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CFD Study of Cuttings Transport in Vertical Rotation Drill Pipe for Multi Muds

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Abstract: The ability of drilling fluids to clean the borehole is considered an important factor in choosing drilling mud. Which is affected by many parameters such as mud type, cutting size, cutting concentration in the mud, drill pipe rotation speed, and mud inlet velocity. The present research investigated the influence of drilling fluid that flow into the rotary pipe and coming out of the annulus with the influence of the above mentioned parameters on the cutting transport ratio (CTR). A Computational Fluid Dynamics (CFD) software ANSYS FLUENT 18.2 has been utilized to simulate a model of 3-D two phase (solid-liquid) turbulent flow, steady-state, with stander k-ϵ in a vertical wellbore. The momentum and continuity equations, which are the governing equations, are numerically resolved using CFD with fluent soft package. The results are presented as follows: streamline , contours.

The results show that with a decrease in each of the cutting diameter, cutting concentration in the mud, and cutting density, the CTR by mud will increase. Moreover, as the drill pipe rotation speed increases and the mud inlet speed increases, the cutting transport ratio will increase.

Keywords: CFD; mud; cuttings transport ratio; vertical drill pipe; rotation

1. Introduction

Current developments in well drilling present unique challenges to drilling fluid design and applications. Drilling fluids perform many functions: removing cutting from the wellbore, cooling and lubricating the drill bit, transferring hydraulic power to the dawn hole, etc. The most important function of drilling fluid is their ability to clean the well, which considering very important factor in choosing drilling mud. The cleaning ability of the drilling mud is affected by many parameters such as the type of mud, the size of the cut, the concentration of the pieces in the mud, the rotation speed of the drill pipe and the inlet speed of the mud.

Numerous researchers have labored in the field of removing cuttings at last years. Many remarkable results were obtained from this non-exclusive bibliography, which it were be utilized to progress field practices, particularly amongst the working companies most participatory in event-related desynchronization (ERD) improvement. Regardless of the phenomenological method, there is no available foretelling model that may be utilized in pre-engineering. The model should consider many parameters , to name just a few, cuttings shape, drilling mud rheological properties and its development during the flow through the well's bit, inclination, rotation speed and drill pipe eccentricity. At the latest years, well monitoring technologies have been sophisticated in real time: CFD (Computational Fluid Dynamics) and PWD (Pressure While Drilling) are presently utilized as a criterion to supply a better assessment of the well circumstances. These new instruments are never utilized as foretelling instruments. CFD for example, affirm, in an amiable way, the cuttings amount which extracted from the well could be compared with the notional cuttings quantity, however, it doesn't provide indications on the agreeable amount of cuttings within the hole.

Zeidler [1] studied the transport of drilled particles in a vertical well using both water and drilling mud, By developed an experimental apparatus to serve this purpose. The results showed that the particle transportation can be increased by the revolving of the drill pipe as a result to shifting particles far from the inward annular wall into zones of higher speeds. Moreover, turbulent flow causes an increase in it also. A theoretical study by Azar and Sanchez [2] was conducted depending on lab studies and the reported in field cases. They studied many factors impact on hole cleaning while drilling directional wells. They found that an increase in flow rate will always cause more efficient removal of drilled cuttings out of the annular space. As well as, drill pipe rotation has mild to significant influences on well cleaning in slant drilling. The mud properties that impact on annular hole cleaning are the viscosity and mud density. Increase in mud density enhances cuttings suspension and therefore their transport; however, increase in mud density causes a decrease in rate of penetration and therefore, higher drilling cost. On the other hand, an increase in mud viscosity decreases hole cleaning in directional well drilling. Under equal conditions, an increase in rate of penetration (ROP) causes an increase in the drilled cuttings concentration in the annulus. Depending on the analyses of the process of hole cleaning and the experimental study Li and Walker [3] developed a computer program that could be used to improve the particles transmission for the process of slide drilling. Their program designed to foretell the bed height for various angles of inclination at various operating conditions. Based on the experimental work and using different mud systems, Ozbayoglu et al. [4] examined the influence of drill string twirl on hole cleaning performance for horizontal well. Their observations show that there is an important effect for the rotation of drill pipe on the ability of fluid to cuttings transport. They observed an amelioration in hole cleaning while the drill pipe is rotated. They found that one of the most important effects of drill string rotation is drastically reduce the critical velocity of fluid which is required to remove the static cuttings bed completely. Moreover, when the cuttings are inserted and because of the decrease in the cuttings bed area, when compared with non-rotation case, frictional pressure losses reduce when the rotation of drill pipe is increased. They found that the viscosity of the clay appears to have some effects on well cleaning at low speeds of rotation, this effects diminishes when the rotation speed is increased. After one year Fadairo et al. [5] showed in them theoretical research that the lifting power of the mud will be change affected by the nuance in the angle of deviation even if it is slightest nuance. There will be a decrease in the ability of the mud to carrying cuttings when the drilling direction is shifted from vertical to horizontal direction. They found that this occurs because of the cuttings proclivity to lie down over the low sidewall of the annulus instead of being lifted out. The experimental work for Piroozian et al. [6] showed a noticeable increase in the quantity of recovered cuttings at the increasing of the plastic viscosity of the mud. Surprisingly, the excess amount of viscosity reverse the result. They concluded that occurs while the flow is turbulent. Analyzing the effect of velocity on hole cleaning shown an affirmative contribution for the velocity to the stationary bed removal. The annular velocity additional increase fetch a significant increase in the transport of cuttings, it can reach a maximum percentage of 98% more considerable in higher fluid and higher hole inclinations. At the most viscous and maximum velocity of the drilling fluid, a recovering for most parts of injected cuttings were happened.

