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COMPUTATIONAL FLUID DYNAMICS AND HEAT TRANSFER IN ROTATING PDC DRILL BIT UNDER DIRECT AND REVERSE CIRCULATION

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Abstract. Polycrystalline Diamond Compact (PDC) drill bits are employed in deep water oil well drilling operations, due to their increased robustness and lifetime. In the direct circulation mode, the drilling fluid is descendant through the drill pipe and ascendant in the annular section. Alternatively, in the reverse circulation mode, the drilling fluid is descendant through the annular section and ascendant through the drill pipe. The latter mode may be used for more stable downhole formation and by the fact that it dismisses the need for rigid risers. A thorough computational fluid dynamics (CFD) parametric study on turbulent flow around rotating drill bits still lacks in the literature. In the present work, turbulent fluid flow and heat transfer in a rotating primitive PDC drill bit model is performed for a broad range of volumetric flow rates. The primitive geometric model consists of a simplified reproduction of commercial bits, yet keeping unimpaired their functional features. The proposed model reduced computational time by 92%, compared to a commercial drill bit geometry. Numerical simulations allowed prediction of recirculation zones in the fluid domain and intensified wear regions over the bit surfaces. Head losses, turbulent flow patterns and temperatures were also evaluated in both direct and reverse circulation, the latter showing reduced vorticity and friction.

Keywords: Oil well drilling, Reverse circulation, Computational Fluid Dynamics, SST turbulence model.

1. INTRODUCTION

Deep water oil well drilling is prone to significant physical complexity, due to the fact that oil reservoirs are found at high pressure and random rock formations. Adequate control of operational parameters is critical to reduce environmental damage, increase efficiency and reduce operational costs (Bourgoyne, 1986). In response to such operational challenges, drill bits design comes to aid, alongside with the development of new drilling methods and parameters.

Polycrystalline Diamond Compact (PDC) bits are known for greater robustness and lifetime, remaining an applicable tool to such aggressive conditions. Reverse circulation, an alternative circulation method, is presumed to provide better wellbore stability compared to the traditional direct circulation. Also, this mode of circulation would dismiss the need for rigid risers, which can take many days to install. In order to investigate efficiency for these design proposals, numerical modeling using Computational Fluid Dynamics (CFD) softwares poses an attractive solution, allowing designers to investigate a wide variety of geometric features with reduced time and predict failure modes otherwise challenging to visualize experimentally.

In an effort to understand and predict wear and failure modes for PDC bits, researchers investigated the influence of heat transfer phenomena on the drilling process. In order to get insights on wear prediction, Glowka et. al. (1985) developed an analytical method to estimate temperatures for a PDC cutter. Appl et. al (1993) measured temperatures and forces on a PDC cutter with the aid of an experimental bench, proposing relations between the measured loads and

wear rates. Numerical studies on drilling hydraulics give valuable insights on understanding the drilling process. Sansoni (2005) developed a simplified numerical model for the downhole region using non-Newtonian fluid under reverse circulation with solid particles. It was shown that reverse circulation provided better cuttings removal capability. Wells et. al. (2008) proposed a more detailed PDC bit model, evaluating it under direct circulation and testing it experimentally. It was found that the rate of penetration is strongly dependent on the flow velocities around the bit cutters. Daroz (2015) carried out a parametrical analysis on the effects of operational parameters and fluid properties on flow around a simplified tricone roller cone drill bit under direct and reverse circulation. Bacelar (2016) investigated the same effects for a numerical model of a PDC bit, considering both direct and reverse circulations. Vieira (2017) conducted an experimental analysis on the performance of both circulation methods in downhole cleaning, representing the drill bit by a sudden contraction. As a result from these works, it was shown that volumetric flow rate has strong influence on flow patterns; alternatively, it was found that reverse circulation can cause fewer recirculation zones and be capable of giving equal or better efficiency on downhole cleaning and cuttings removal.

In the present study, flow patterns and temperature fields are calculated for a broad range of volumetric flow rate under direct and reverse circulation by developing a downhole numerical model based on a primitive geometry for the PDC bit. The primitive geometry is shown to reproduce the same basic hydraulic functions of a full commercial part, while also reducing simulation time by an enormous factor.

