Study of drilling muds on the anti-erosion property of a fluidic amplifier in directional drilling

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ABSTRACT. Due to some drawbacks of conventional drilling methods and drilling tools, the application of hydraulic hammers with a fluidic amplifier have been extensively popularized since its emergence in recent years. However, the performance life of a fluidic amplifier is still unsatisfactory in oil and gas wells drilling, especially the heavy wear or erosion of the fluidic amplifier leads to the reduction of service life time of hydraulic hammers, which is derived from the incision of drilling muds with high speed and pressure. In order to investigate the influence of drilling muds, such as particle size, solid content and jet velocity, on the anti-erosion property of a fluidic amplifier, several groups of drilling muds with different performance parameters have been utilized to numerical simulation on basis of Computational Fluid Dynamics (CFD). Simulation results have shown that the jet nozzle of fluidic amplifiers is primarily abraded, afterwards are the lateral plates and the wedge of the fluidic amplifier, which shows extraordinary agreement with the actual cases of fluidic amplifier in drilling process. It can be concluded that particle size, solid content and jet velocity have a great influence on the anti-erosion property of a fluidic amplifier, and the erosion rate linearly varies with the particle size of drilling muds, nevertheless exponentially varies with solid content and jet velocity of drilling muds. As to improve the service life time of a fluidic amplifier, the mud purification system or low solid clay-free mud system is suggested in the operation of directional well drilling.

KEYWORDS. Fluidic amplifier; Anti-erosion property; Erosion rate; Hydraulic hammer; CFD simulation.

INTRODUCTION

Hydraulic hammer with a fluidic amplifier has been regarded as the most efficient drilling tool in hard rock or complicated formations to date [1-3]. Due to some drawbacks of conventional drilling methods and tools occurred in previous drilling operation, the application of hydraulic hammers with a fluidic amplifier have been extensively popularized since its emergence in recent years, which can overcome the drilling problems of rotary drilling technique. The hydraulic hammer with a fluidic amplifier can improve the rate of penetration (ROP), enhance the quality of borehole, extend the performance life of drilling tools and reduce the drilling cost [4].

However, the performance life of a fluidic amplifier is still unsatisfactory in oil and gas drilling engineering [5]. As shown in Fig. 1, the heavy wear or erosion of fluidic amplifier is derived from the incision of drilling muds with high speed and pressure [6]. Large particles in drilling muds serve as abrasive grain beam to washout the fluidic amplifier, which accelerates the failure of hydraulic hammers in drilling process, thus the service life of fluidic amplifiers is reduced. The average performance life of each fluidic amplifier in oil and gas wells drilling is appropriately 30 hours, whereby the minimum service life of a fluidic amplifier is 15 hours, and the maximum service life is 113 hours, which has huge improvements on service life in subsequent optimization [7, 8].
In previous researches, the service life of a fluidic amplifier has been studied by drilling crews and researchers. W.T. Li have analyzed the effect of material of fluidic amplifier on its service life time, and numerical models of the damage mechanism of fluidic amplifiers are established [9]. In order to improve the actual service life of a fluidic amplifier, the processing technique of a fluidic amplifier in hydraulic hammers has also been discussed in his work. Meanwhile, series of experiments on fluids flow distribution in fluidic amplifiers have been conducted by J.J. Chen on the basis of Particle Image Velocimetry (PIV), which contributes to improving the service life of hydraulic hammers with a fluidic amplifier [10]. Some other related work has been finished with different experiments and apparatuses in order to study the service life of a fluidic amplifier in various performance conditions [11, 12].
Since 1980s, the numerical modelling technique in drilling engineering has been popularized throughout the world [13]. Bai Yalei and Ming Xiao established a model to investigate the pressure distribution of the flow inside the fluidic amplifier, and the deflection of induced main jet is obtained by numerical simulation [14]. In the meantime, the grain movement of abrasive water jet is analyzed by Dong Xing, and the friction between the mixture of water and abrasive grains has been acquired by numerical simulation [15]. Moreover, the erosion characteristics of typical materials in abrasive water jet (AWJ) were numerically simulated by Y.Z. Song, and valid results have been obtained according his research [16]. Thus simulation of drilling muds on anti-erosion property of a fluidic amplifier can be effectively conducted, which is a successful approach to reduce the experiments cost and test time in the design of fluidic amplifiers.