Several researchers like (Okrajni and Azar; Pilehvari et al.; Jawad and Ferda; Kelessidis et al.; Mohammadsalehi and Malekzadeh) [7,8.9,10,11] believed that changing the type of flow system from turbulent to laminar flow, because of the increasing of drilling fluid viscosity, it will lead to deterioration of the borehole cleaning. They have been demonstrated that in turbulent flow cuttings can be displaced better than in laminar flow. Otherwise, some researchers, like (Ford et al.; Iyoho and Takahashi; Belavadi and Chukwu; Shou; Li et al.) [12, 13, 14 ,15,16] claimed that increasing viscosity will amelioration the cleaning process of the hole.

Ozbayoglu et al. [17] showed that the best cuttings lifting performance was found to have occurred in the vertical hole. But an increase in the hole inclination from vertical to horizontal has decreased the cuttings transport performance. Ismail et al. [18] studied the effect of annular mud velocities on drilled cuttings removal using water-based mud with polypropylene beads in vertical, deviated, and horizontal holes. They showed in their experimental work that the CTR decreases as hole inclination increases from vertical to horizontal. The 50° hole angle appears as the critical angle because cuttings bed sliding tendency has higher chances to occur. Consequently, an increase in hydraulic power is needed for an effective wellbore cleaning. Moraveji et al. [19] investigated cutting transport with aerated mud and the impact of various drilling parameters, particularly pipe rotation. The outcomes acquired by this model showed that in horizontal annulus and low flow rates of liquid, the pipe rotation becomes more effective by increasing the air flow rate, while the efficiency of cutting transport with the aerated mud reduces by increasing the inclination. Al-Yasiri et al. [20] studied the influence of Nanoparticles and the effects of various parameters such as flow rate, pipe rotation, drilling fluids rheology, cuttings density, concentration, shape, and drilling fluids-cuttings particle coupling regimes on the cuttings transport in a vertical wellbore. It showed that the cuttings transport process and fluid viscosity can be significantly enhanced by addition nanomaterial to the fluid, and the process is highly effected by cuttings characteristics such as in shape, situ concentration, and density. Finally, Busch and Johansen [21] investigated numerically the effect of synchronous and asynchronous whirling drill string motion for water and a more viscous, shear-thinning fluid on the cuttings bed and cuttings transport using the Two Fluid Model in conjunction with the Kinetic Theory Of Granular Flows and closures from soil mechanics to rheologically describe granular matter. They found that whirling motion of cuttings helps tremendously to disperse the solids into region of the main flow and improves the quality of hole cleaning and cuttings transport.

The present study aims to investigate the influence of various parameters (cutting diameter, cutting injection (addition) concentration, mud entry velocity, drilling pipe rotation speed) on the wellbore cleaning process by calculation of cutting transport ratio (CTR) using the commercial CFD software ANSYS FLUENT.

2. Geometric modeling

The geometry of the case study is designed by a concentric annulus formed by two cylindrical structures. The inner one (rotary tube) rotates with a various rotating speed. Mud steps inside the rotary tube at its end that is nearest to the surface and exits the farthest one, where it meets the pieces of drilled rocks (cutting) coming from the bit to carry them by flowing in the opposite direction in the annulus, and back to the surface. The annuals have a length (9 m) and inner and outer tube diameters (54.42 mm, 127 mm), respectively. Figure (1) shows the geometry of the case study.

