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Numerical study of drilling fluids pressure drop in wellbores with pipe rotation

Sara J Flayh¹, Hussein S Sultan² and Ahmed K Alshara³

¹Petroleum Engineering Department, University of Misan, Iraq

²Petroleum Engineering Department, University of Bassra, Iraq

³Civil Engineering Department, University of Misan, Iraq

Abstract. Determining of the pressure loss is very complicated task in the petroleum drilling industry. In the present study the effect of different drilling muds flowing inside rotating pipe and exist from an annuals investigated. The effect of rotating speed and inlet speed. The flow is turbulent , steady and 3D with non-Newtonian fluid. The governing equations (continuity and momentum) are solved numerically using CFD with fluent soft package. The results are presented as : stream line , contours , pressure drop and wall shear stress. The results show that pressure drop is decreased when pipe rotational speed increase. slight increasing in shear stress at pipe rotating speed less than 200 rpm for same inlet velocity. Moreover, remarkable shear stress increasing can be observed as the rotational speed equal to or higher than 200 rpm.

Keywords: CFD, Non-Newtonian fluids, pipe rotation, pressure loss, drilling fluid .

1. Introduction

The current developments in the drilling of wells presents unique challenges for drilling fluid design and applications. Main parameters effect cuttings transport are the shear stress and pressure drop which is the most important parameter to prevent stationary bed because shear stress is related to the pressure losses. Moreover, the presence of cuttings and pipe rotation make controlling on pressure loss in annulus becomes more difficult. There is another important parameter effect cuttings transport is the pipe rotation but become more respectable when using non-Newtonian fluids (fluids not obey to the Newtonian law for viscosity) such as drilling mud. Pipe rotation drastically decreases frictional pressure loss inside the wellbores. Drilling muds which have viscosity dependent on shear rate, show non-Newtonian behavior. This behavior is complicated to describe with simple models so that the proper selection of rheological model to describe drilling fluid rheology is so important for calculations . Operations at higher temperature seem to be the new normal for the oil and gas industry. Drilling into the reservoirs with elevated temperature and pressure requires a fluid with stable rheological properties. Temperature has an undoubted huge effect on drilling mud property as drilling through high temperature zone in a formation with water based mud constitutes a problem of significant proportion in the petroleum industry. Many research have transact with the behavior of drilling fluid rheology at different period of pressure and temperature . Numerous studies of the rheology have been described where rheological models have been applied to characterize the data. Ahmed et al. showed that the flow in the annulus is complicated because of many variables , for example drillstring eccentricity, rotation speed , lateral motion, time, cuttings, and fluid parameters [1]. Duan et al. explained that the drill pipe rotation decreases the cuttings concentration in a horizontal wellbore , also resulted in a significant reduction in frictional pressure loss [2]. Sorgun et al. concluded that the CFD model can assessment pressure drop better than slot flow equations when



compared their study data with experimental data [3]. Ofei et al. employed a CFD method to analyze the effects of fluid velocity, annular diameter ratio (from 0.64 to 0.90), and drill pipe rotation on the prediction of pressure losses and cuttings concentration for two phase flow in eccentric horizontal annular geometries [4]. Sun et al. concluded that the pipe rotation has so important effect on the distribution of cuttings in the inclined wellbore and offered a CFD simulation of the effects of drill pipe rotation on cuttings transport behavior in the complex structure well using an Euler model [5]. The studies of Subramanian et al. and Anifowoshe et al. showed that the annular pressure losses for non-Newtonian fluids depend on drill pipe rotation speed, fluid properties, flow regimes (laminar/transitional/turbulent), diameter ratio, eccentricity and equivalent hydrodynamic roughness [6], [7]. Several of research go to use another type of drilling mud known as aerated mud, appropriate hole cleaning has a great effect on decreasing the drilling time and cost. Moraveji et al. are one of those researchers who deal with aerated mud, in their study they show that pipe rotation has a much greater impact on cutting transport when increasing the inclination which also reduces efficiency of cutting transport with the aerated mud [8]. Akhshik et al. explained that in the addition to the liquid flow rate, the cutting transport efficiency is affected by gas-liquid ratio, ambient temperature and injection pressure [9]. Ebikapaye et al. explained that temperature has an undoubted huge effect on drilling mud property as drilling through high temperature zone in a formation with water based mud [15]. Ahmad et al. concluded that viscosity decreases with increasing temperature until the temperature reaches 150°C, and the viscosity plateaus at minimum values for all different rotor speeds [16]. The present study is aim to : investigate the effect of multi drilling muds on the performance of drilling process using computational fluid dynamic CFD with Fluent soft package. Also, to show the effect of rotating on the pressure drop and shear stress inside the annulus rotating pipe.