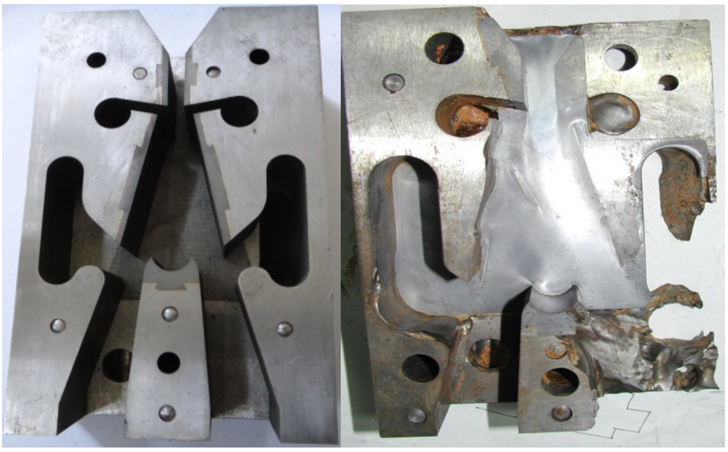

Figure 1: Failure of a fluidic amplifier before and after erosion by drilling muds.

The study of drilling muds on anti-erosion property of a fluidic amplifier is another efficient way to improve the service life time of hydraulic hammer. In this paper, numerical models of fluidic amplifier have been established with several groups of drilling muds, and different fluid velocity, grain sizes as well as solid contents of drilling muds have utilized to the simulation. In end, the erosion rate and fluid velocity in a fluidic amplifier has been obtained by Computational Fluid Dynamics (CFD), which promotes the improvement of service life time of hydraulic hammers with a fluidic amplifier.

THEORY AND METHODOLOGY

There are conclusively 3 theories suited for the erosion of a fluidic amplifier in hydraulic hammers, and they are elasto-plastic deformation theory, micro-cutting theory and the secondary erosion theory.

Elasto-plastic Deformation Theory

The Elasto-plastic Deformation Theory are proposed by Marshall and Evans, it insists that the indentation area will be developed once the solid particles in drilling muds scour through the surface of fluidic amplifiers. Elasto-plastic deformation domain will be subsequently formed underneath the indentation area, and the axial fracture induced by external loads will be transformed into radial fracture, where after the volumetric wearing capacity V can be derived from formula 1.

$$V = V_0^{3.2} r^{3.7} \rho^{1.58} k_c^{-1.3} H^{-0.62} \tag{1}$$

where, V_0 denotes the velocity of solid particles, r denotes the radius of particle, ρ denotes the density of particle, H denotes the strength of particles, and k_c denotes the stress factor of materials.

Micro-cutting Theory

The erosion of solid particles with sharped corner on ideal plastic materials has been studied by Finnie, and the micro-cutting theory was proposed according to a series of analysis and experiments. The volumetric wearing capacity V can be derived from formula 2, which is closely related to the incision angle.

$$V = \frac{mv}{P}(\alpha) \tag{2}$$

where, m denotes the mass of a single particle, v denotes the velocity of moving particles, P denotes elastic fluid pressure of flow domain and α denotes the incision angle of solid particles.

The micro-cutting theory is feasible to the erosion of solid particles on elastic materials while the incision angle is plenty small. While the incision angle of solid particles is approximate to 90°, large deviation of erosion volume on brittle materials will be obtained.

Secondary Erosion Theory

There are two stages for the erosion process of typical materials, which is proposed by Tilly with his research on abrasive materials. First of all, the solid particles washout the surface of abrasive material, then the abrasive material will be rewashed by some solid particles with minor size. The presence of secondary erosion theory is essentially according with micro-cutting theory.

