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Analysis of Drilling Turbine Blades Erosion Based on Numerical Simulation

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Abstract

Turbodrills are axial hydraulic turbines used for drilling hydrocarbons in extreme conditions. These turbines convert hydraulic power from flows of mud into mechanical power to rotate the drill-bit. This paper addresses modeling turbine blades erosion provoked by mudflow having liquid and solid phases, through evaluating the fluid as a continuous phase, while the sand particles as a discrete phase. The hybrid Eulerian-Lagrangian model is considered to simulate the binary phase turbulent flow. On the other hand, the erosion rate is calculated according to the Grant-Tabakoff model. For further insights into the effect of erosion rates on the blades surfaces, sand particles diameter and flow rate are varied. The mean erosion rate on the blade surfaces was found to increase linearly with flow rate, but not linearly with particle size. In this context, it is suggested that the threshold particle size in the flows be reduced to 150 μm, for a longer lifetime of the drilling turbine.

Keywords*: Erosion; Drilling fluid; Multiphase flow; Drilling turbine; Blades.*

1. Introduction

Turbodrills and positive displacement motors have been the backbone of extended reach drilling and complex directional drilling service delivery for many years. Today, turbodrill systems are consistently stabilized in operation to ensure these advantages: upgraded borehole stability, superior resistance to sedimentary rocks trends, boosted inclination control, better rotational behavior, less deferential-pressure sticking, and enhanced dogleg capabilities [1]. The turbodrills are mainly composed of a multistage vane-type rotor and stator section, a bearing section, drive shaft, bent housing, an intermediate stabilizer, and drill bit. Each stage in the power section of the turbodrill actually delivers an equal amount of torque over the drive shaft. The kinetic energy of the drilling-fluid flow stream routed through a series of axial turbines stages provides the rotation and torque suitable for powering a drill bit, without the need to rotate the drill string [2]. The rig mud pumps are the source of hydraulic power needed to circulate drilling fluids through drill string and annulus. Mud streams entering a turbodrill from the drill string is 100% turbulent. Hydraulic turbines operate reliably with all kinds of drilling fluids in unbalanced multiphase flow environments, since some muds are more abrasive and/or more corrosive than others are. These may include water, salt water, oil-base, oil emulsion, high-viscous fluids, or those containing lost circulation substances and compressible fluids. The amount of sand present in drilling fluids shall always be monitored in agreement with industry standard practices, because the drilling turbines will experience some abrasion. It will require an adequate mud system to avoid over-wear or plugging, while finer fibrous and coarse granular materials are usually acceptable. However, both coarse fibrous materials and nut plugs are unsuitable [1,3]. It is well known that collisions of solid or liquid particles against a solid surface causes erosive wear. Such particles being contained in the streaming medium, having enough kinetic energy even to damage the metal surface. The gaseous medium carries both liquid and erosive liquid particles, whereas the liquid medium carries a mixture of solid and erosive solid particles. In general, erosion can be classified into two classes: erosion by solid particles and erosion by liquid droplets [4]. Erosion in the presence of multiphase bubble flow is challenging to prevent, but analysis of material properties and failure mechanisms will help to understand and address the actual causes of degradation. Particle flow behavior and the erosion phenomenon in both static and rotating structures have been the subject of numerous experimental and numerical studies [4-6]. Most early erosion models were based on Finnie's work, which is considered the precursor of ductile material erosion models [7]. He concluded that wear erosion is a complex function that depends on particle impact characteristics, particle materials and target wall properties. Other researchers later improved this model. Studies by Grant and Tabakoff [4] provide a more sophisticated erosion model that is commonly used in turbomachinery flow simulation software. Chitrakar *et al.* [8] have investigated sand erosion impacts on a hydraulic turbine as a function of multiple design variables including material selection, material behavior, and hydraulics. Hamed *et al.* [9] give an overview concerning the study of erosion and fouling in turbomachinery and the associated performance degradation. Various tests were performed to analyze the influence of temperature, impact particle composition, velocity and angle of incidence, and the surface material composition on erosion rates. In a paper by Khanal *et al.* [10], they investigated the link between the erosion rate and the angular distribution of turbine blades. In their numerical analyses, they showed that erosion could be reduced by using more efficient hydraulic design techniques for hydraulic turbines. In a numerical analysis of a hydropower turbine, Gutam *et al.* [11] made predictions of the erosion rate for stationary, guided, and rotating blades as a function of particle shape, size, and concentration, along with the turbine operating parameters.