2. Model Geometry

The geometric of the problem consists of a concentric annulus created by two cylindrical bodies. The inner cylinder (rotate pipe) rotates with a various rotating speed around its axis. The drilling mud enters interior the rotate pipe from one end and exits from the other return back to the surface by flowing inside the annulus. The length of the annulus is (9m) and the diameters of the inside and outside pipes are (54.42mm , 127mm) respectively. Boundary conditions of the problem include the specific values for the velocity inlet and drilling pipe rotation speed as given in Table 1 and Table 2. It should be mentioned that each value of the inlet velocity was tested with all values of rotating speed as shown in the results.

Table 1. The values of u

Inlet velocity u (m/s)
0.18
0.3
0.4
0.5

Table 2. The values of ω

Rotation speed ω (rpm)
80
100
150
200
250
300

3. CFD Model Solution Method

This study was simulated using CFD model for various drilling muds, inlet velocities and pipe rotation speeds. The assumption are (steady state flow , Non- Newtonian flow , turbulent flow and isothermal conditions), and k- ϵ model used for turbulent flow. The inner drill pipe was described as a rotational wall depending on the pipe rotation speed.

The equation of continuity for liquid can be written as [10,11]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho U = 0 \quad \dots\dots(1)$$

Where ρ is the density, U is the velocity vector, and t is the time.

The momentum equation for fluid is expressed as [10,12]:

$$\rho \left[\frac{\partial U}{\partial t} + U \cdot \nabla U \right] = -\nabla P + \nabla \cdot \tau + \rho g - M \quad \dots(2)$$

where P is the pressure, g is the gravitational acceleration, τ is the viscous stress tensor, and M is the interfacial momentum transfer per unit volume.

The above governing equations are obeyed to the following boundary conditions :

- 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 like drilling muds which have viscosity dependent on shear rate, show non-Newtonian behavior. This behavior is complicated to describe with simple models. The simplest model often used to describe the flow properties of drilling muds is the Bingham plastic model which describes the behavior of a fluid which need to submitted to a minimum stress so it can flow, the yield stress:

$$\tau = \tau_y + \mu_p \times \gamma' \quad (3)$$

where τ_y is the yield stress, γ' is the shear rate and μ_p is the plastic viscosity. This model is almost proven to be unrealistic description of drilling mud rheograms [13].

Herschel-Bulkley and Casson models are more appropriate models. The former modifies the power law model by introducing a yield stress:

$$\tau = \tau_y + k \times \gamma'^n \quad (4)$$

where k is the consistency index and n is the power law index.

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

$$\sqrt{\tau} = \sqrt{\tau_y} + \sqrt{\mu_p} \times \sqrt{\gamma'} \quad (5)$$

In this study Herschel-Bulkley model was used to describe the flow properties for various drilling muds (OBM :oil base mud , WBM : water base mud , SBM :synthetic base mud). The rheological constant for the OBM and SBM formulations which used in this study are inspired from the study by Davison et al. as given in Table 3 [13].

Table 3. The rheological properties of drilling muds

Mud type	τ	n	K	Type of mud
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

5. CFD model validation

The CFD model is validated with the data of Marcelo et al. [14]. The simulation conditions were inlet velocity ($u = 0.0728$ m/s), Reynolds number ($Re = 200$), diameters for outside and inside pipe respectively (101.6mm , 50.8mm), and concentric annulus ($\varepsilon = 0$). Figure 1 presents the axial velocity

simulated in this work. The simulated profile showed a good agreement with the work of Marcelo et al. (2016). The relative error for the maximum velocity was 2.11% and the error for the average velocity was 2.24%.