2. MATHEMATICAL MODELING

The primitive geometric model is represented in Fig. (1). This simplified model aims to keep their functional features and axial symmetry of 120°, so that mesh size and simulation time can be further decreased.

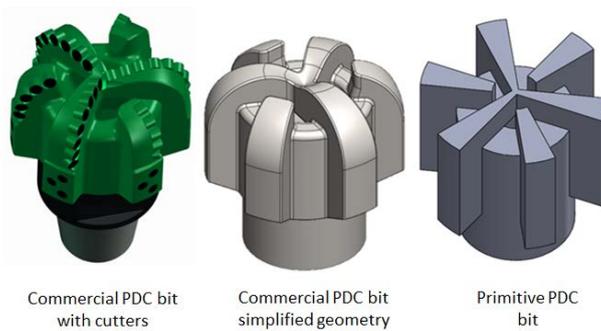


Figure 1. Primitive model based on detailed models

The drilling mud is modeled as Newtonian fluid with constant properties, whose values were derived from a parametric study carried out by Bacelar (2016). Fluid flow is modeled as turbulent, incompressible and at steady state. Gravity is neglected, since imposing a constant volumetric flow rate at the inlet is sufficient to promote the expected fluid motion. The physical domain is illustrated in Fig. (2). It is assumed that the domain has tangential periodicity and the walls are considered to be smooth and impermeable. Under the above circumstances, the equations for conservation of mass and momentum take the following form, respectively:

$$\nabla \cdot \mathbf{u} = 0 \quad (1)$$

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla P + \mu \nabla^2 \mathbf{u} \quad (2)$$

where \mathbf{u} represents the velocity field, P is the pressure, μ is the dynamic viscosity and ρ the fluid density.

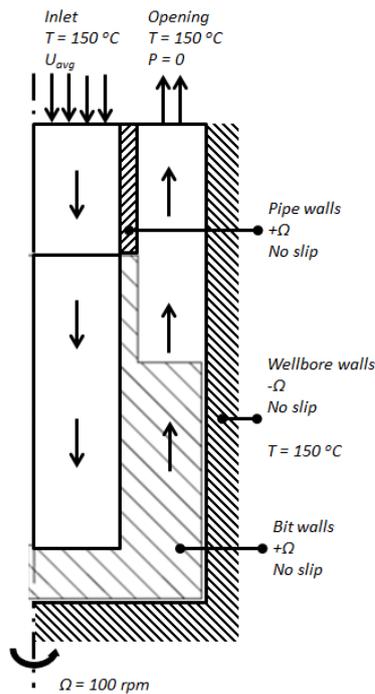


Figure 2. Schematic for the physical domain under direct circulation and boundary conditions.

In order to solve those equations for turbulent flows, such quantities are averaged in time, to yield the Reynolds Averaged Navier Stokes equations (RANS). The Reynolds Averaged Navier Stokes equations show dependence on the calculation of turbulent viscosity, which is solved by the $k-\omega$ SST turbulence model. Using both $k-\varepsilon$ and $k-\omega$ turbulence models, the $k-\omega$ SST turbulence model can provide better results predicting automatically flows near and far from the walls. On the down side, this turbulence model is not capable of correctly representing laminar regions inside the domain, which might take place in such complex geometry. Heat transfer is modeled by the equation for energy conservation for fluid and solid domains:

$$(\rho c_p) \frac{DT}{Dt} = \nabla \cdot (k \nabla T) \quad (3)$$

Wall and boundary temperatures (Fig. 2) are based on a model proposed by Raymond (1969) for prediction of rock formation temperatures. Thermal loads caused by the cutters are modeled by an uniform and constant surface heat generation rate of 5540 kW/m², as represented in Fig. (3).