No.	Particle size μm	Velocity m/s	Solid content %
1#	20	68.9	2
2#	45	68.9	2
3#	75	68.9	2
4#	45	61.3	2
5#	45	76.6	2
6#	45	68.9	4
7#	45	68.9	8

Table 1: The properties and obtained acoustic velocities of prepared samples with water-saturated sand.

Each theory of anti-erosion property has its own features and specific feasibility, whereas the limitation of each theory is still existed. In the study process of anti-erosion property of a fluidic amplifier, a single theory should not merely be considered as the theoretical basis, and the practice value of each theory should be taken into consideration, which promotes the structure design of hydraulic hammers with a fluidic amplifier. Thus appropriate theory about anti-erosion property simulation of a fluidic amplifier should be selected and applied. Allowing for the material property of a fluidic amplifier, the elasto-plastic deformation theory and micro-cutting theory are employed in the simulation of anti-erosion property of a fluidic amplifier.

CFD SIMULATION

Totally 7 groups of drilling muds with different performance parameters are utilized into CFD simulation, as shown in Tab. 1. There are 3 variables in the whole simulation, which are particle size, velocity and solid content, respectively. In order to obtain more accurate results, the numerical modelling, meshing and solving process are successfully completed.

Numerical Modelling and Meshing

As shown in Fig. 2, the numerical model of a fluidic amplifier was established by software Inventor according to the parameter of a 203 mm hydraulic hammer. The material models of a fluidic amplifier were defined as 35CrMo and cemented carbide.

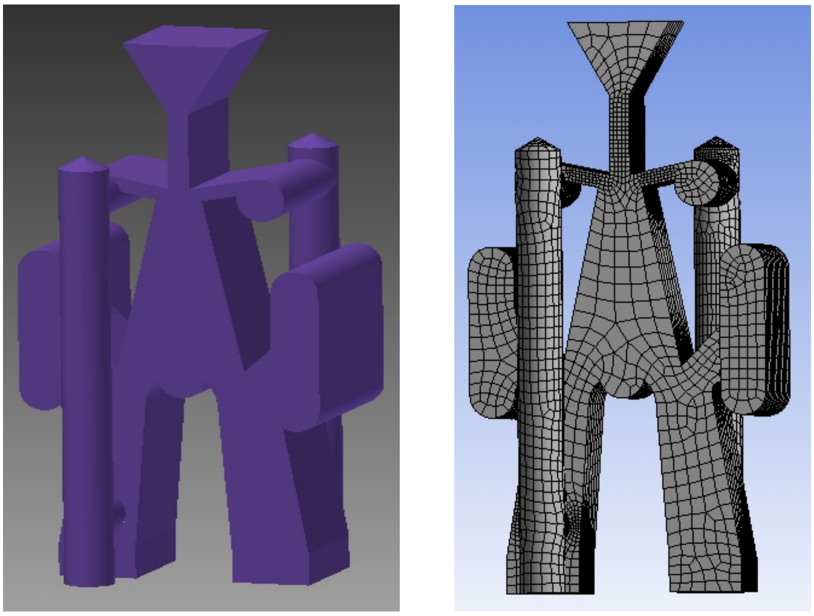

Figure 2: Numerical model and meshes of a fluidic amplifier in hydraulic hammers.

The parameter of the jet nozzle in a fluidic amplifier is 8.7 mm X 50 mm, and the length of fluidic amplifier is 250 mm. In total, four computed domains are defined in the numerical model of fluidic amplifier, including the domain of jet nozzle, the domain of slagging nozzle, the domain of control nozzle and the domain of output nozzle. The main jet flows through the nozzle with high speed and pressure. In order to improve the strength of a fluidic amplifier, the contact area with drilling muds has been enhanced by cemented carbide, which is partly brazed into the fluidic amplifier. The meshing process will be accomplished by Workbench once the numerical model of a fluidic amplifier is established.

There are totally 168190 grids in each of numerical model of a fluidic amplifier, and the meshed grids are hexahedrons, which are obtained by free meshing of Workbench. All of the meshed grids are volume grids with a maximum diameter of 3mm, and the grid coordination is excellent. The contact domains of a fluidic amplifier with drilling muds are remeshed within a refinement of 2 mm. The meshed grids of a fluidic amplifier are shown as Fig. 2.

