporary velocity field V^* given by:

$$V^{*^{n+1}} = V^n + \Delta t\left[-\left(V^n.\nabla\right)V^n - \nabla P^n + \nabla^2 V^n / \mathrm{Re}_{rot}\right]$$

WhereV^n is the velocity field at the time step n. Then a scalar potential function ϕ is applied to satisfy the Poisson condition on V^*, which is solved using an SOR method. The final velocity field is obtained from:

$$V^{n+1} = V^n + grad\phi$$

The pressure field is corrected by solving:

$$P^{n+1} = P^n - \phi / \Delta t$$

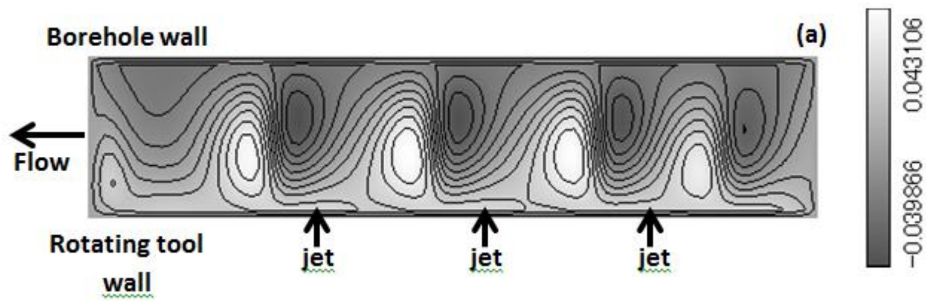
For time integration a firstorder scheme is applied, with a central finite difference method at the second order for spatial discretization in the (r, z) plane defined by the annular gap between the outer tube and borehole wall.

3. Numerical Results

The flow calculations were performed for different values ofRe_{rot}, Re_{ax}, and Re_j. To better understand the effect of each of these parameters, the results are reported in terms of ratios defined by: VJ= $\mathrm{Re}_j/\mathrm{Re}_{rot}$andVX= $\mathrm{Re}_{ax}/\mathrm{Re}_{rot}$ where the values are compared to the rotational Reynolds number. The gap width is described by the parameter $\gamma = R_i / R_o = 0.5$. In this range of *VJ* and *VX* investigated the calculations have shown the existence of flow recirculations resulting from the combination of the jetting flow and the rotation of the jetting tool.

In Figure 2, contours of the flow streamline calculated from the velocity field are shown for two Reynolds numbers Re_{rot}=150 and Re_{rot}=180, and keeping the values VJ=1.0 and VX=0.04. The flow patterns, Figure 2, show that as long as the jets have the same intensity ration to the rotation (i.e.,VJ=1.0), the recirculations observed show a quite similar flow pattern except for the relative size of each of the recirculation zones. The difference can be seen in Figure 3 where the axial velocity,V,at the middle of the annulus is plotted against the whole length of the jetting zone L= z/H for the two values of *Re* and same values of *VJ* and *VX*. For Re_{rot}=180, it can be seen that the magnitude of the axial velocity is larger compared to the one related to Re_{rot}=150, although the same number of recirculation zones is obtained for these parameters.

The stronger recirculations are near the rotating wall while the recirculation zones near the wellbore wall are slightly weaker but extend to the same axial distance. These results indicate that in case the nozzle jet effect has equal magnitude as the rotation effect, any slight change in the jetting tool rotation will not greatly affect the flow pattern obtained.



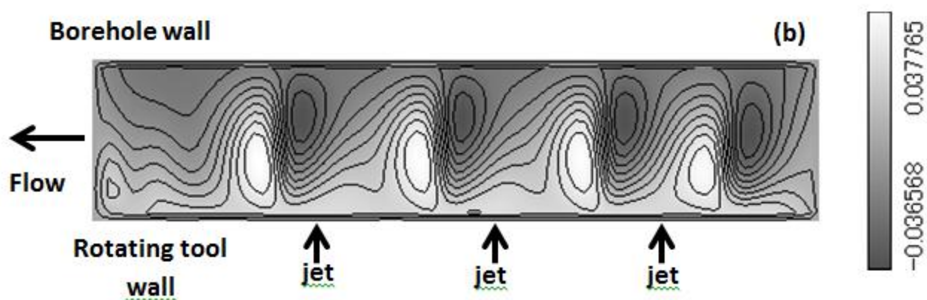


Fig.2.Iso-contours of the flow streamlines.
(a) Re_{rot}=150, VJ=1.0, VX=0.04, (b) Re_{rot}=180, VJ=1.0, VX=0.04