A novel type of steady-state simulations is presented in this paper to identify the most vulnerable regions to erosion by particles contained in the drilling mud of axial hydraulic turbines. Various parameters, including sand particle diameter and flow rate, were considered to analyze how equipment-operating conditions influence the erosion phenomenon.

2. Numerical models for particle-laden turbulent flow

2.1. Governing equations

One-way coupling is adopted to simulate the fluid-sand particle interaction within the hydraulic turbine. Because the flow is generally steady, the amount of sand particles is small and well filtered (large diameter particles are not present), which means that the flow will not be disturbed and the particles will be transported by the stream. The one-way coupling is adequate for giving an idea on the erosion rate with its distribution over the blade surface [10].

2.2. Fluid phase

Since the fluid flow in turbomachinery is always turbulent, the flow field (velocity-pressure) is calculated using the Reynolds averaged Navier-Stokes (RANS) equations. In this paper, while referring to our previous work [12], the RANS equations (1) and (2) are obtained by averaging time and defining the instantaneous field as the sum of the mean and fluctuating component. With this, the two-equation k-ε model is used for incorporating turbulence effects.

$$\frac{\partial \rho_f}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho_f U_j\right) = 0 \quad (1)$$

$$\rho_f \frac{\partial U_j}{\partial t} + \rho_f U_i \frac{\partial U_j}{\partial x_j} + \rho_f f_i = \frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j}\left(-pS_{ij} + \mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \overline{\rho U_i' U_j'}\right) \ldots \quad (2)$$

2.3. Solid phase

In this analysis, without considering the influence of the particles on the fluid flow, a one-way coupling is adopted. The idea is to track the transport of isolated spherical particles in the continuous medium and thereby understand their motion and trajectory as a function of the forces acting on them. As indicated by Kannojiya *et al.* [6], these forces are governed by the motion equation (3).

$$m_p \frac{dV_p}{dt} = F_D \quad \ldots\ldots \quad (3)$$

The term F_D is defined as follows:

$F_D = \frac{1}{2} C_D \rho_f A_f |V_S| V_S$ ... (4)

where: C_D represents the drag coefficient, ρ_f the fluid density, A_f the particle cross-section, and V_S the fluid-particle slip velocity.

The drag coefficient is calculated based on the Schiller-Naumann drag model (5) used by the ANSYS CFX software.

$C_D = max\left(\frac{24}{Re_p}\left(1 + 0.15 Re_p^{0.687}, 0.44\right)\right)$ ... (5)

Given that, the relative Reynolds number Re_p for the particle is obtained from:

$Re_p = \frac{\rho_f |V_R| d_p}{\mu_f}$ ...... (6)

whereas, V_R the relative particle-fluid speed, d_p the particle diameter, and $\boldsymbol{\mu_f}$ the fluid viscosity.

2.4. Erosion model

The erosion is mainly due to sand particles, especially quartz, which is harder than the drilling turbine parts. As a result, the particles behavior has been predicted using the quartz properties. Based on the erosion model of Tabakoff and Grant [13], the local erosion rate E is stated in formula format as follows:

$E = f(\gamma)\left(\frac{V_P}{V_1}\right) cos^2\gamma[1 - R_T^2] + f(V_{PN})$ ... (7)

where, the constant V_P represents the particle velocity.

The following equations (8-9) issued from the quartz-steel correlation are used to describe the erosion rate model (6).

$f(\gamma) = \left[1 + k_2 k_{12} \sin\left(\gamma \frac{\pi}{2\gamma_0}\right)\right]^2$ ...... (8)

$k_2 = \begin{Bmatrix} 1.0 \; si \; \gamma \leq 2\gamma_0 \\ 0.0 \; si \; \gamma > 2\gamma_0 \end{Bmatrix}$

All model constants have either a velocity dimension or a dimensionless value.

$R_T = 1 - \frac{V_P}{V_3} \sin\gamma$ .... (9)

$f(V_{PN}) = \left(\frac{V_P}{V_2} \sin\gamma\right)^4$ ... (10)

The following expression (11) allows us to estimate the overall erosion rate.