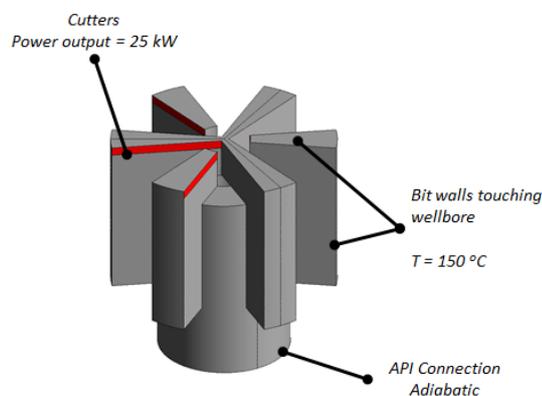


Figure 3. Schematic for thermal boundary conditions

The drill bit is discretized using unstructured mesh. The equations are discretized and solved using the finite volume method based on elements (FVMbE) and the fully coupled solver *CFX*. Advection terms are approximated by First Order *Upwind* scheme, while turbulent quantities were solved using *High Resolution* scheme. The *RMS* residuals for the equations of conservation and pressure, velocity temperature values at defined regions of the domain were defined as stopping criteria for simulations. Solutions were interrupted when *RMS* residuals reached values below 10^{-5} and values for temperature, velocity and pressure became stable. Mesh size for the PDC bit fluid domain was defined by execution of a mesh independence study, evaluating values for maximum velocity and inlet pressure, as shown in Figure 4.

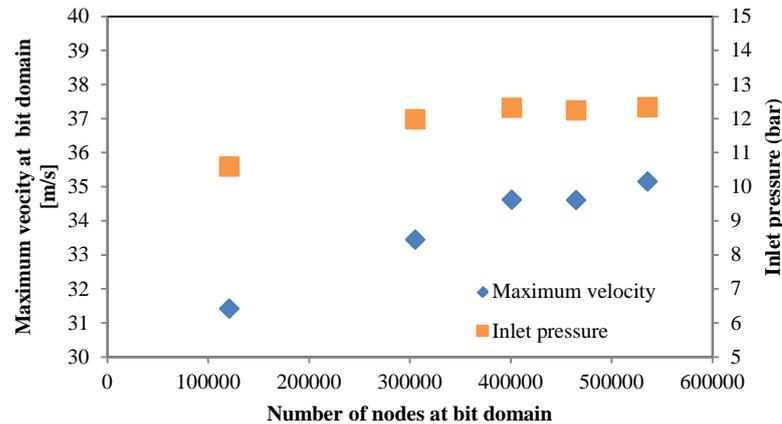


Figure 4. Diagram of inlet pressure and maximum velocity versus mesh size. Inlet pressure range from 500 kPa to 1500 kPa.

3. RESULTS

In order to verify and validate the turbulence and heat transfer models assigned for this work, a numerical reproduction of an experimental study on turbulent flow conducted by Rothe et. al. (1997) was carried out. In this study, the turbulent flow of air through an annulus with static walls and constant surface heat flux at the outer wall was investigated. The annular geometry has a radius ratio of 0.86, for which turbulent flow at $Re = 10000$ was evaluated. A numerical model was simulated employing similar meshing techniques and physical models as the ones for the PDC bit model. Nondimensional axial velocity and temperature profiles were taken at positions of fully developed flow and compared, as seen in Fig. 5 and Fig. 6.

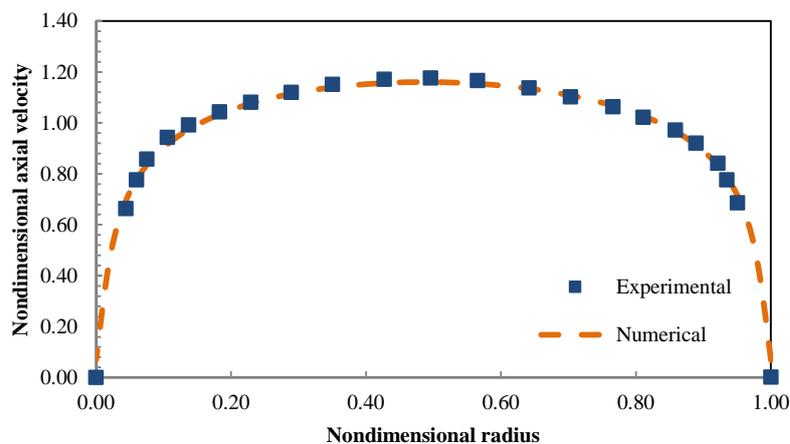


Figure 5. Diagram of nondimensionalized axial velocity versus nondimensionalized radius