Boundary Conditions

In order to gain much more steady wall-attachment effect of a fluidic amplifier while the hydraulic hammer is in performance, the out-put pressure boundary condition of 1 atm. is defined, and the inlet pressure boundary condition is

identically defined as 1 atm. The input volumetric flow rate is assigned as 30 L/s, which is conforming to the actual flow rate of a fluidic amplifier in hydraulic hammers with external diameter of 203 mm.
The hydraulic diameter of the jet nozzle in a fluidic amplifier is 14.8mm, besides the hydraulic diameter of slagging nozzles and output nozzles are 26.5 mm and 39 mm, respectively. The parameters of boundary condition in a fluidic amplifier are shown as Tab. 2.

Flow rates (L/s)	18
Inlet Velocity (m/s)	68.9
Inlet hydraulic diameter	14.8
Inlet Reynolds number	651405
Outlet Reynolds number	1777204
Inlet turbulence intensity	3%
Inlet turbulence intensity	2.65%
Inlet area (mm^2)	435

Table 2: The parameters of boundary condition in a fluidic amplifier.

Solver Settings

The fluid in a fluidic amplifier is turbulent flow due to the high velocity and pressure in hydraulic hammers, hence the numerical solution was finished in software Fluent. All of the models are solved by second order upwind discretization method, which is suitable for turbulent kinetic energy and dissipation rate in numerical simulations. As for the drilling muds in directional drilling, the solid content are strictly controlled in drilling operation, thus the solid content of drilling muds is less than 10%.
With regard to the drilling muds used in Victory Oilfield in China, the average density of drilling muds is 1.2 g/m^3, and the viscosity of drilling muds is 8 mPa.s. Moreover, the density of solid particles in drilling muds is 2.3 g/m^3, and average grain size of solid particles is 45 μm. Thus the erosion property of drilling muds on a fluidic amplifier can be obtained with various material models and boundary conditions in Fluent with the same solver settings.

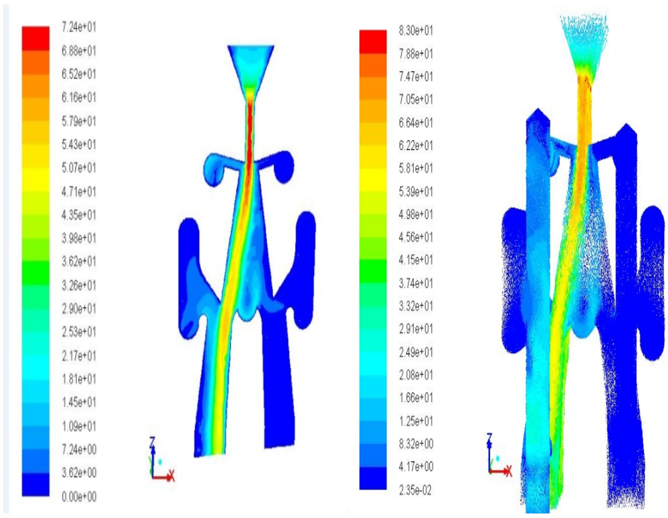

Figure 3: The velocity contours of a fluidic amplifier in hydraulic hammers [L/s] while the particle size of drilling muds is 45μm.