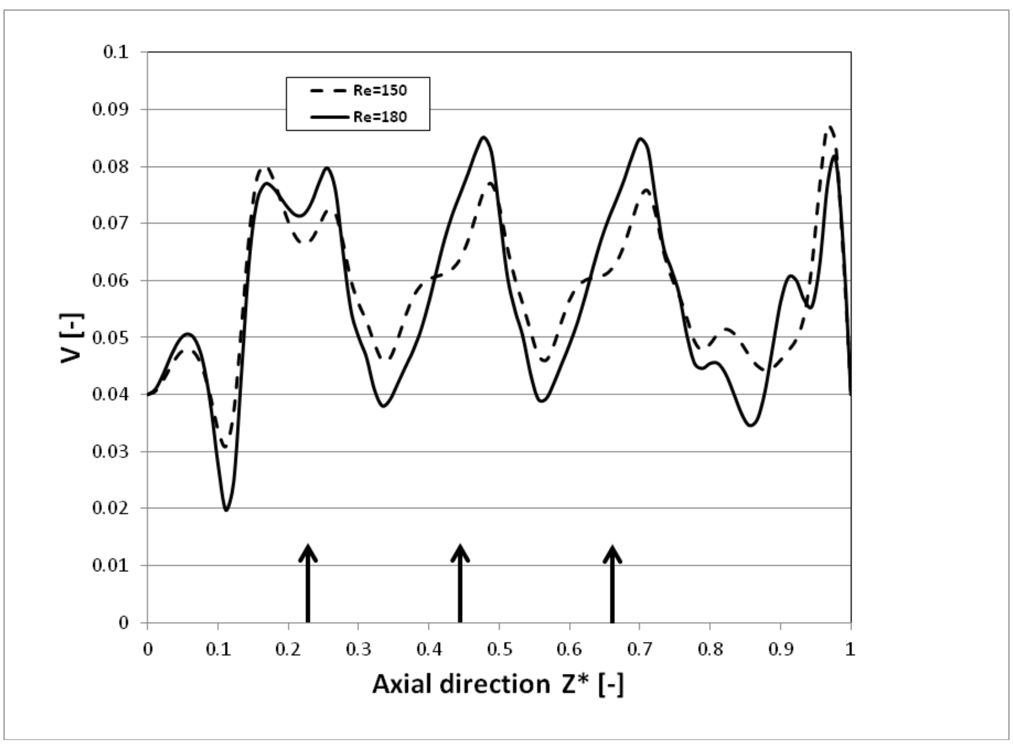


Fig. 3.Axial velocity evolution at the middle of the annulus for
Re_{rot}=150 and Re_{rot}=180(VJ=1.0 and VX=0.04)

The flow patterns are more likely to be highly affected by changes in the ratio *VJ*, i.e., if the nozzle jet has less intensity than the rotation, the flow pattern observed are completely different as seen in Figure 4, where contour plots of the streamlines are shown for the same Re_{rot} and same *VX* but for different values of *VJ*.

In Figure 4a where *VJ* has half the intensity of the rotation, it can be seen that the number of flow recirculations increased to six, occupying smaller axial distances, especially near the rotating wall. Near the wellbore wall the recirculations have weakervortical intensity and are not equally distributed axially. In Figure 5 the difference can be better seen on the axial distribution of the axial velocity component in the middle of the annulus. For VJ=0.5 the magnitude of the axial velocity is higher than when VJ=1.0 for the same Re_{rot} and *VX* values. This indicates that the rotational effect dominated the distribution of the flow by generating more recirculation zones in the annulus for the defined axial distance.