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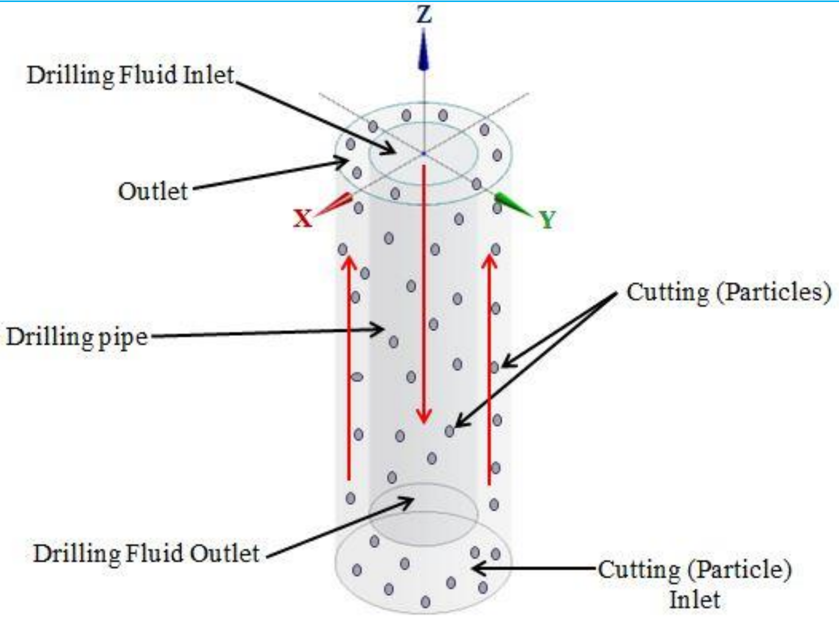

Fig. 1 Geometry of vertical wellbore.

3. CFD Model Solution Method

The present study was simulated using a CFD model for different values of cutting diameter, injection concentration (add), entry velocity and tube rotation speed. Non- Newtonian flow , isothermal conditions, steady state flow and turbulent flow are the assumptions of the present model, for turbulent flow k-ε model has been used, while for multiphase flow Eulerian–Eulerian model has been used. The inner drill pipe has been described as a rotating wall that depends on the speed of rotation of the pipe. The continuity equation can be written as follows [22] , equal for both phases

$$\nabla . \epsilon V = 0 \tag{1}$$

Where
ϵ : volume fraction
V : vector of velocity.

The momentum equations for fluid–solid flow is expressed as [22]

$$\rho_l \epsilon_l [V_l . \nabla V_l] = -\epsilon_l \nabla \mathrm{P} + \epsilon_l \nabla . \bar{\bar{\tau}}_l + \epsilon_l \rho_l g - I \tag{2}$$

$$\rho_s \epsilon_s [V_s \cdot \nabla V_s] = -\epsilon_s \nabla P + \epsilon_s \nabla \cdot \bar{\bar{\tau}}_l + \nabla \cdot \bar{\bar{\tau}}_s - \nabla P_s + \epsilon_s P_s g + I \tag{3}$$

Where
ρ : density
P : pressure
g : gravitational acceleration
$\bar{\bar{\tau}}$: viscous stress tensor
I : interfacial momentum transfer per unit volume.

Also, the subscripts *l*, *s* refer to liquid and solid respectively.
The following are the boundary conditions to which the aforementioned governing equations are subject :

- Uniform inlet velocity at inner pipe.
- No slip condition at the walls.
- Outlet flow condition at the end of annulus.
- Inner pipe is rotated with angular velocity ω.

4. Fluid Rheology

Fluids that have a shear rate dependent viscosity, it's behaviour can be classified as non-Newtonian. One of the most important examples of this type of fluid is drilling fluids. Simple models could not describe the behavior of a non-Newtonian fluid because of its complex behavior. To describe the flow properties of muds oftentimes Bingham plastic model is utilized, which is considered the simplest model, it describes the behavior of a fluid that must undergo a minimum stress in order to flow, the yield stress:

$$\tau = \tau_y + \mu_p \times \gamma^{\cdot} \tag{3}$$

Where

τ_y : yield stress

$\gamma^{\cdot}$: shear rate

μ_p : plastic viscosity.

Bingham plastic model is nearly proven to be an unrealistic characterization of drilling fluids diagrams [23].
The more appropriate models are Herschel-Bulkley and Casson. The first one modifies the model of power law by introducing a yield stress:

$$\tau = \tau_y + k \times \gamma^{\cdot n} \tag{4}$$

Where
k : the consistency index
n : the power law index

The Casson model combines a yield stress with greater shear-thinning behavior than the Bingham plastic model:

$$\sqrt{\tau} = \sqrt{\tau_y} + \sqrt{\mu_p} \times \sqrt{\gamma^{\cdot}} \tag{5}$$

In this study, the flow characteristics of oil-base mud are described using the Herschel-Bulkley model. The study by Davison et al. [23] was the inspiration to the rheological constants which used in the current study (τ=7.481 ,n=0.845 ,κ=0.265).

5. CFD model validation

The CFD model was validated using data obtained from the Marcello and Renato study [24]. Simulation conditions (0.0728 m/s , 200) for inlet velocity and Reynolds number , concentric annulus (ε = 0), and (101.6mm , 50.8mm) for outer and inner pipe diameters respectively. The axial velocity simulated in the present work is shown in Figure 2. Good agreement was observed when compared the work of Marcelo and Renato (2016) with the profile of present simulation, where the error of mean velocity and the relative error of maximum velocity were 2.24% and 2.11%, respectively.