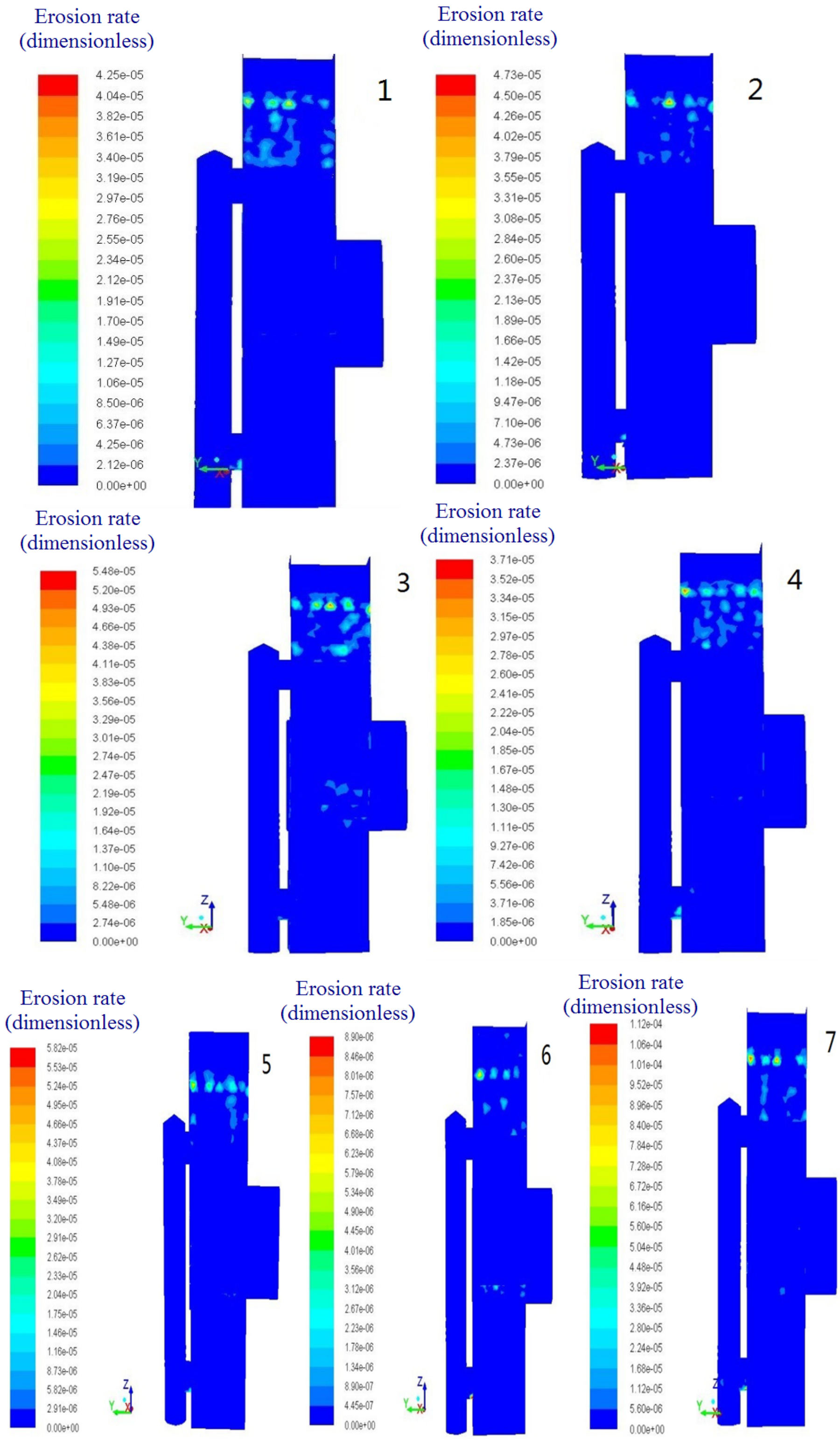

Figure 4: The erosion rates of a fluidic amplifier in hydraulic hammers with 7 groups of various drilling muds.

RESULTS AND DISCUSSIONS

The erosion property of drilling muds on a fluidic amplifier has been numerically modeled by CFD simulation. Especially the particle size, jet velocity and the solid content of drilling muds have been separately analyzed. The discrete phase model of Fluent has been utilized to all numerical simulations, thereby the jet velocity and erosion contour of a fluidic amplifier can be expressed by the particle distribution according to simulation results, which indicates the easy-to-wear position of a fluidic amplifier. In addition, the erosion of drilling muds on a fluidic amplifier can be discussed with various materials of the amplifier. The erosion rate of a fluidic amplifier in hydraulic hammers is obtained according to the simulation results.

