Simulation study of rotor erosion for a continuous-wave pulse generator by computational fluid dynamics

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ABSTRACT
Continuous-wave pulse generator plays an important role in generating high-quality pulse signals in measurement while drilling systems. However, the generator affects the quality of pressure wave signals due to erosion on the continuous wave generator rotary valve caused by drilling fluid during operation. In this paper, the computational fluid dynamics (CFD) model of a rotary valve was established by ANSYS finite element method, and a series of three dimensional flow field simulation experiments were conducted to analyze the influence of factors, such as drilling fluid density, viscosity, inclusion particle diameter, and particle mass flow on the erosion of the rotary valve. Experiments show that the rotor erosion increases with increasing drilling fluid density, viscosity, diameter, and mass flow of particles in the drilling fluid. Moreover, the rotor erosion exponentially increases with increasing viscosity of the drilling fluid. The results provide necessary data for drilling fluid system improvement, rotor material selection, and surface structure treatment.

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1. Introduction
Efficient and reliable measurement while drilling/logging while drilling (MWD/LWD) technology can effectively enhance geo-steering and stratigraphic evaluation capabilities and improve oil and gas drilling-encounter ratio in oil and gas drilling operations. Drilling fluid pulse, as a key downhole data transmission system in MWD/LWD technology, is a widely used data transmission tool due to its overall reliability, low development cost, and wide application (Hussain, Huelvan, & Adams, 2014; Shen, Huang, & Gao, 2009; Su & Dou, 2005). In particular, continuous-wave drilling fluid pulse with high transmission rates is the frontier development direction of drilling fluid pulse transmission (Hutin, Tennent, & Kashikar, 2001; Ingolf, Detlef, Dang, Hanno, & John, 2008).

The continuous wave fluid pulse transmission system is mainly composed of a downhole continuous wave pulse generator and a ground data processing sub-system. The core components of the continuous wave pulse generator include a stator and a rotor. Both components have the same numbers of blades, which produce continuous pressure waves by changing the throttle area between the rotor and the stator. The rotor is eroded by the high-flow drilling fluid and the entrained particle during pulse generation; in the long run, the structure will be inevitably worn and deformed, leading to reduced quality of the uploaded pulse signal, increased difficulty in demodulation and decoding of ground signal, and serious effects on the normal development of on-site drilling operations (Yan, Geng, & Wei, 2018).

Zhang et al. (2015; Hu et al., 2017) used the computational fluid dynamics (CFD) method to examine the effects of drilling parameters, such as throttle opening, drilling fluid flow rate, and solid particle mass flow, on the erosion of the pressure drilling throttle valve. The flow rate of the drilling fluid exerted the greatest effect on erosion rate, followed by solid mass flow rate. Liu, Xu, and Qi (2005a; Liu, Xu, Qi, & Li, 2005b) proposed the law of erosion and wear in hydraulic machinery by investigating the erosion and wear properties of metal materials that are commonly used in water turbines, then the anti-wear measures were suggested. In this study, the mass concentration of solid particles in the slurry was controlled by changing the mixing ratio of water and SiC particles, adjusting the particle size and impact speed of the particles. It is found that the erosion rate of stainless steel and high-chromium cast iron gradually increased with increasing abrasive grain size, slurry concentration, and abrasive impact velocity. It was also considered that the material structure had a great influ-
ence on erosion performance, and the erosion can be reduced by selecting a proper material. Zhao et al. (2018) applied the solid-liquid two-phase flow discrete model to study the influence of particle parameters, on the internal flow path erosion; the rate and erosion distributions were mainly analyzed by changing particle velocity, diameter, and volume ratio at a certain drilling fluid. The results showed that the average erosion rate of the inner flow channel increased with increasing particle inlet velocity. The average erosion rate of the internal flow passage first decreased, then increased, and finally tended to be stable with increasing particle diameter.

It is shown that existing literature mainly observes the erosion results by erosion principle, simulation prediction, and actual test, focused on the influence of drilling tool material, drilling fluid flow rate, and solid particles on the erosion of drilling tools (Hu et al., 2017; Huang, Xie, Huang, Li, & Xie, 2017; Liu, Xu, and Qi, 2005a; Liu, Xu, Qi, & Li, 2005b; Zhang et al., 2015; Zhao et al., 2018), lacking detailed analysis of rotor erosion caused by various parameters of drilling fluid. The present study aims to determine the influence of various drilling fluid parameters on rotor erosion. The three-dimensional (3D) flow field of FLUENT was analyzed to understand the rotor erosion condition with respect to the drilling fluid ratio. Results indicate the importance of predicting the working life of the rotor and improving the quality of downhole pulse generation.