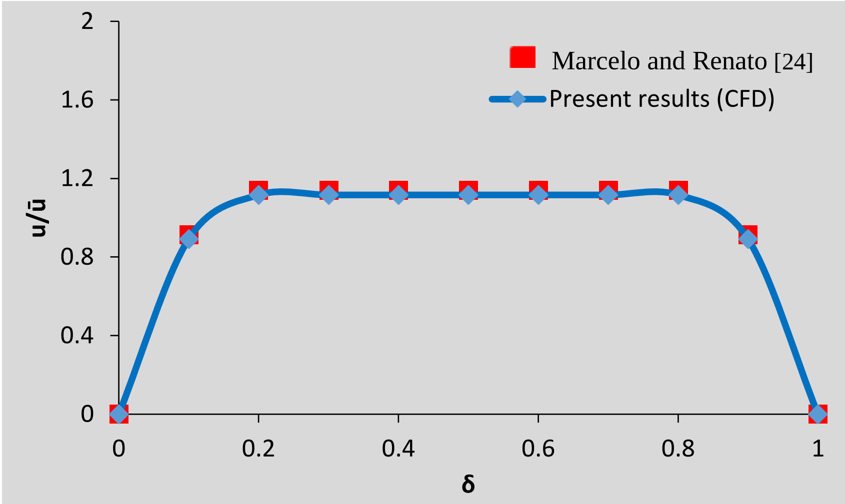

Fig. 2 Comparison of the current study with Marcello and Renato (2016) data.

6. Results and Discussion

In current study, 3D two phase (liquid - solid) turbulent flow is simulated for vertical wellbore with OBM as drilling fluid, rotary drill pipe, and cutting presence to verify the influence of various parameters (cutting diameter, cutting injection (addition) concentration, mud entry velocity, drilling pipe rotation speed) on the wellbore cleaning process by calculation of cutting transport ratio (CTR). The cutting material is considered as sandstone rock from formation of petroleum reservoir which generated from drilling process by bits. Moreover, the hole cleaning capacity has been tested for several types of muds and for the type of rock at the producing layer.

There are several proposed equations for calculating the cutting transport ratio by drilling fluids (CTR), the equation that is used in the current study is as follows [25]:

$$\mathrm{CTR}(\%) = \frac{\text{final cutting weight} * 100\%}{\text{initial cutting weight}} \tag{6}$$

The cutting are transporting from the bottom of the well to the surface in the annulus by the drilling mud that pumped through the drill pipe. This is indicated by Figure (3) where Figure (3a) shows the cutting at the bottom of the well that come from the drill bit, while Figure (3b) illustrates the cutting upward movement through the annulus to the surface, Figure (3c) shows the coming out of the cutting to the surface, Figure (3d) explains that as long as the drilling process continues, the above-mentioned process will be repeated.