$\dot{E} = E.\dot{N}.m_p$ .... (11)

where m_p being the mass of the particle and $\dot{N}$ the number rate.

3. Analysis procedure

In line with our previous paper on the flow inside an axial drilling turbine [12-13], we use the same configurations (geometry, mesh, physical properties), as shown in Fig. 1a. Furthermore, the one-way coupling is applied to explore the blades erosion phenomenon. To do so, different aspects are considered.

- Studying the hydraulic flow through a drilling turbine stage via the Reynolds averaged Navier-Stokes (RANS) equations.
- In terms of the convergence criterion, set the overall root mean square (RMS) value of the model to 10^{-6}.
- Define the paths of quartz particles via the flow field information, and specify its impact angles and trajectories on the blade surface.
- Calculate the erosion rates as per the Tabakoff and Grant model [4].
- Then plot both the contours of the flow field, and the local distribution of erosion on the surfaces including its average value.

Also, explore how sand flow rates and particle sizes affect the flow fields, the local distribution of erosion, and the average erosion rates.

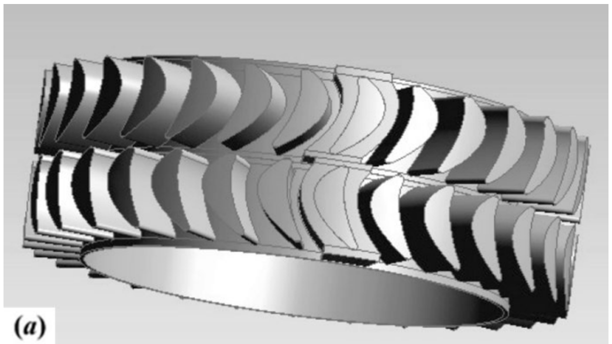

Fig.1. (a) Turbodrill stage configuration

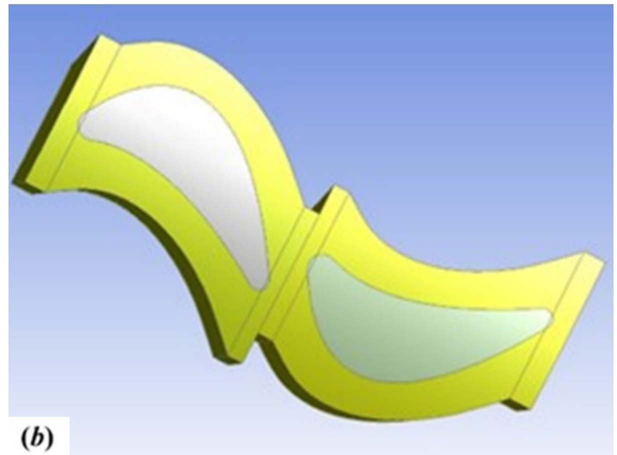

Fig.1. (b) Stator-Rotor configuration

4. Results and discussion

4.1. Geometry, mesh, and boundary conditions

As stated in the previous article [13], we have the same stator and rotor geometry for the turbine stage, having a diameter of the hub and shroud that is 108 and 134 mm, respectively. Given that the blade height is 14 mm, the stator and rotor pitch equal to 22 mm, while the number of blades for both being 30 [14]. We can therefore see in Fig. 1b how a stator-rotor stage was configured. In ANSYS CFX 2020, only one passage is used to simulate both the stator and the rotor using the CFX periodic interface. This periodic function allows us to save time and solve the passing domains of the stator and rotor, whose solution is transferred to the other passages. Once the blade row geometry is defined, a high-quality 3D hexahedral mesh is generated in the fluid regions to ensure reliable simulation results. Based on the appropriate mesh sensitivity analyses, this field is divided into 1600000 elements. Within the fluid region of the turbine stage, the following boundary conditions apply.

- The inlet static pressure is set to 13.78 MPa, knowing that a radial equilibrium equation is used to distribute them along the span of the blades.
- No slip conditions are present on the walls of the stator and rotor blades as well as the hub and shroud.
- The overall mass flow rate at the outlet is 33.97 kg/s, with a turbulence intensity of 5%.
- Owing to the periodicity of the rotation, only one blade pass will be modeled (Blade-to-blade methods).
- For dealing with the interaction between the fixed stator and the moving rotor, a mixing-plane approach is used.
- The stator is fixed, while the rotor rotates at 1000 rpm.