2. Calculation model

2.1. Discrete phase governing equation

The principle of solid particle motion prediction is based on the force impacted on the particle to calculate the moving trajectory, which indicates that the motion of particles is associated with the existing scale and distribution pattern of erosion and the Lagrangian reference system is adopted to evaluate the trajectories of discrete phase in FLUENT (Huber & Sommerfeld, 1998).

According to the inertia and load balance of discrete particle, the motion equation of a discrete particle can be written as follows:

\[
\frac{d\mathbf{u}_p}{dt} = F_D(u - u_p) + g_p(\rho_p - \rho) \rho_p + F_y
\]

(1)

where \(F_D(u - u_p)\) is the resistance per unit mass of particles, \(u\) is the liquid phase velocity (m/s), \(u_p\) is the particle velocity (m/s), \(\rho\) is the continuous phase liquid density (kg/m³), \(\rho_p\) is the particle density, \(g_y\) is the gravitational acceleration (m/s²) in the y direction, \(F_y\) represents the other forces in the y direction (e.g. virtual mass force, pressure gradient force, and Saffman lift force).

\[
F_D = \frac{18 \mu}{\rho_p d_p^2} \frac{C_d \Re_p}{24}
\]

(2)

\[
\Re_p = \frac{\rho d_p |u_p - u|}{\mu}
\]

(3)

where \(\Re_p\) is the relative Reynolds number, \(C_d\) is the drag coefficient, \(d_p\) is the particle diameter (m), \(\mu\) is the liquid viscosity (pa·s).

\[
C_d = a_1 + \frac{a_2}{\Re_p} + \frac{a_3}{\Re_p^2}
\]

(4)

Since the particles in the drilling fluid are spherical particles, the damping coefficient \(C_d\) can refer to Eq. (4), then \(a_1, a_2, \) and \(a_3\) are constants over a range of Reynolds numbers (Morsi & Alexander, 1972).

Based on the specific work environment of the rotor for a continuous wave pulse generator, the virtual mass force and pressure gradient force are negligible when the fluid density is much smaller than the particle density. Besides, no heat exchange is involved in the analysis, so the thermophoretic force is not taken into account. The flow field in the rotor belongs to the typical turbulence, and the Brown force is only applicable to the laminar flow, which means that the Brown force is not applicable. The saffman lift force is suitable for submicron particles, and the drilling fluid in the analysis is waterjet sand with an average particle size of 58–74 µm and therefore the saffman lift force can be ignored (You, Qi, & Xu, 2001). Thus, only drag force and gravity are considered in the erosion analysis.

2.2. Erosion model

Pipeline shape, fluid parameters, and particle parameters are important factors contributing to the erosion effect. Main parameters, such as flow rate, particle mass flow rate, particle diameter, fluid viscosity, and fluid density, are involved in the simulation. Since the rotor is made of typical medium carbon steel, one type of plastic material, the empirical erosion formula of solid particles impacting on plastic materials obtained by Ahlert and Edwards et al. (Ahlert, 1994) can be adopted, which is shown as follows:

\[
R_{erosion} = \sum_{n=1}^{N} \frac{m_p C(dp)f(\theta)u_p b(v)}{A_{face}}
\]

(5)

\[
f(\theta) = 2.69\theta + 1.61\theta^2 - 8.84\theta^3 + 7.33\theta^4 - 1.85\theta^5
\]

(6)

where \(R_{erosion}\) is the wall erosion velocity (kg/(m²·s)); \(f(\theta)\) is the invasion angle function; \(C(dp)\) is the particle diameter...
function, $1.8 \times 10^{-9}$; $N$ is the number of particles colliding with the wall; $u_p$ is the particle velocity relative to the wall; $b(v)$ is the relative velocity function, taking 2.6; $m_p$ is the mass flow of particle; $\theta$ is the collision angle of the particles against the wall (°); and $A_{\text{face}}$ is the area of the wall cell (m²).