It is shown that the numerical results agree well with experimental data. Values evaluated at the bulk region of the flow are very close, while near wall regions show small deviations. Such differences demand better turbulence model

calibration and mesh adjustments for near wall modeling. However, it can be noticed that the $k-\omega$ SST turbulence model can provide satisfactory results for near wall and bulk regions of the flow.

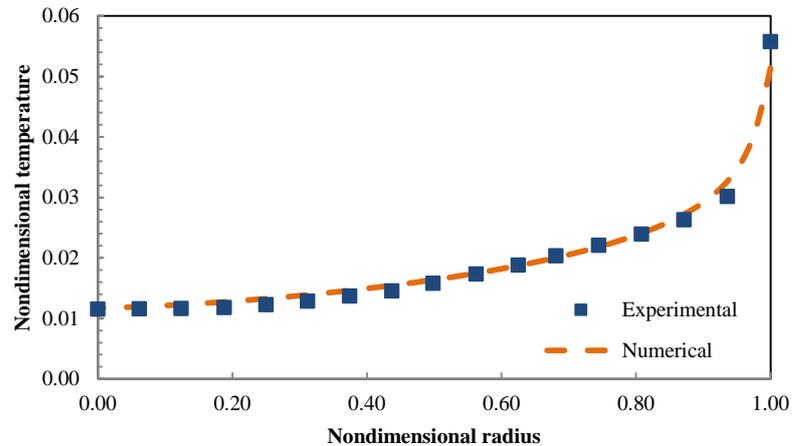


Figure 6. Diagram of nondimensionalized temperature versus nondimensionalized radius

The proposed primitive PDC bit model was investigated for a broad range of volumetric flow rates. According to previous studies, this operational parameter has the most significant influence on the performance. Figure 7 shows the flow patterns around the bit surfaces for direct and reverse circulation. The flow velocities at the well bottom are greater for direct circulation as the fluid is accelerated through the inner pipe and collides at the bottom, providing better cooling and washing capabilities. On the other hand, the flow velocities are less chaotic for reverse circulation and streamlines show less recirculation zones, which are associated to better downhole stability and reduced pressure losses.

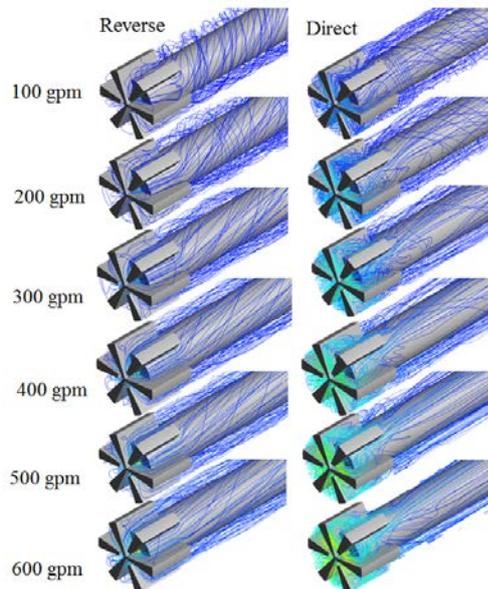


Figure 7. Flow patterns enhanced by streamlines for reverse (left) and direct (right) circulation. Flow rate range from $0.006309 \text{ m}^3/\text{s}$ to $0.037854 \text{ m}^3/\text{s}$.

Figure 8 shows the variation of head loss as a function of volumetric flow rate (Q). It can be noticed that for low values of Q , both circulation techniques perform similar and require same amount of hydraulic power input. However, for higher Q , more power due to head loss is required, especially for direct circulation, adding more cost to such operation at a nonlinear rate, caused by higher fluid velocities and recirculation seen from flow patterns of Figure 7. Such trends are in good agreement with previous results of Daroz (2015) and Bacelar (2016).