The circulating mud inside the turbodrill as a Newtonian liquid has the following physical properties: density = 1196 kg/m^3; viscosity = 8.899 × 10^{-4} kg/m.s; thermal conductivity= 0.6069 W/m.K. In the following, we model the sand particles according to the properties of quartz: density = 2650 kg/m^3 ; particles diameter ranges from 50-500 μm; particles number 626400 s/kg.

4.2. Effect of particle size

For further understanding of how particle diameter actually affects the erosion pattern, a set of particle sizes ranging from 0.050 mm to 0.5 mm was used. Other settings were held constant. As one could observe in Fig. 2, the obtained simulation results made it clear that as the sand particle size increases, there is in fact a substantial increase in the average erosion rate [7]. Above 50 μm, the erosion rate value became fairly significant, up to a maximum size of 500 μm for an average erosion rate of 2.10^{-4} (kg/m^{2}s). These findings are due to the fact that small particles being transported by the fluid flow avoiding any possible contact with the blade surface, yet large particles being in direct contact with the blade surface, causing severe impacts and thus a higher erosion rate [1]. These erosion rates distributions on the blade surface for 100, 150, 200 and 500 µm particles respectively are shown in Fig. 3a-d. It is remarkable that this erosion rate is particularly high for particle sizes below 100 µm, making the affected zones concentrated at the rotor edges. With a particle diameter of 150 µm, the erosion spreads over the blade surfaces, especially the rotor leading-edge, the stator trailing-edge, and a few parts of their concave sides.

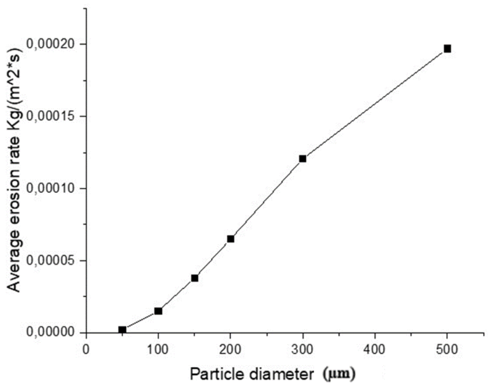

Fig.2. Average erosion rate versus particle diameter

This analysis supports the specifications outlined by the turbodrill manufacturer. They assert that all particles exceeding 177 µm require filtration [1]. For larger diameters of 200, 500 µm, we observe substantial erosion rates on both the rotor and stator surfaces. As the blade surfaces erode over time due to the continuous circulation of sand-containing mud, premature wear of the hydraulic turbine will occur. Such surface deterioration has a negative impact on the hydraulic and mechanical performance of the turbodrill.