2.3. Wall collision rebound equation

Energy transfer and loss occur when solid particles collide with the wall due to changes in velocity components. The ratio of the velocity components before and after the collision is typically used to measure energy loss. The non-stochastic recovery coefficient proposed by Forder, Thew, and Harrison (1998) and the stochastic recovery coefficient proposed by Grant and Tabakoff (1975) is commonly used for measurement. In the present study, solid-phase particles are discrete-phase particles so Grant recovery coefficients are adopted. The normal and tangential recovery coefficients are expressed as follows:

$$\varepsilon_N = 0.993 - 1.76\theta + 1.56\theta^2 - 0.49\theta^3 \quad (7)$$

$$\varepsilon_T = 0.998 - 1.66\theta + 2.11\theta^2 - 0.67\theta^3 \quad (8)$$

3. Finite element modeling

3.1. Fluid model and mesh generation

When the continuous wave drilling fluid pulse generator works, the drilling fluid flows into the upper inlet, flows through the stator and rotor in turn, and flows out from the outlet. We have drawn a 3D mechanical model and built a fluid model based on the physical object of the continuous wave drilling fluid pulse generator (Figure 1).

We select 3D hexahedral 20-node unit Solid186 to divide the fluid model into multiple computing units when meshing. The localization of the structure around the stator and the rotor is partially refined to obtain excellent calculation results (Figure 2). The skewness of the model is 0.42, its change in cell size is 1.02, and its minimum orthogonal mass is higher than 0.15. These parameters satisfy the grid quality requirements of fluent simulation.

3.2. Math parameter setting of fluent

(1) Model setting: In the simulation, the fluid in the pipeline is assumed to be under incompressible turbulence. The continuous phase simulation model and solution are established using the RNG k-model and simple algorithm, respectively. The discrete random walk model is activated in the simulation.

(2) Regional settings: All fluids.

(3) Wall setting: The computational fluid domain boundary is a non-slip boundary.

(4) Fluid properties: The parameters of the drilling fluid are determined by referring to the drilling site. The viscosity is 10–20 mpa.s, the density is 1030–1200 kg/m³, the diameter of particles is 58–74 um and the mass flow of particles is 0.39–0.99 kg/s.

(5) Initial conditions: The fluid velocity is 4 m/s, the initial value of the inlet and outlet pressure is 0 (the inlet boundary is set as velocity inlet and the outlet boundary is set as pressure outlet), and the solid phase particles flow from the inlet with the fluid at the same speed.
Motion setting: The rotor rotates at 120 r/min relative to the stator.

### 3.3. Conditional hypothesis

1. During the fluid simulation, the drilling fluid is a single-phase incompressible fluid; as such, its density, viscosity, and other properties do not change in the simulation calculation.
2. The components of the drilling fluid pulse generator are rigid bodies, and the stator blades are not deformed during operation.
3. No other channels for drilling fluids are available, except for the inlet and outlet.
4. The fluid flow in the stator cavity and the influence of the downstream shaft on the internal flow field of the rotor are ignored.

### 4. Results

#### 4.1. Erosion characteristics

The drilling fluid is blocked by the rotating rotor after being diverted by the stator, and the flow direction abruptly changes. The inclusion particles change under the drag of the drilling fluid. However, a considerable part of the particles does not flow directly through the throttle port with the drilling fluid but affect the edge of the rotor and its surrounding areas due to the inertia of the particles, resulting in severe erosion over time (Jia, Fang, & Li, 2010).

Figure 3 shows the flow path of the particle as it passes through the stator and rotor gaps. Most of the particles directly washed the upper surface of the rotor, and some of the particles hit the surface of the rotary valve, thereby eroding the side of the rotor blade after springback. As the flow area formed by the stator decreases, the flow velocities of the fluid and the solid phase particles increase, causing the fluid to move in multiple directions. A strong eddy current is formed under the rotor, resulting in rotor erosion by the particles.

Figure 4 shows an erosion nephogram that represents the extent and distribution of rotor erosion. The surface of the rotor is evidently eroded, the erosion degree of the four blades is similar, and the distribution is relatively uniform. However, the edge of the blade is more obvious than the intermediate part.