As shown in Fig. 3, while the input flow rate of drilling muds is 30 L/s, the velocity contours of a fluidic amplifier in hydraulic hammers are obtained, and the distribution of solid particles in drilling muds are also presented. It can be concluded that the wall attachment effect of drilling muds in a fluidic amplifier is steady, which means the hydraulic hammer can normally work. The maximum velocity of drilling muds is 72.4 m/s, and the velocity of slagging nozzle is near to 0, it may be caused by the output pressure boundary condition, which is accessed to natural environment.

The distribution of solid particles in a fluidic amplifier is also presented in Fig. 3. It can be implied that the solid particles are accumulated in the flow domain, and a small quantity of solid particles assemble in slagging nozzle. The inner wall of the fluidic amplifier is severely abraded due to the uneven distribution of solid particles with high velocity and pressure. The simulation results show highly agreements with actual cases, as shown in Fig. 1.

The erosion rate of drilling muds on a fluidic amplifier is shown as Fig. 4. Totally 7 groups of drilling muds with different performance parameters are deployed in the numerical simulations, and the anti-erosion property of a fluidic amplifier can vary with the drilling muds.

It can be inferred that the erosion of a fluidic amplifier is mainly accumulated near the jet nozzle, the maximum erosion rate is ranging from 8.9×10^{-5} to 1.12×10^{-4}. While the jet velocity of drilling muds is excessing 68.9 m/s, the erosion of drilling muds on a fluidic amplifier is dramatically changing to some extent. Moreover, the effect of particle size in drilling muds on erosion rate of a fluidic amplifier can be discussed by 1#, 2# and 3# samples. Simultaneously, the effect of solid content in drilling muds on erosion rate can be implied by sample2#, sample 6# and sample 7#. In end, the effects of drilling muds with various performance parameters on erosion rate of a fluidic amplifier has been discussed and concluded.

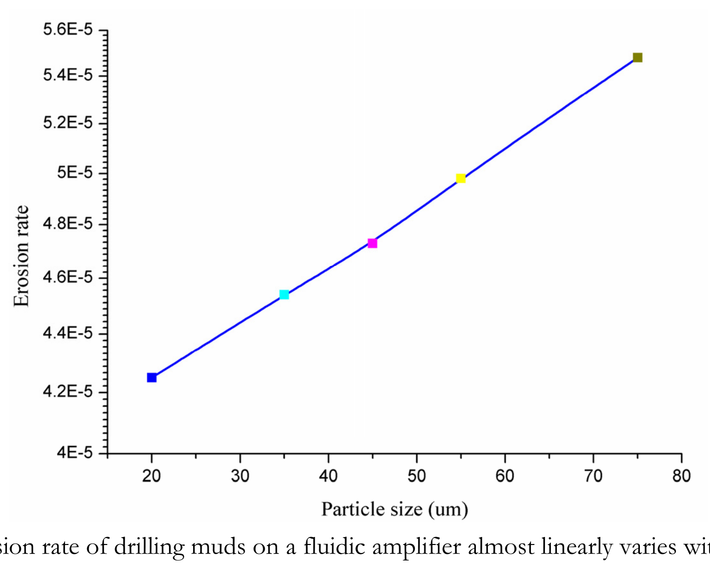

Figure 5: Erosion rate of drilling muds on a fluidic amplifier almost linearly varies with particle size.

Effects of Particle Size on Anti-erosion Property

The particle size of drilling muds has a great influence on the anti-erosion property of a fluidic amplifier. As shown in Fig. 5, the erosion rate is nearly linearly varying with the particle size of drilling muds. The minimum erosion rate of a fluidic amplifier is 4.25×10^{-5} while the particle size of drilling muds is 20 μm. Nevertheless the maximum erosion rate is

5.48×10^{-5} while the particle size in drilling muds is 75 μm. The erosion rate difference is 22.4% when particle size is ranging from 20 μm to 75 μm. Thus the effect of particle size on anti-erosion property should be drawn enough attention. Suggestions can be provided that the particle size of drilling mud should be less than 20 μm, which means the low solids clay-free mud system is preferentially selected while in drilling process. Otherwise, the mud purification system is proposed due to the existence of large particles in drilling muds while drilling directional wells or vertical wells.