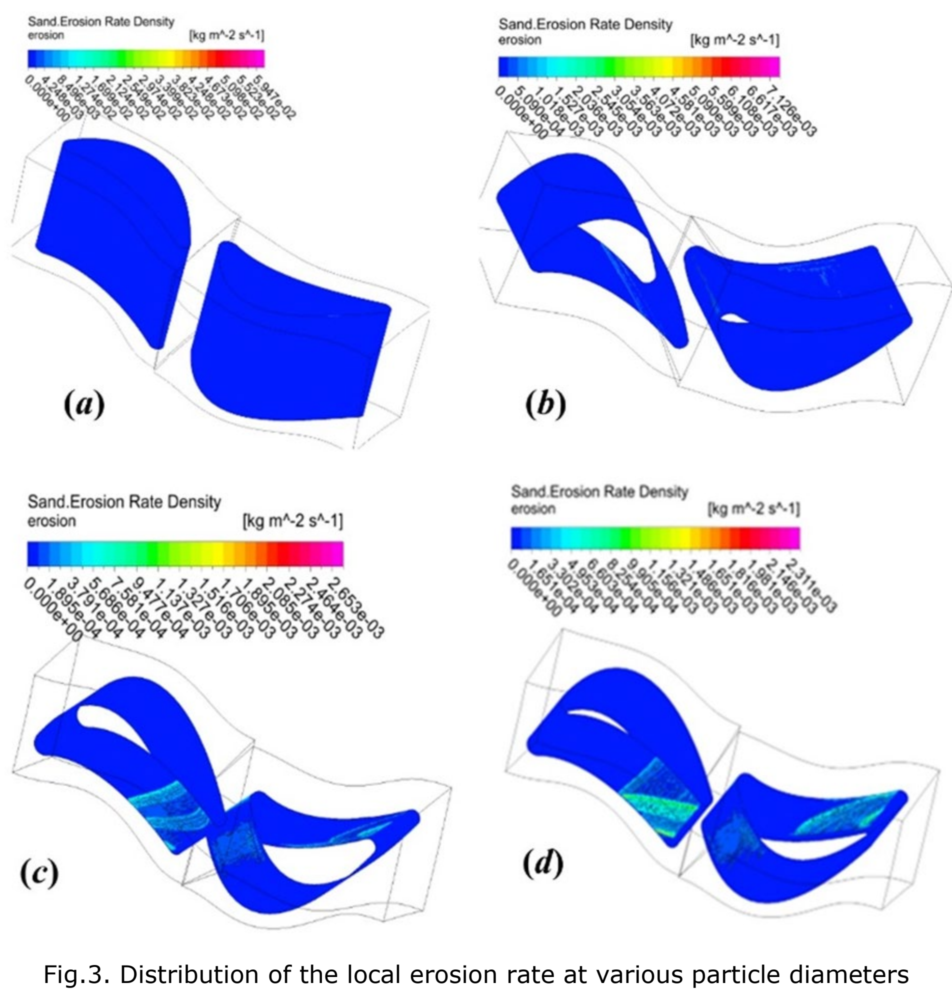

Fig.3. Distribution of the local erosion rate at various particle diameters

4.3. Effect of particles flow rate

In this section, the effect of particles flow rate on the turbine blade erosion is examined over a range of 0.17 to 1.2 kg/s. While maintaining a constant overall mudflow, the particle diameter is fixed at 150 μm.

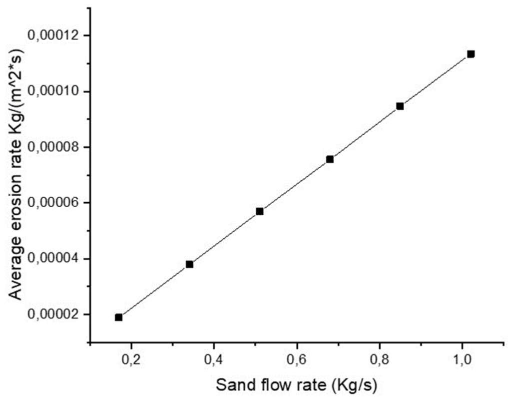

Fig.4. The average erosion rate vs. the sand flow rate

As can be seen in Fig. 4, the average erosion rate on the total surface of both the stator and rotor blades is given in terms of sand flow rate. We observe that both erosion rate and particle flow rate have a virtually linear relationship for fixed particle diameters [8]. This suggests that for a given sediment flow rate and operating conditions, the erosion rate is practically constant. Under such conditions, it is very important to select the appropriate drilling fluid to ensure the durability of the turbodrill blades. Regarding the erosion rates distribution on the blade surface, Fig. 5a-c, reflect the effect of sand flow rates of 0.17, 0.34 and 0.68 kg/s, respectively. It is evident that the regions affected by erosion have remained broadly the same, albeit the rate of erosion has increased significantly from a maximum of 3.88×10^{-3} to 1.489×10^{-2} kg/m^{2}s. In contrast to particle size, sand flow rate has a limited effect. With larger particle size, the more material will be removed from the eroding region.