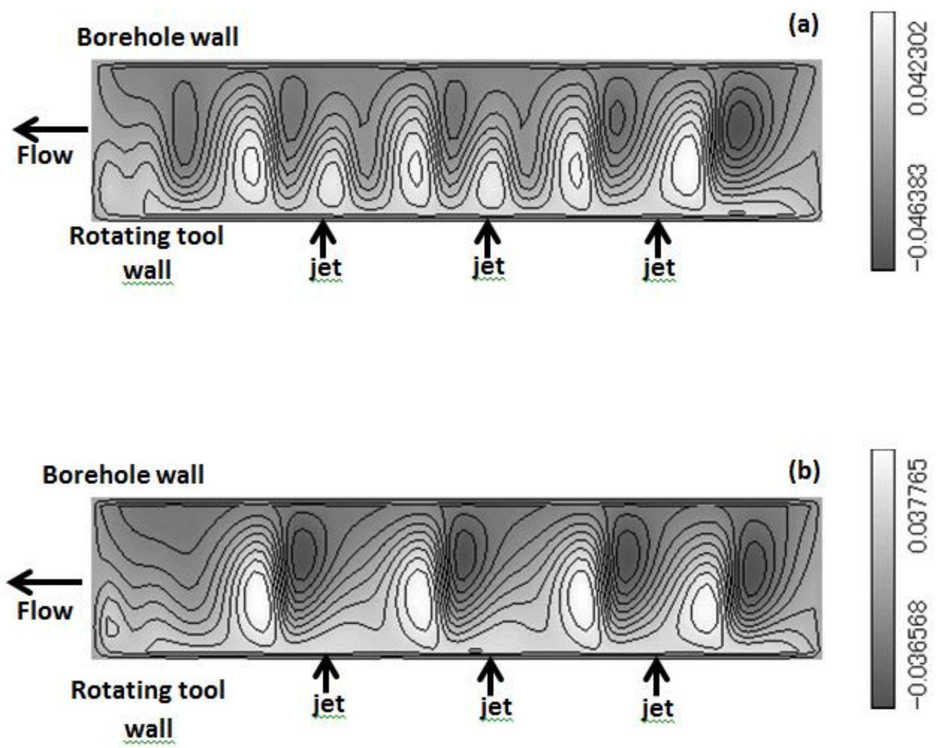


Fig. 4.Iso-contours of the flow streamlines.
(a) Re_{rot}=180, VJ=0.5, VX=0.04, (b) Re_{rot}=180, VJ=1.0, VX=0.04

The effect of the return axial flow was simulated as well. In fact, the fluid jetted against the wellbore wall will accumulate and then flow back to the surface. This return flow is as important as the rotating jet since it allows cleaning the removed mud cake substances towards the surface. The effect of the axial flow is shown in Figure 6. When the axial flow intensity increases from VX=0.04 to VX=0.1, corresponding to one-tenth of the intensity of the rotation, the recirculations are destroyed in the annulus, Figure 6b. The effect on the cleaning efficiency can be deducted from the shear rate at the borehole wall; increasing the shear rate would result in better cleaning.

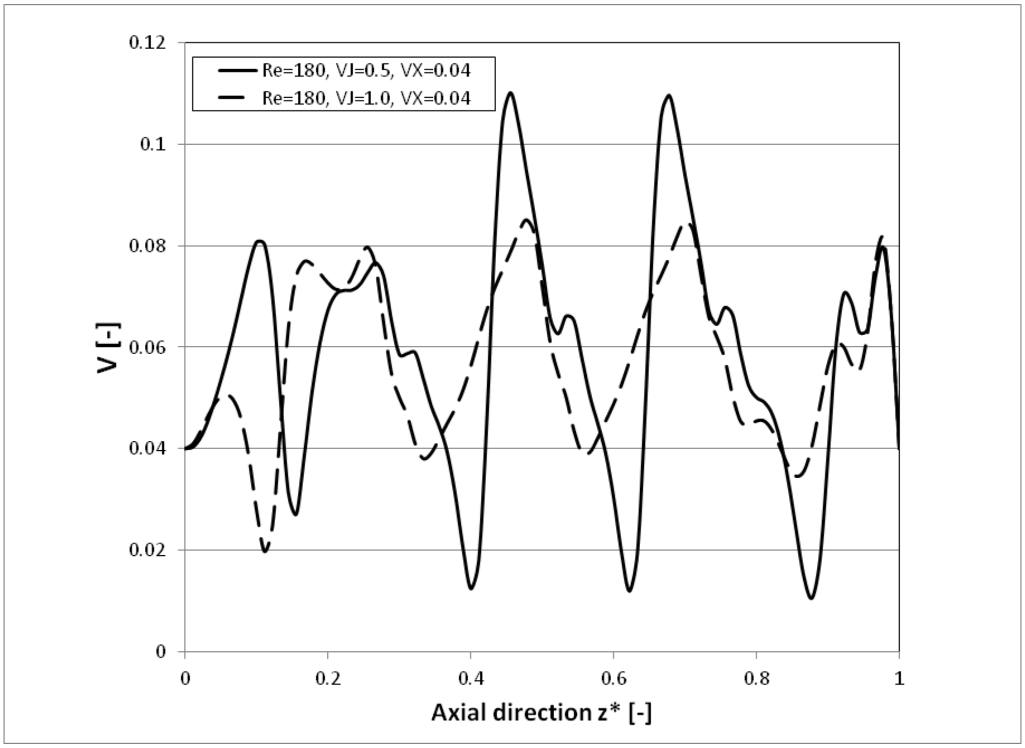


Fig. 5.Effect of jet intensity on the axial velocity at the middle of the annulus for values ofVJ=1.0 and VJ=0.5 (Re_{rot}=180, VX=0.04)