Effects of Solid Content on Anti-erosion Property

As shown is Fig. 6, the anti-erosion property of a fluidic amplifier is affected by the solid content of drilling muds. It can be concluded that the erosion rate of a fluidic amplifier is almost exponentially varies with the solid content of drilling muds. While the solid content of drilling muds exceeds 8%, the maximum erosion rate of the fluidic amplifier is more than 1.12×10^{-4}. Otherwise the minimum erosion rate of the fluidic amplifier is less than 4.73×10^{-4} while the solid content of drilling muds is 2%.

The actual simulation results are slightly different with the fitted erosion rate, and the deviation between simulation results and fitted erosion rate is less than 4%, which is acceptable in real operation of hydraulic hammers with a fluidic amplifier. The erosion of a fluidic amplifier is lower, the longer service life of the hydraulic hammer will be. In order to improve the service life time of the fluidic amplifier, the solid content of drilling mud system should be controlled below 8%, thus the mud purification system and low solid clay-free mud system are still suggested in horizontal directional or vertical well drilling.

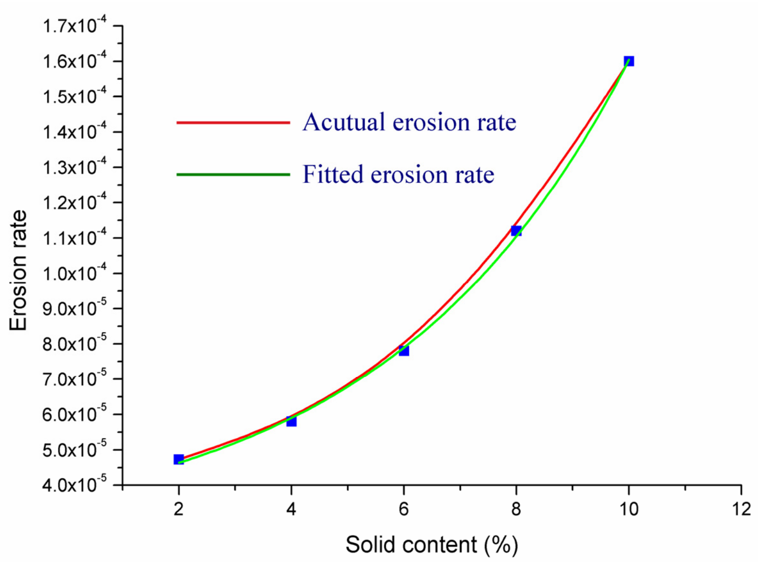

Figure 6: Erosion rate of drilling muds on a fluidic amplifier varies with the solid content of drilling muds.

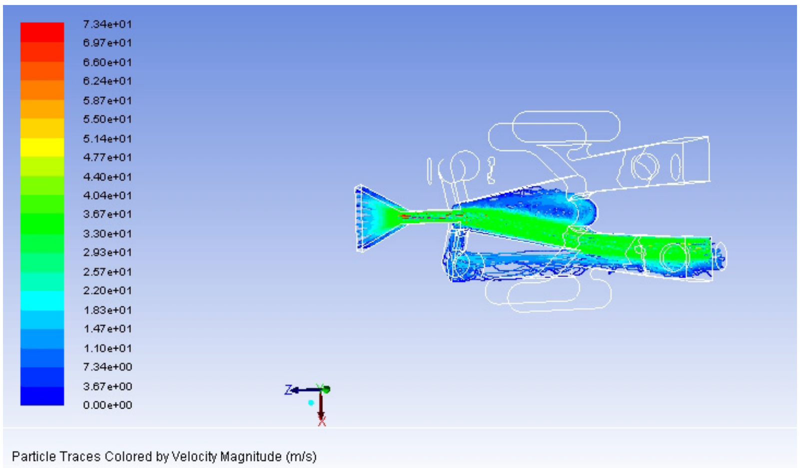

Figure 7: The moving trajectory of solid particles colored by velocity magnitude.