#### 4.2. Analysis of influencing factors

The rotor erosion of continuous-wave drilling fluid pulse generator is affected by many factors, such as pipe shape, fluid parameters, and particle parameters. In particular, the temperature is also one of the important factors influencing the erosion during operation, since it is revealed that the density and viscosity of drilling fluid decrease with the increase of the temperature (Al-Jubouri & Amani, 2012; Ebikapaye, 2018; Song & Wang, 2012). That is to say, by studying the influence parameters like density, viscosity on the erosion effect may also indirectly reflect the relationship between temperature and erosion effects. Further, the temperature while drilling operation has a negligible impact on the strength of the rotor material itself, and as for certain drilling fluid, it is impossible to only change the system temperature while maintaining its density and viscosity constant. Thus, the influence of temperature is omitted, and the features of drilling fluid are mainly discussed. In this study, the pipe shape
is set as the mechanical structure characteristic of the continuous wave pulse generator, which is difficult to change during use. The practical effects of fluid and particle parameters, including drilling fluid density, viscosity, particle diameter, and mass flow rate, were investigated on the basis of the aforementioned main setup parameters.

### 4.2.1. Effect of drilling fluid density

Without loss of generality, the drilling fluid viscosity, particle diameter, and mass flow rate are 10 mpa·s, 74 µm, and 0.39 kg/s, respectively. Figure 5 shows the relationship of (a) particle residence time and (b) rotor erosion rate to drilling fluid density. The residence time of particle grains in the flow field increases linearly with the drilling fluid density [Figure 5(a)], and the red line represents the particle retention time fitting curve. The mathematical relationship of the fitting curve is

$$ T_s = 0.00223 \rho_m - 2.1387 \quad (9) $$

where $\rho_m$ is the drilling fluid density (kg/m³); and $T_s$ is the particle residence time (ms).

Figure 5 (b) shows that the relationship between rotor erosion rate and drilling fluid density is also approximately linear. The rotor erosion rate is 0.014 mg/g when the drilling fluid density is 1020 kg/m³, and the rate increases to 0.023 mg/g when the drilling fluid density increases to 1200 kg/m³. The red line in Figure 5(b) is the linear fitting curve of the rotor erosion rate. The mathematical relationship is:

$$ \varepsilon = 5.33942 \times 10^{-5} \rho_m - 0.04053 \quad (10) $$

where $\varepsilon$ is the erosion rate of the rotor (mg/g).

The simulation results show that the increase in the drilling fluid density significantly affects the rotor erosion rate. At a certain flow rate of drilling fluid, the variation in the drilling fluid density will affect the throttling pressure difference between the rotor’s inlet and the stator’s outlet, resulting in the fluctuation of the solid particle erosion rate. The drilling fluid density increases with increasing inflow–outflow end throttle pressure difference, thereby prolonging the residence time of the solid particles on the inner wall of the rotary valve and increasing the erosion rate.

### 4.2.2. Effect of drilling fluid viscosity

Drilling fluid viscosity is an important factor that affects the rotor flow field and erosion performance. Figure 6 shows the relationship of (a) particle retention time and (b) rotor erosion rate to drilling fluid viscosity under the following conditions: drilling fluid density of 1090 kg/m³, the particle diameter of 74 µm, and mass flow of 0.39 kg/s. Figure 6(a) shows that the particle residence time increases approximately linearly with the drilling fluid viscosity. The mathematical relationship is expressed as follows:

$$ T_s = 0.00749 \mu + 0.20238 \quad (11) $$

where $\mu$ is the viscosity of the drilling fluid (mpa.s).

The flowability of particles increases with increasing viscosity of the drilling fluid. When flow passes through the fixed and rotor gaps, the flow trajectory along with the drilling fluid easily changes; as such, the number of particles on the upper surface of the impact rotor decreases, and that at the edge increases. Figure 6(b) shows that the rotor erosion rate increases exponentially with increasing drilling fluid density. When the drilling fluid viscosity increases from 10 mpa·s to 20 mpa·s, the rotor erosion rate increases from 0.018 mg/g to 0.026 mg/g. When the viscosity of the drilling fluid increases to 18 mpa·s, the rotor erosion rate increases rapidly. The exponential fitting curve is expressed as:

$$ \varepsilon = 6.4556 \times 10^{-5} e^{4.11473 \mu + 0.01789} \quad (12) $$

**Figure 5.** Effect of Drilling Fluid Density on Rotor Erosion. (a) Particle residence time; (b) Rotor erosion rate.
4.2.3. Effect of particles diameter

Rotor erosion is mainly due to the inclusion of particles and barite in the drilling fluid. In particular, the small volume and a large number of particle grains are the main causes of erosion. The flow-following property of particle decreases greatly with the increasing diameter of particles in the drilling fluid. When the gravel passes through the clearance between the stator and the rotor, it cannot change the trajectory with the fluid well, thereby increasing the probability of collision with the rotor and the erosion rate of the rotor. The main erosion is concentrated near the central axis of the rotor. Under the same flow velocity, the larger the diameter of the particles is, the greater the energy when affecting the rotor surface and the more serious the erosion and wear on the rotor surface will be.