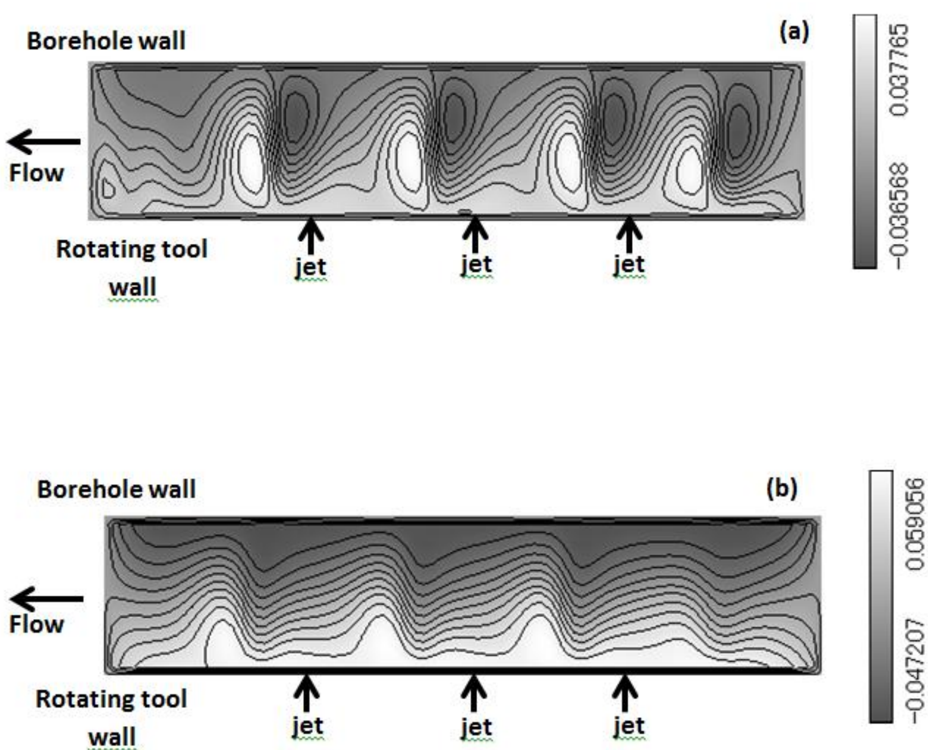


Fig. 6.Iso-contours of the flow streamlines.
(a) Re_{rot}=180, VJ=1.0, VX=0.04, (b) Re_{rot}=180, VJ=1.0, VX=0.1

In Figure 7, the axial component of the shear rate calculated at the wellbore wall is plotted against the whole length of the distance investigated. It is clearly seen that the presence of the recirculations (VX=0.04) resulted in axial shear rate with higher magnitude. This is due to the fact that therecirculations allow better fluid passage on the borehole wall and therefore achieved better cleaning due to the increase of the shear rate on the borehole wall compared to a pure axial flow in the gap region. Therefore the presence of these flow recirculations is highly desired in the design of the rotating jet cleaning system.