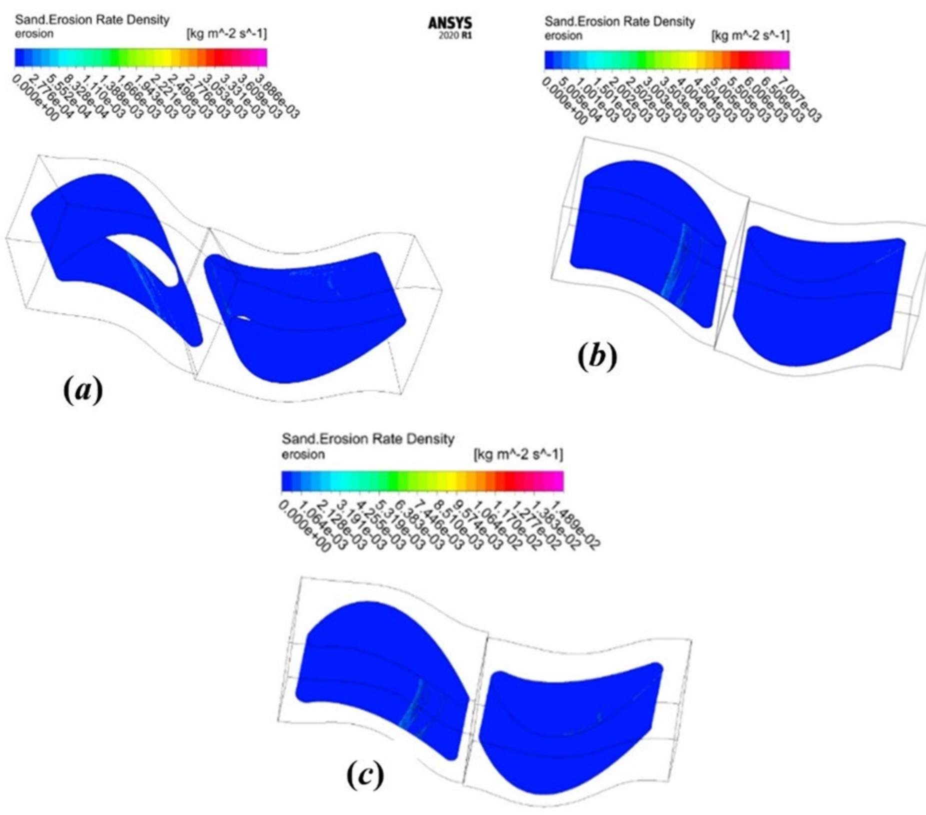

Fig.5. Local erosion rate distribution for multi-sand flow rates

4.4. Flow features and erosion distribution

Here, we focus in particular on the flow nature and fluid/solid surface interactions. Bearing in mind that the overall sand flow rate (fluid + solid) = 33.97 kg/s, the sand particle flow rate = 0.34 kg/s (sand content = 1 %) and the particle diameter = 200 μm. In Fig. 6, we have displayed the particle trajectory alongside the local erosion distribution on the turbine blades.