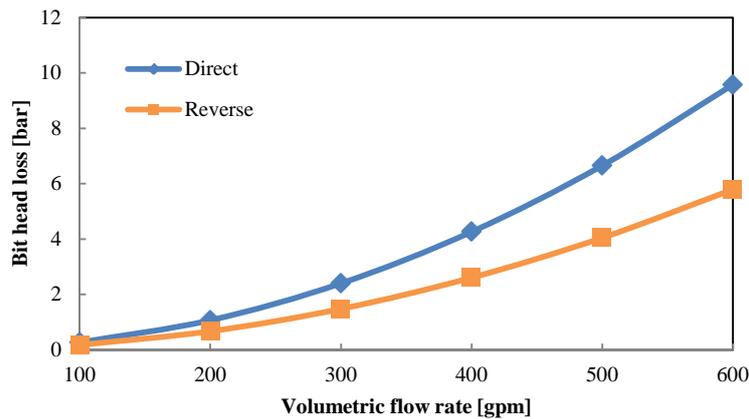


Figure 8. Diagram of head loss versus flow rate. Vertical range from 0 to 1200 kPa, horizontal range from 0.006309 m³/s to 0.037854 m³/s.

It was found that, for both circulation techniques, the sudden contractions between the inner drill pipe and the slots are the regions most likely to suffer from abrasive wear due to wall shear. Fig. 9 shows contours of wall shear for direct and reverse circulation as a function of volumetric flow rate. On the other side, it is shown that, for direct circulation, more regions close to the cutters are prone to most intense wall shear, explained by the higher flow velocities at the well bottom (Fig. 7).

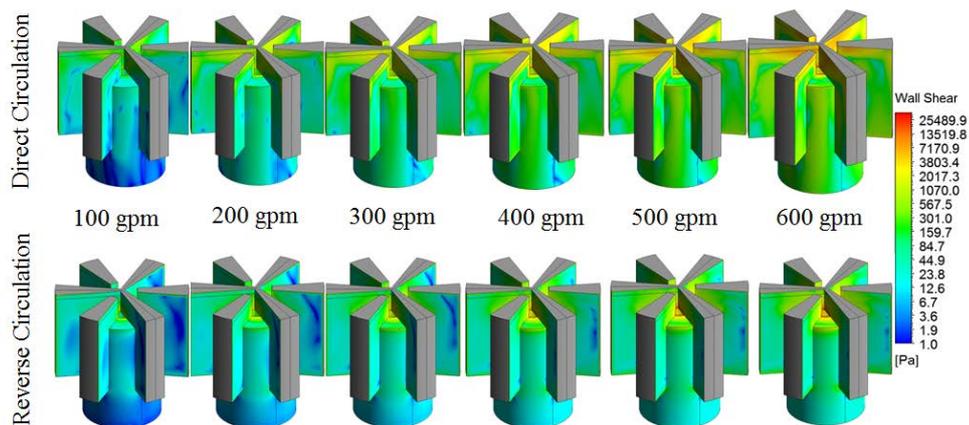


Figure 9. Wall shear stress contours on bit surfaces for direct (top) and reverse (bottom) circulation. Flow rate range from 0.006309 m³/s to 0.037854 m³/s.

Figure 10 shows the temperature field in the drill bit surface as a function of volumetric flow rate. At first, it can be noticed that temperatures are heavily dependent on circulation methods. Direct circulation achieves lower temperatures and smaller heat affected zones when compared to the reverse circulation. Alternatively, it is shown that heat affected zones are more effectively hindered when increasing flow rate for direct circulation than for reverse circulation. Such behavior shows agreement with predictions based on flow patterns showing higher velocities, shear stresses and recirculation achieved for direct circulation (Figures 7 and 9).