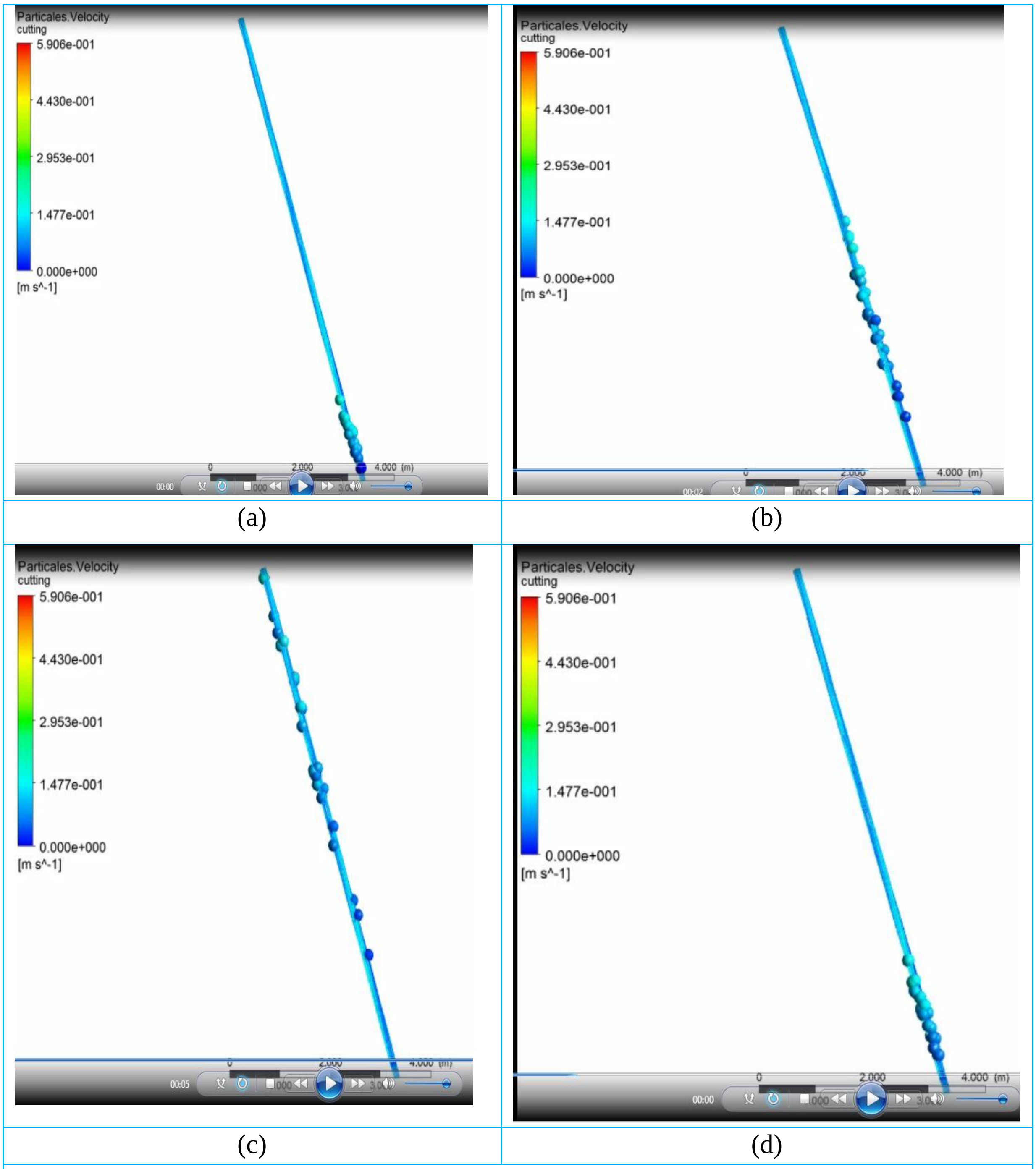

Fig. 3 Contours for Transporting Cutting by Mud.

6.1.The Effect of Cutting Diameter on CTR

The results of using different sizes of cutting in a vertical wellbore are shown in Figure (4), it is clear that the smaller the cutting diameter, the better the wellbore cleaning process. The reason for this is that with a decrease in the cutting diameter, the slip velocity will decreases as it is directly proportional to the cutting diameter and thus this will lead to an increase in the drilling fluid's effectiveness in lifting the cutting. From other hand, the more lightweight the cutting are, the easier it is to be carried by the drilling fluid and thus a better cleaning process. The effect of several values of cutting diameter d = 0.001, 0.002, 0.003, 0.004, 0.005 m on CTR was examined. This simulation is performed with cutting concentration 4%, and the rotational speed are constant 150 rpm with two values of mud inlet velocity (0.18, 0.5 m/s).