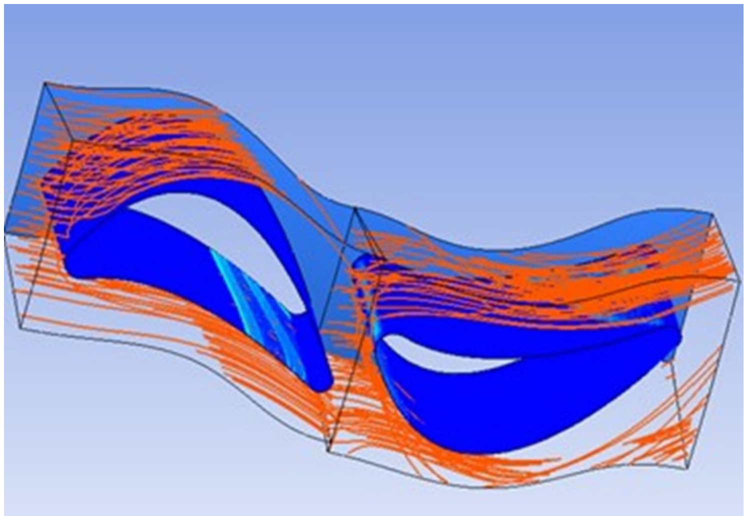

Fig.6. Particle trajectories and the local distribution of erosion

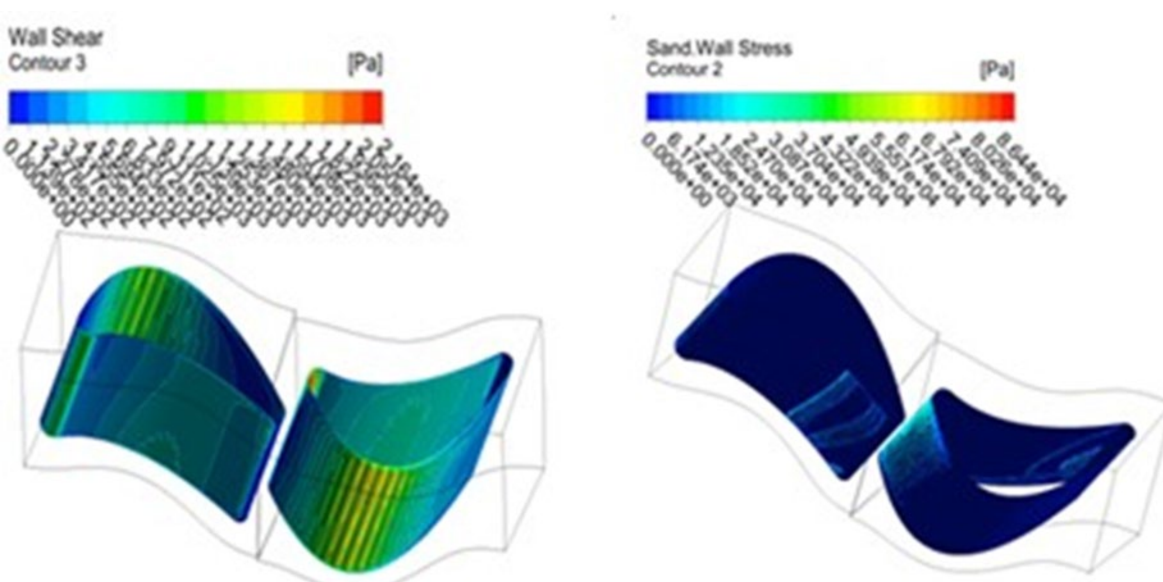

Fig.7. Fluid-wall shear and sand wall stress distribution

Although particle impacts are serious on the stator's high-angle surfaces, the most affected regions by such impacts are the leading edge of the rotor and the concave side near the trailing edge. Adopting a particle diameter of 200 μm explains why there were so many surface impacts. With small diameters, there would be less drag and particles would be transported by the flow [16]. This would limit surface erosion of the blades. It should be added that this erosive behavior comes from accelerated particle movements relative to fluid velocities. The fact that the rotor speed increases significantly as the blades rotate makes it obvious that the intensity of the velocity was involved in the erosive behavior. In the following Fig. 7, the fluiddriven stress distribution (wall shear stress) is compared to the friction induced by the sand particles along the blade surfaces. It appears that fluid friction is distributed over all the surfaces of the turbine stage, whereas friction due to sand particles are restricted to specific regions corresponding to those dominated by the erosion phenomenon. Furthermore, the fluid friction acting on the surfaces is much less than the stresses imposed on them by sand particle impacts. This is quite reasonable, as it is a solid-solid interaction.

5. Conclusion

Following an investigation of particle size and sand flows influences on both the local and average erosion rates of the turbodrill blades, we have drawn the following conclusions:

- The average erosion rate on the blade surfaces is found to have increased linearly with flow rate yet non-linearly with particle size.
- With contouring of the local erosion, we were able to identify the regions where this phenomenon predominates, as it becomes significant on the blades from 150 µm. This finding was confirmed by the experimental results as well.

Based on this study, we suggest reducing the threshold particle size allowed in the flow to 150 µm, for extended turbodrill lifetime.

Acknowledgments

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Nomenclature

U	*rotor velocity*	F_D	*drag force*
U_i	*time averaged velocity*	ρ_f	*fluid density*
u_i	*fluctuation velocity*	μ_f	*fluid viscosity*
Ω	*rotational speed*	A_f	*effective particle crossing*
ρ	*mud density*	V_S	*slip velocity*
$\dot{m}$	*mass flow rate*	E	*local erosion rate*
$\dot{E}$	*overall erosion rate*	Re_p	*Reynolds number of the particle*
V_p	*particle velocity*	V_R	*relative speed between the particle and the fluid*
C_D	*drag coefficient*	d_p	*particle diameter*

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