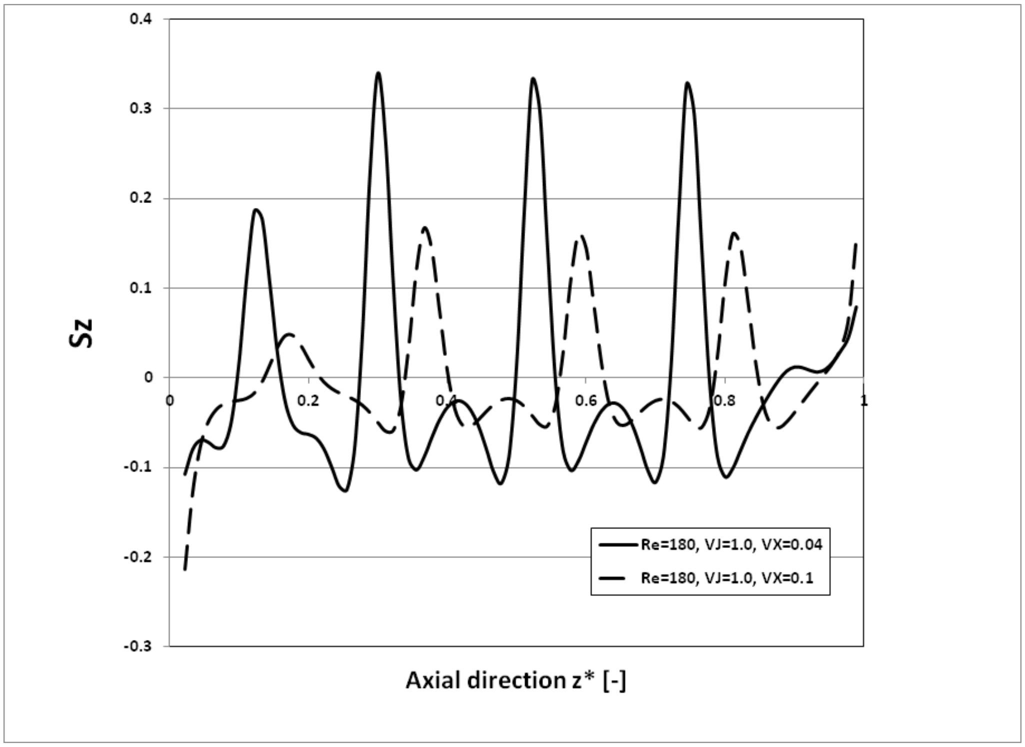


Fig. 7.Effect of the axial return flow intensity on the evolution of the axial component of the shear rate near the borehole wall for VX=0.04 and VX=0.1 (Re_{rot}=180, VJ=0.1).

4. Conclusions

The present work revealed that flow recirculations generated in the annulus between a rotating jet device and the wellbore wall for mud cake cleaning would be highly desirable to achieve the best cleaning results. The numerical calculations have shown that the magnitude of the axial velocity would be the highest for jet intensity equal to the rotation intensity. A higher return axial flow could destroy the recirculation zone and lead to a decreased local axial shear rate.

These results suggest that a careful flow analysis has to be performed prior to the cleaning operation to set the optimum flow conditions that allow the best mud cake cleaning process.

References

Amsden, A.A., &Harlow, F.H. (1970).A Simplified MAC Technique for Incompressible Fluid Flow Calculations.Journal of Computational Physics,6, 322-325.

Al-Otaibi, M.B., Nasr-El-Din, H.A.,&Siddiqui, M.A.(2004). Wellbore Cleanup by Water Jetting and Specific Enzyme Treatments in Multilateral Wells: A Case Study. Paper IADC/SPE 87206, presented at the IADC/SPE Drilling Conference, Dallas, Texas, 2-4 March. DOI: 10.2118/87206-MS.

Aslam, J., &Alsalat, T.(2000). High-Pressure Water Jetting: An Effective Method to Remove Drilling Damage. Paper SPE 58780, presented at the 2000 SPE international Symposium on Formation Damage Control, Lafayette, Louisiana, 23-24 February.

Champion, B., Van der Bas, F.,&Nitters, G.(2003).The Application of High Power Sound Wavesfor Wellbore Cleaning. Paper SPE 82197, presented at the SPE European FormationDamage Conference, The Hague, the Netherlands 13-14 May.

Chenevert, M.E., &Dewan, J.T. (2001).A Model for Filtration of Water-Base Mud During Drilling: Determination of Mudcake Parameters. Journal of Petrophysics,42, 237-247.

Chin, W.C. (1995). Formation Invasion with Applications to Measurement While-Drilling, Time-Lapse Analysis, and Formation Damage.Houston: Gulf Publication Co.

Fletcher, C.A.J.(1970). Computational Techniques for Fluid Dynamics.Berlin: Springer.

Hwang, J.Y., &Yang, K.S.(2004).Numerical Study of Taylor–CouetteFlow with an Axial Flow.Computers & Fluids, 33, 97-118.

Noui-Mehidi, M.N., Ohmura, N., &Kataoka, K.(2002).Mechanism of Mode Selection for Taylor Vortex Flow between Conical Rotating Cylinders.Journal of Fluids and Structure,16, 247-262.

Ohmura, N., Kataoka, K., Kataoka, T.,&Naitoh, Y. (1994).Numerical and Experimental Study of Bifurcation Phenomena in a Finite-length Taylor-Couette System.Proceedings of 5th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery, (ISROMAC-5). A, 561-572.