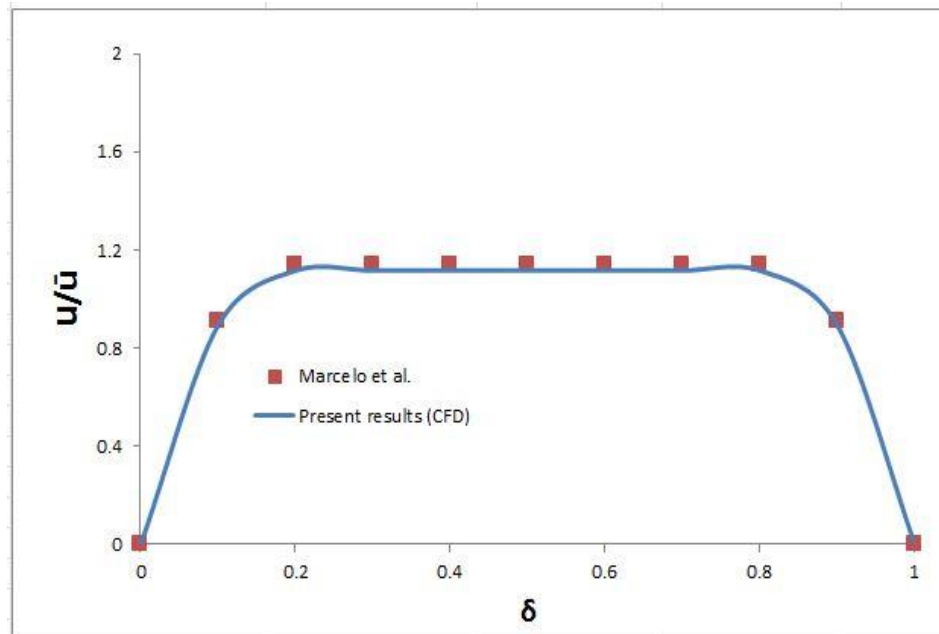


Figure 1. Comparison between the present study and the data of Marcelo et al. (2016).

6. Results and Discussion

The selection of drilling fluids to cover the most commonly used fluids, including oil base mud (OBM), synthetic base mud (SBM) and water base mud (WBM). The base oil used for the OBM was a low-toxicity mineral oil whilst for the SBM a linear alpha olefin (LAO) was used but in the WBMs the salt/polymer-based WBM and bentonite-based WBM are used. The conditions under which the fluid properties were measured was 20°C. In this section the inlet velocity and pipe rotation speed effects are presented for both cases investigated without inner cylinder rotation and with inner cylinder rotation .

a. Inlet velocity effect on pressure drop

b. Non- Rotating cases ($\omega = 0$ rpm)

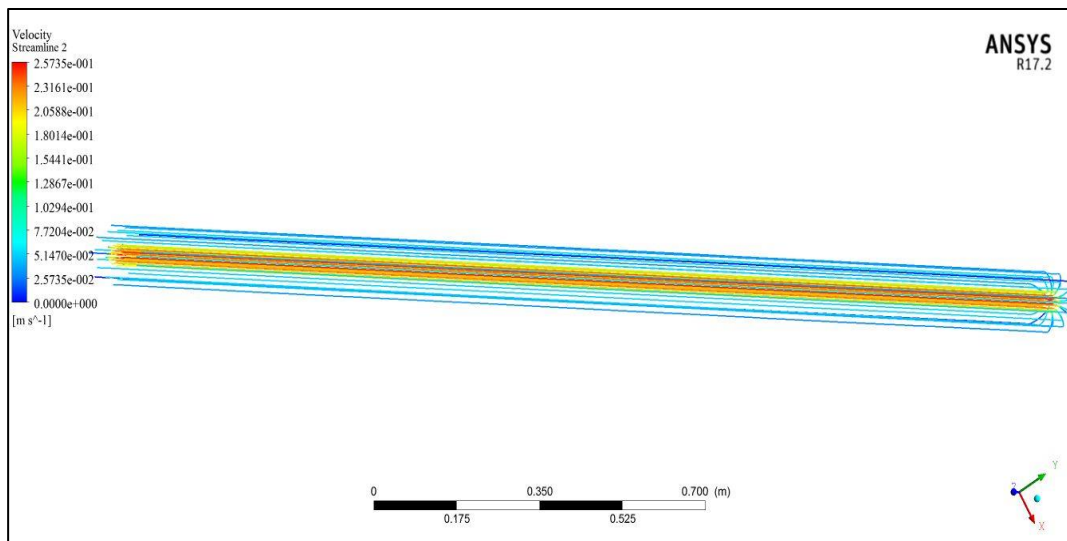
The effect of inlet velocity on pressure is studied for different drilling muds. The results show that increasing of velocity leads to increase pressure drop as listed in Table 4. From the table it can be noted that the mud 2 gives lowest pressure drop for all cases of inlet velocity. Therefore it will be used as case study for our research.