Figure 7 shows the relationship of the (a) residence time of particles and (b) the erosion rate of the rotor to the diameter of particles under the following conditions: drilling fluid density of 1030 kg/m³, the viscosity of 10 mpa.s, and grit mass flow of 0.39 kg/s. The residence time of particle grains increases approximately linearly with the diameter of particle grains [Figure 7 (a)]. The fitting curve is expressed as follows:

\[ T_s = 6.225 \times 10^{-4} D - 0.02075 \]  

where D is the particle diameter (µm).

As the diameter of the particles in the drilling fluid increases from 58 µm to 74 µm, the rotor erosion rate increases from 0.014 mg/g to 0.024 mg/g [Figure 7(b)]. The increase is approximately linear, and the fitting curve is expressed as follows:

\[ \varepsilon = 0.00822D - 0.27905 \]  

4.2.4. Effect of particles mass flow rate

The percentage of particles in the drilling fluid increases with increasing mass flow rate of particles. The collision of the particles with the pipeline and rotor during the flow greatly increases the uncertainty of particle movement, resulting in decreased particle flowability. In this regard, the gravel easily collides with the rotor and the inner wall of the pipeline, causing erosion and wear. Figure 8 shows the effect of particle mass flow (a) on particle retention time and (b) rotor erosion rate under the following conditions: the drilling fluid density of 1030 kg/m³, the
viscosity of 10 mpa-s, and the particle diameter of 74 µm. The particle residence time increases linearly with the particle mass flow rate [Figure 8(a)]. The fitting curve is expressed as:

$$T_s = 0.02586 q_m + 0.00392$$ (15)

where $q_m$ is the particle mass flow rate.

Figure 8(b) shows that the degree of erosion of the rotor varies linearly with the mass flow of the particles. The simulation curve agrees well with the fitted curve expressed as:

$$
\varepsilon = 0.29571 q_m + 0.11534 \quad (16)
$$

The simulation results show that under the same experimental conditions, the large mass flow of particles causes evident rotor erosion.

5. Conclusion

The rotor of a continuous-wave pulse generator is severely eroded by high flowing drilling fluid and particle grains, thereby affecting the quality of the uploaded pulse signal. A finite element fluid model of the stator and rotor was established, and CFD analysis and simulation studies were conducted to clarify the effect of drilling fluid density, viscosity, particle diameter, and mass flow on rotor erosion. Then some meaningful conclusions are obtained:

1. The throttling pressure difference between the rotor’s inlet and the stator’s outlet increases with increasing drilling fluid density, leading to increased solid particle velocity. Moreover, the retention time of particles and the erosion rate of the rotor increase approximately linearly with density.

2. The erosion rate of the rotor increases exponentially with increasing drilling fluid viscosity. The residence time of particles increases linearly with the drilling fluid viscosity. High drilling fluid viscosity causes uniform pressure on the blade and edge of the rotor. The number of solid particles increases with increasing flow, thereby aggravating the erosion at the edge of the rotor.

3. Increasing the particle diameter and mass flow rate in the drilling fluid increases the retention time of particles and the erosion rate of the rotor approximately linearly. In particular, the flow-following property of solid particles is satisfactory when the diameter of the particles is small. The erosion of the rotor is mainly concentrated at the edge at this time. The erosion of the rotor slowly shifts to the direction near the rotation axis with an increasing diameter of solid particles.

It is sure that the results obtained from these CFD analyses and simulations also provide reasonable guidance for further researches. In particular, the composition ratio of the used drilling fluid should be optimized to reduce erosion of the rotor or other downhole components without disturbing the drilling operations; it is also suggested that the rotor’s working life can dramatically increase by choosing high strength machined material and adopting surface hardening treatment process; Furthermore, investigating the erosion effect of different rotor structures with changeable factors by adopting the proposed method seems to be one of the very interesting research direction, which is benefit to filter more appropriate rotor shape for various field operation.

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Disclosure statement

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