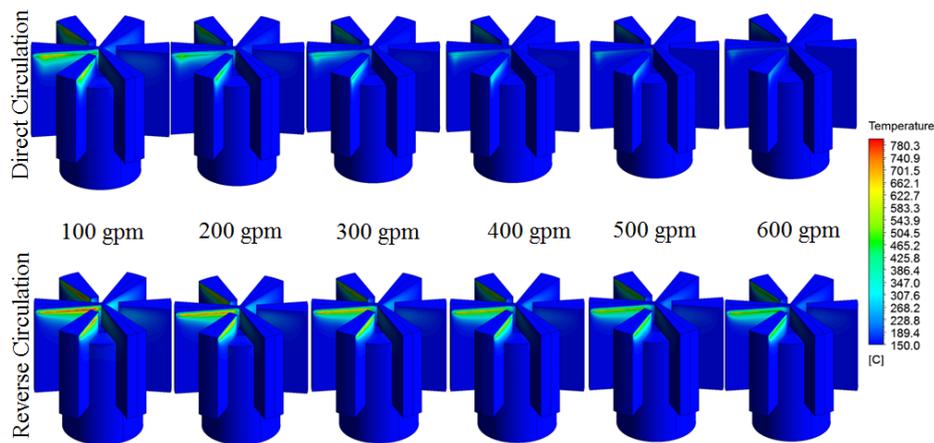


Figure 10. Temperature contours on bit surfaces for direct (top) and reverse (bottom) circulation. Temperature range from 423 K to 1053 K, flow rate range from 0.006309 m³/s to 0.037854 m³/s.

Figure 11 shows the variation of maximum temperatures at the bit body as a function of volumetric flow rate and circulation method. At first, it is shown that temperatures decrease proportionally with higher Q for both circulation methods, showing strong dependence on flow rate and circulation methods.

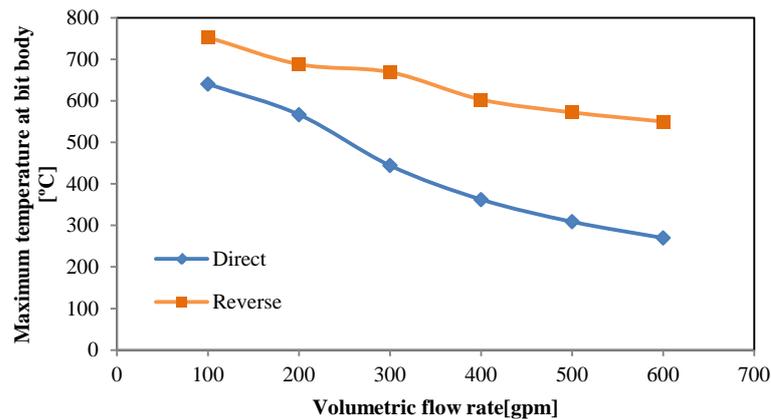


Figure 11. Diagram of maximum bit temperature versus flow rate. Vertical range from 273 K to 1073 K, horizontal range from 0.006309 m³/s to 0.037854 m³/s.

On the other hand, it can be noticed that, once again, direct circulation provides better cooling capabilities, especially for higher Q . Temperatures achieved at direct circulation are at least 100° lower than those achieved by reverse circulation. It can be pointed out that the temperature variation found for the simulated operational range could warn designers for possible changes in material properties dependent on temperature, such as phase transformation, which can explain premature wear reported from field operations.

4. CONCLUSIONS

A simplified numerical model based on a primitive PDC bit geometry was proposed for bit hydraulics and heat transfer analysis. It was shown that both circulation methods show different performances under a wide range of volumetric flow rate, highlighting potential applications for both methods. Recirculation zones and intense wear regions were identified for direct circulation, which can also promote better drill bit cooling. Reverse circulation method provides lower head losses in addition to better downhole stability, while remaining less efficient to provide a proper drill bit cooling. The primitive geometry can be used as a starting point for geometric optimization of PDC drill bits adapted to reverse circulation. For future studies, non-Newtonian fluid models for turbulent flow are likely to be employed, achieving better fidelity at modeling bit hydraulics.

5. ACKNOWLEDGEMENTS

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