Table 4. The effect of inlet velocity on pressure drop

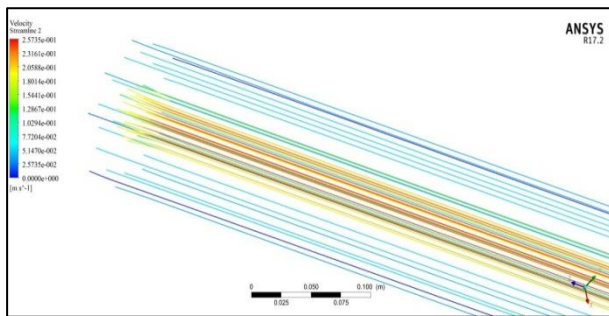
Inlet velocity (m/s)	ΔP (Pascal)				
	Mud 1	Mud 2	Mud 3	Mud 4	Mud 5
0.18	31034.63	14988.65	29389.95	21858.351	18757.485
0.3	37578.075	18451.89	34259.831	26313.37	22311.185
0.4	42373.368	21171.246	37875.041	29501.259	24668.079
0.5	46856.776	23882.191	41277.998	32301.236	26751.359

Figure 2 Shows the contours of stream lines for mud1 at $u=0.18$ m/s , (Figure 2 a) indicate the contour for whole domain which clearly show that the maximum velocities be at the pipe and the lowest velocities be at the annulus due to continuity principles. Also, the Figures (b & c) in Fig 2 show the contours of stream lines at the part of pipe where (Figure 2 b) illustrates the stream lines at the inlet,

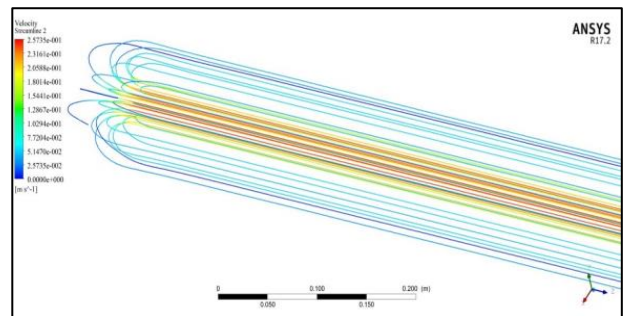
outlet and the center , while the (Figure 2 c) shows the stream lines at the rupturing of fluid in the annulus.



(a)



(b)



(c)

Figure 2. Contours of stream line (a) Whole domain , (b) Inlet , outlet and center , (c) Returning part of annulus .

The contour of velocity magnitude is shown in the Figure 3 for five muds at inlet and outlet when $u=0.5$ m/s. Where the Figs 3 a , b , c , d and e for drilling muds mud 1 , mud 2 , mud 3 , mud 4 and mud 5 respectively. It can be seen that for all figures that the maximum velocity at the center of pipe and the velocity at the annulus is less than pipe. Also , the maximum value of velocity for each mud is varying from mud to another because change the properties of each mud.