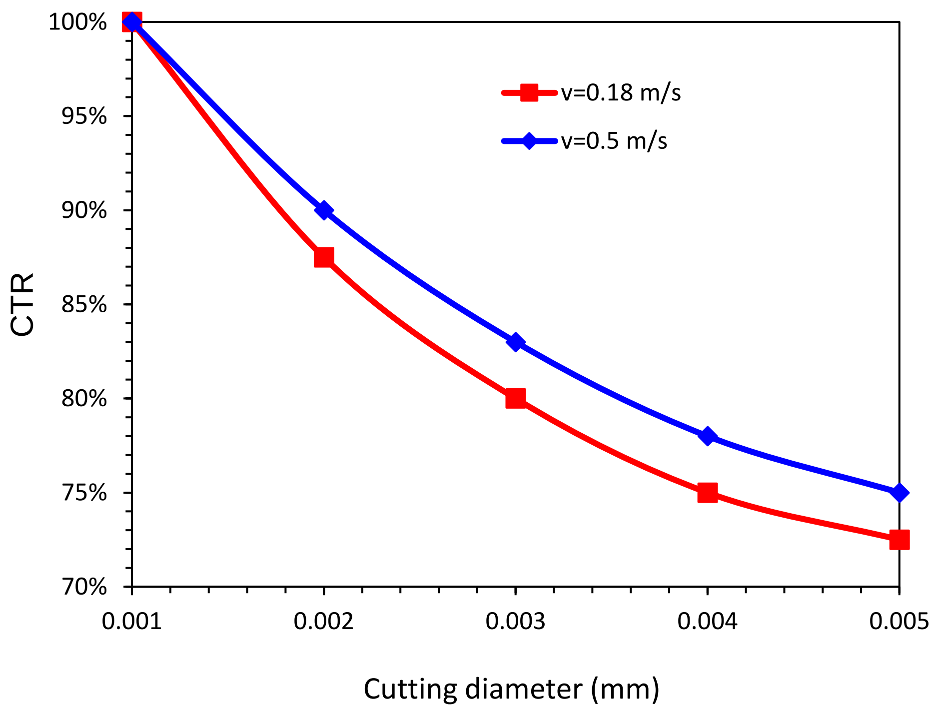

Fig. 4 The Effect of Cutting Size on CTR

6.2.The Effect of Cutting Concentration on CTR

The cutting concentration in the drilling fluid is an indication of the rate of penetration. The simulation with various values of cutting mass flow rate as (0.01, 0.02, 0.03, and 0.04 kg/s), which are respectively (1%, 2%, 3%, and 4%), was implemented to investigate its influence on CTR, while the other parameters are constant for all values (Mud inlet velocity 0.18 m/s, drill pipe rotational speed 150 rpm, cutting diameter 3mm). As shown in Figure (5) the lower the cutting concentration, the better cleaning of the wellbore is obtained. This behavior because the increase in the percentage of the cutting concentration leads to an increase in the cutting existing in the drilling mud, and thus its proximity to each other and this causes a decrease in the effects of the adjacent layer.

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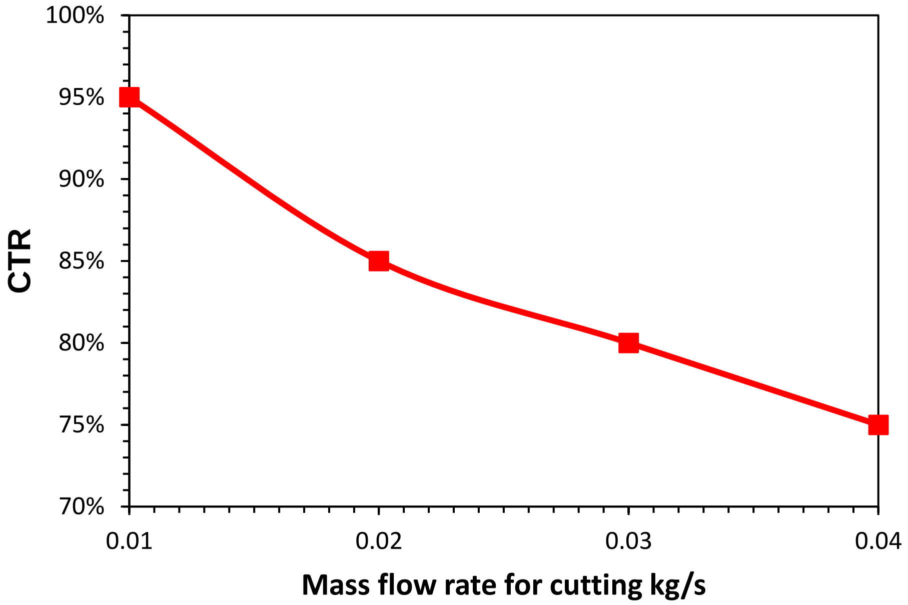

Fig. 5 The Effect of Cutting Mass Flow Rate on CTR.

6.3. The Effect of Mud Inlet Velocity on CTR

The inlet velocity of the drilling mud has a great influence on the cutting transport ratio, so the effect of varying mud inlet velocity v_1 =0.18, 0.3, 0.4, 0.5 m/s is investigated. As the velocity of the fluid rises in the annulus axial direction, the drag force practiced on the small drilled rock pieces increases and the slip velocity will decrease at the higher drag coefficient, thus resulting in a higher transmission ratio of the cutting. The simulation of this case was done with fixed values for rotational speed, cutting mass flow rate, and cutting diameter (100 rpm, 0.04 kg/s, and 0.003 m respectively). Figure (6) illustrates what was explained above.