The moving particles of drilling muds in a fluidic amplifier are distributed as shown in Fig. 7. The particles of drilling muds principally aggregate in the jet nozzle, and the jet nozzle is the first contact area between drilling muds and the amplifier. It can be concluded that the most severely abraded position of a fluidic amplifier is the jet nozzle, afterwards are the lateral plates and the wedge of the fluidic amplifier due to the high velocity as well as pressure of the drilling muds. Simulation results show extraordinary agreements with the actual cases of a fluidic amplifier in directional well drilling. Interpretation can be drawn that the moving velocity of drilling muds contact with the lateral plates is relatively lower than the main jet due to the wall-attachment effect, the action time of solids in drilling muds is increasing, leading to the increase of erosion on lateral plates of a fluidic amplifier. In addition, the wedge of a fluidic amplifier is eroded by drilling muds with a large incision angle, thus the erosion of the wedge in a fluidic amplifier is serious, which needs more attention in the operation of drilling process.

Effects of Jet Velocity of Drilling Muds on Anti-erosion Property

The effect of jet velocity of drilling muds on erosion rate of a fluidic amplifier has been analyzed by 2#, 4# and 5# drilling muds, i.e. the particle size and solid content are constant while the simulation with various drilling muds is conducted. As shown in Fig. 8, it can be concluded that erosion rate of a fluidic amplifier is approximately exponentially increases with the jet velocity. The effect of jet velocity and solid content of drilling muds show great agreements on the erosion rate of a fluidic amplifier.

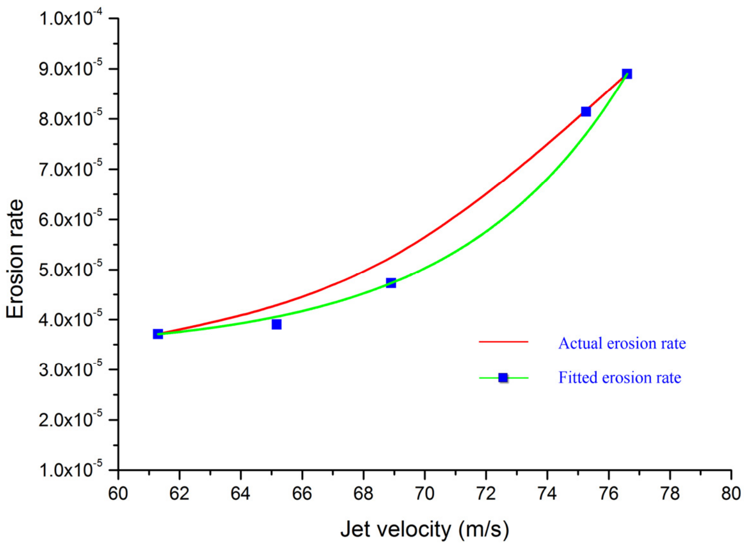

Figure 8: Erosion rate of drilling muds on a fluidic amplifier varies with jet velocity.

The maximum erosion rate is 8.9×10^{-5} while the jet velocity is less than 75 m/s. While the jet velocity is increasing by 15m/s, the deviation of erosion rate on the fluidic amplifier increases nearly 2 times allowing for the fitted erosion rate. Thus in the design of a fluidic amplifier, the jet velocity should be less than 75 m/s in order to improve the service life time of hydraulic hammers with a fluidic amplifier.

CONCLUSIONS

1) The effects of particle size, solid content and jet velocity of drilling muds on anti-erosion of a fluidic amplifier has been numerically studied by simulation models and analysis.
2) The erosion rate of drilling muds on a fluidic amplifier nearly linearly varies with the particle size of drilling muds, and almost exponentially varies with solid content and jet velocity of drilling muds.
3) It can be concluded that the jet nozzle of a fluidic amplifier is primarily abraded, afterwards are the lateral plates and the wedge of the fluidic amplifier. Simulation results have shown good agreements with actual cases in drilling process.

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