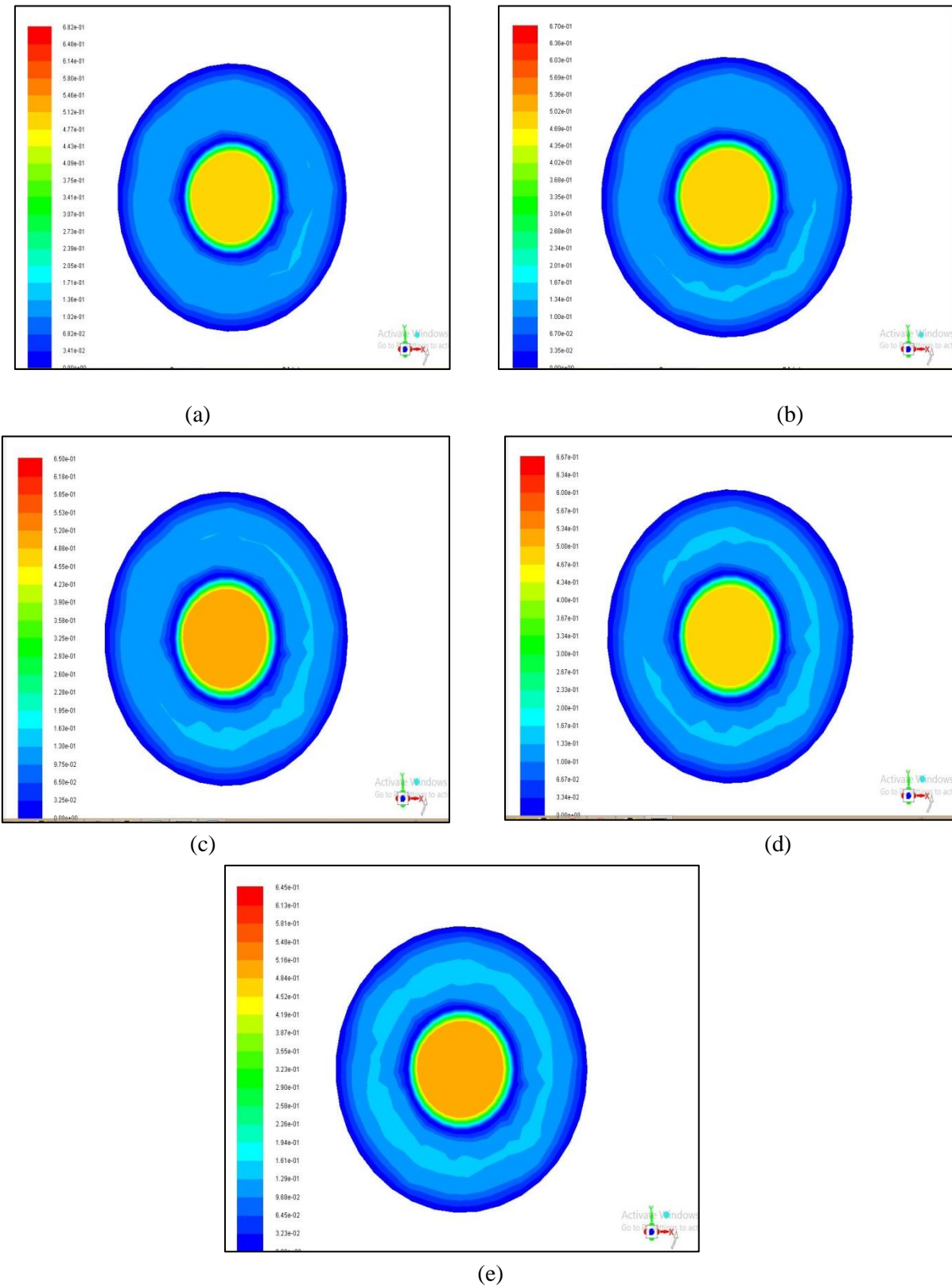


Figure 3. Contours of velocity at inlet and outlet for (a) mud1 , (b) mud2 , (c) mud3 , (d) mud4 , (e) mud5 .