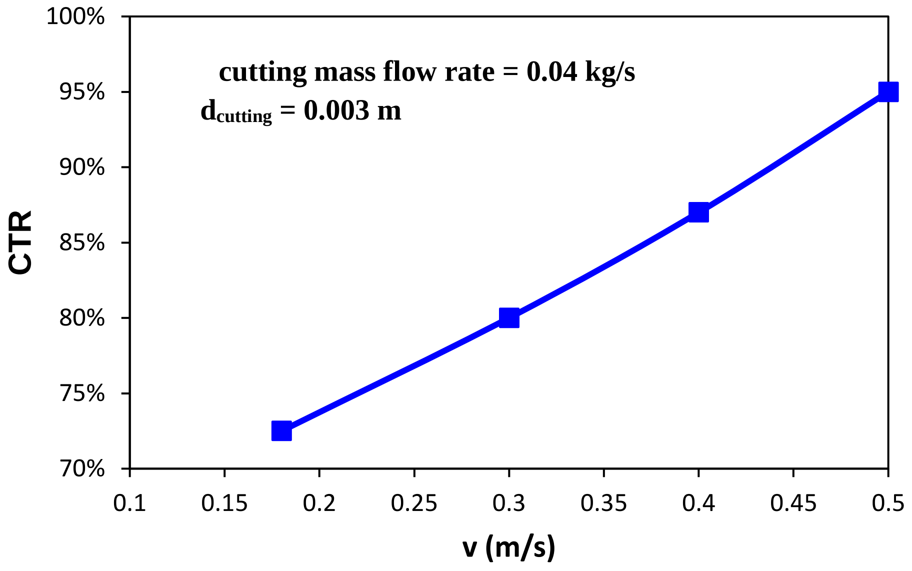

Fig. 6 The Effect of mud inlet velocity on CTR

6.4. The Effect of Drill Pipe Rotation Speed on CTR

The effect of rotational speed ω = 80, 100, 150, 200, 250, 300 rpm on CTR is examined with fixed values for mud inlet velocity, cutting mass flow rate, and cutting diameter (0.18 m/s, 0.04 kg/s, and 0.003 m respectively). Figure 7 shows the CTR profile as a function of the drill pipe rotation speed in the vertical annulus. From the simulation results, it is found that there is a critical rotation speed of the drill pipe to clean the hole in the annulus. With the increase in the rotation speed of the drill pipe, at first the CTR increases , reach the maximum, and then moves to stability. When the rotation speed of the drill pipe increases, at first the CTR increases, reaches its maximum, and then stabilizes. In the increase of drill pipe rotation speed, the tangential velocities of drilling fluid and cuttings are generated near the surface of the drill pipe. The cuttings are dragged by the centrifugal force of the drilling fluid, effectively removing the cuttings bed.

As the rotation speed increases, the friction between the cuttings and the wall increases due to the spiral flow of mixture. In order to clean holes at a lower annular velocity, it is therefore recommended to increase drill pipe rotation.

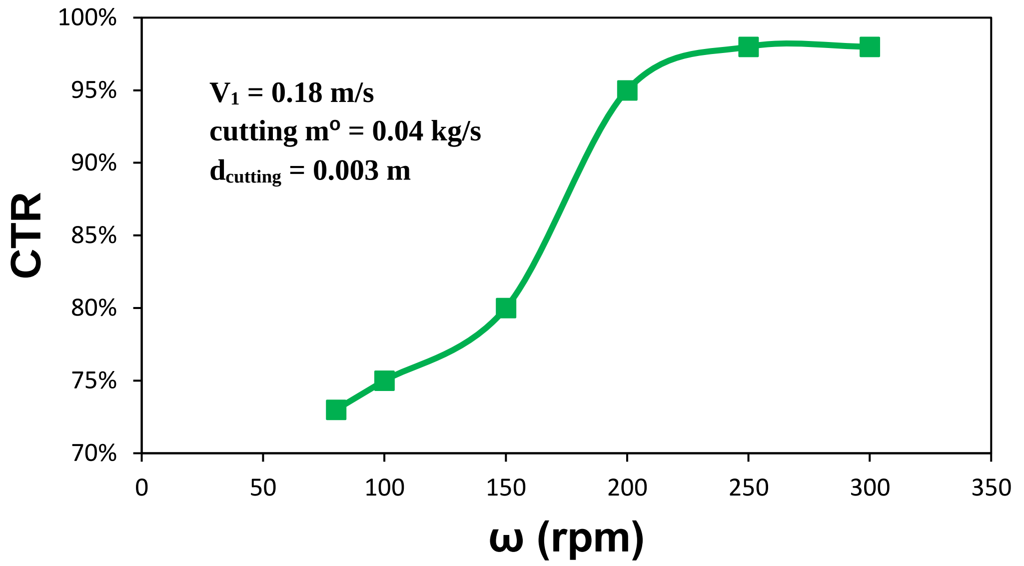

Fig. 7 The Effect of Drill Pipe Rotation on CTR.

6.5. The Effect of Mud type on CTR and Pressure Drop

This section, it is testing the ability of different types of drilling mud (1, 2, 3, 4, and 5), their rheological properties are listed in Table 1, to clean the hole considering the value of pressure drop, with fixed values for mud inlet velocity, cutting mass flow rate, drill pip rotation speed, and cutting diameter (0.18 m/s, 0.04 kg/s, 80 rpm, and 0.003 m respectively). Figure (8) and Figure (9) show that although the other fluids give a better cleaning rate for the well, but they cause a significant increase in the pressure drop compared to the type 2 fluid under the same conditions, which has been used in the current study.