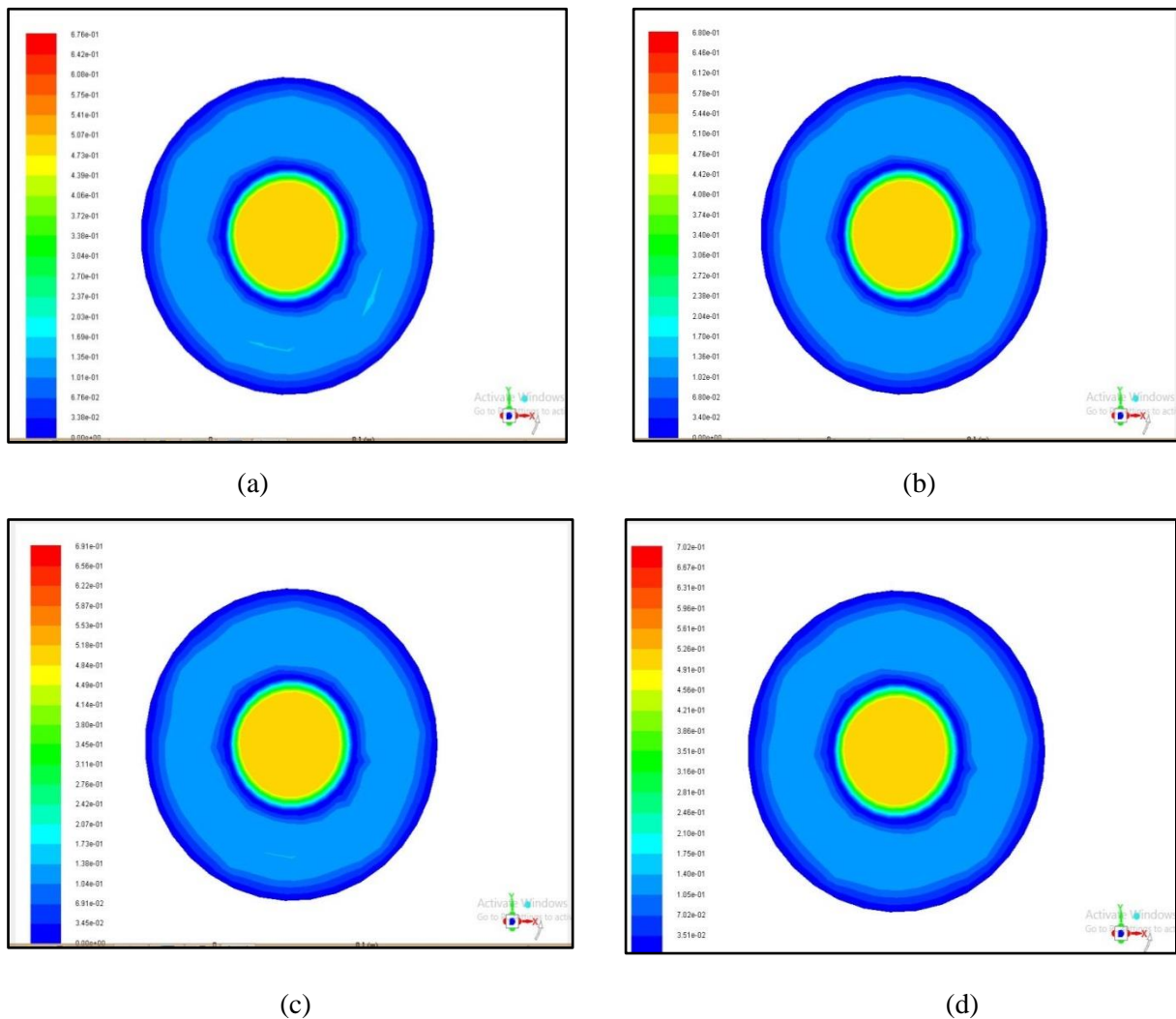
6.1. Rotating cases ($\omega = 80 \text{ rpm} - 200 \text{ rpm}$)

Mud 2 is predicted to be the case study when pipe rotation speed is considerable, because of it gives the minimum values of pressure drop. The results show that increasing of pipe rotation speed for same inlet velocity led to decrease in pressure drop as listed in Table 5. which may return to reduce the effect of shear stress (effect of viscosity) with increasing rotating speed of pipe.

Table 5. The effect of pipe rotation speed on pressure drop for mud 2

ω	u= 0.18	u= 0.3	u= 0.4	u= 0.5
	ΔP	ΔP	ΔP	ΔP
80	14827.97	18545.52	21446.557	24258.88
100	14599.702	18445.158	21382.33	24238.36
150	13997.01	18154.58	21210.13	24123.37
200	13337.99	17811.486	21009.3	23970.139
250	12592.2	17136.53	20307.22	23217.74
300	11928.67	16616.56	19938.14	22921.79

The Figure 4 show the contours of velocity magnitude for mud 2 and $u=0.5 \text{ m/s}$ for four rotating velocity $\omega = 80, 100, 150, 200, 250$ and 300 rpm . The figure indicate that approximately there is no change in the velocity distribution in the pipe and annulus.



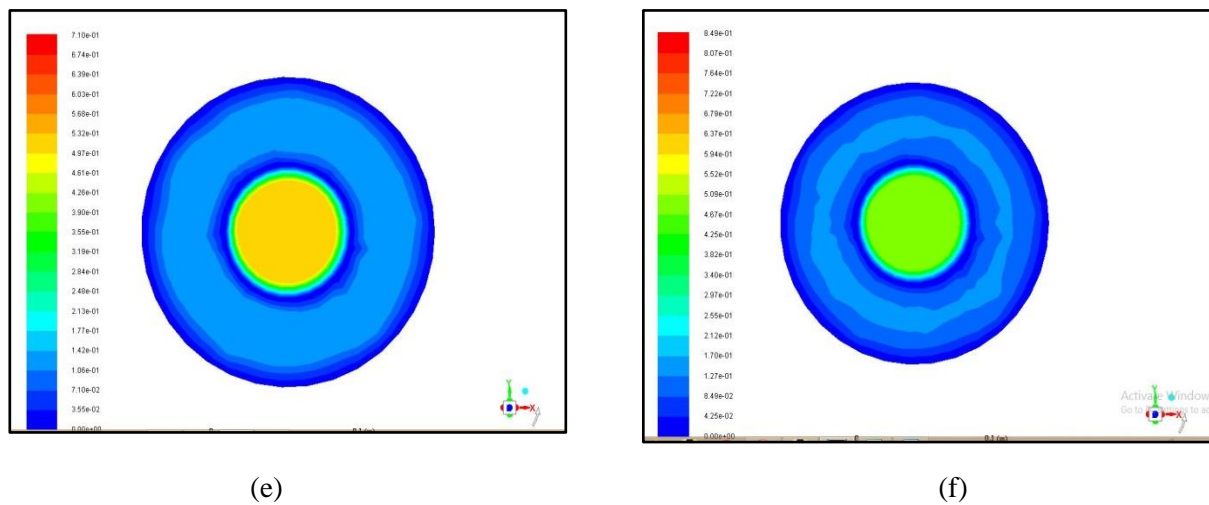


Figure 4. Contour of velocity at inlet and outlet for mud2 (a) $\omega = 80$ rpm , (b) $\omega = 100$ rpm , (c) $\omega = 150$ rpm , (d) $\omega = 200$ rpm , (e) $\omega = 250$ rpm , (f) $\omega = 300$ rpm.

6.2. Inlet velocity effect on shear stress

6.2.1. Non-Rotating cases ($\omega = 0$ rpm) :

The effect of inlet velocity on shear stress is similar to the effect of it on pressure drop when pipe rotation speed is not considerable. The increasing of velocity gives increase in shear stress as listed in Table 6.

Table 6. The effect of inlet velocity on shear stress

Inlet velocity (m/s)	τ				
	Mud 1	Mud 2	Mud 3	Mud 4	Mud 5
0.18	33.31314	16.153	30.68126	23.6129	20.17271
0.3	41.007186	20.418602	36.554262	28.879044	24.13072
0.4	46.785516	23.80273	40.960138	32.518569	26.818386
0.5	52.233113	27.139311	45.114802	35.734554	29.17807

6.2.2. Rotating cases ($\omega = 80$ rpm – 200 rpm) :

Mud 2 is predicted to be the case study when pipe rotation speed is considerable. The results show slight increasing in shear stress at pipe rotating speed less than 200 rpm for same inlet velocity. Moreover, remarkable shear stress increasing can be observed as the rotational speed equal to or higher than 200 rpm and that listed in Table 7.

Table 7. The effect of pipe rotation speed on shear stress for mud 2

ω	u= 0.18	u= 0.3	u= 0.4	u= 0.5
	τ	τ	τ	τ
80	15.8005	20.2662	23.75775	27.13623
100	15.6400	20.2278	23.7500	27.15916
150	16.8148	20.9559	24.29269	27.58637
200	20.9908	23.6387	26.23945	29.0592
250	24.20725	25.92171	27.93947	30.31716
300	28.73251	29.75178	31.17855	33.03444

7. Conclusions

The effect of inlet velocity and drilling pipe rotating speed on pressure drop and shear stress were studied numerically by using CFD simulation. Mud 2 is predicted to be the case study when pipe rotation speed is considerable, because of it gives the minimum values of pressure drop and shear stress. That leads to the following results:

- Increasing inlet velocity gives increase the pressure drop for all type of drilling mud.
- When pipe rotating speed is considerable, the increasing of pipe rotation speed for same inlet velocity leads to decrease in pressure drop.
- The increase of shear stress at the drill pipe and annulus is a result for inlet velocity increasing.
- At pipe rotating speed less than 200 rpm slight increasing in shear stress can be observed for same inlet velocity.
- Remarkable shear stress increasing can be observed as the rotational speed equal to or higher than 200 rpm.

8. Nomenclature

u	inlet velocity (m/s)
U	velocity vector (m/s)
t	time (s)
p	pressure (Pa)
g	gravitational acceleration (m/s ²)
M	interfacial momentum
n	power law index
k	consistency index
Re	Reynolds number
d	diameter (m)
ΔP	pressure drop (Pa)

9. Greek Symbols

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

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