Table 1. The drilling fluids rheological properties

Mud type symbol	τ	n	k	Mud type
1	13.597	0.638	1.441	SBM
2	7.481	0.845	0.265	OBM
3	16.460	0.738	0.581	WBM
4	2.625	0.340	4.989	WBM
5	3.963	0.324	3.825	WBM

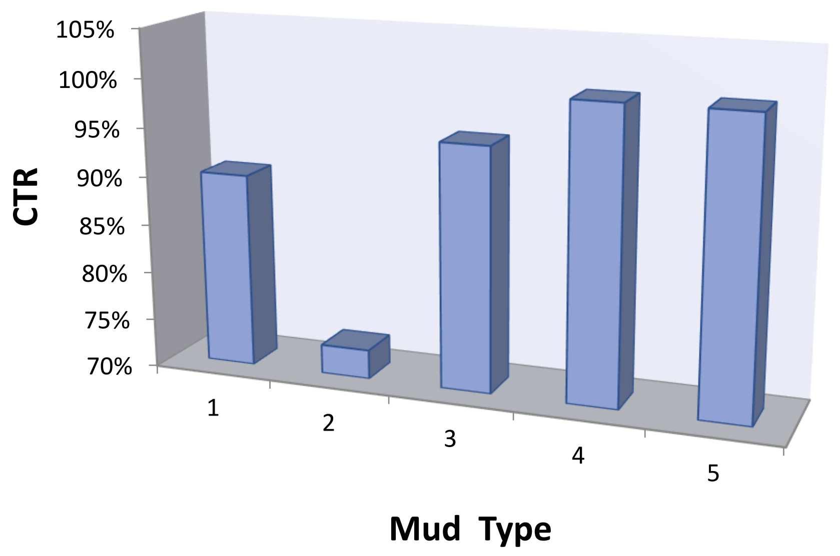

Fig. 8 The Effect of Mud Type on CTR.

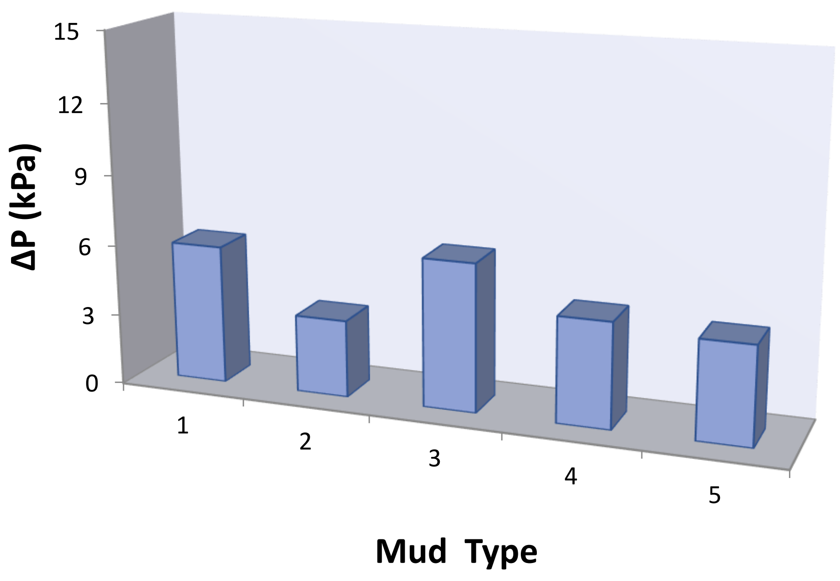

Fig. 9 The Effect of Mud Type on Pressure Drop

7. Conclusions

The vertical wellbore numerical simulation have been carried out to develop a numerical CFD model for the flow of multi-phase drilling fluid in an annular rotating pipe, using ANSYS FLUENT software package. The current study is proposed to discuss the results of the cutting transport ratio in a simulation of vertical wellbore. The following conclusions could be obtained from the current study results:

1. As the cutting diameter decreases or the concentration of the cutting in the mud decreases, the cutting transport ratio (CTR) increases.
2. Cutting transport ratio (CTR) increases as the velocity of mud entry or drill pipe rotation speed increases, reaching a certain value with rotation speed and then remaining constant approximately.
3. In terms of well cleaning, drilling fluids (1, 3, 4 and 5) give better results than the fluid selected (type 2 mud). However, they give high values of pressure drop compared to type 2 mud.

Nomenclature

d	diameter (m)
g	gravitational acceleration (m/s^2)
I	interfacial momentum
k	consistency index
n	power law index
p	pressure (Pa)
Re	Reynolds number
u	inlet velocity (m/s)
V	velocity vector (m/s)

Greek Symbols

ΔP	pressure drop (Pa)
ρ	density (kg/m^3)
τ	shear stress (Pa)
ω	rotating speed (rpm)
τ_y	yield stress for Herschel-Bulkley fluid (Pa)
$\gamma^{\cdot}$	shear rate (s^{-1})
μ_p	plastic viscosity (Pa.m/s)
ε	concentric annulus
δ	dimensionless distance from inner cylinder

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