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ROCK DRILLING WITH ABRASIVE SUSPENSION SWIRLING JET AND EFFECTS OF ADDITIVE POLYACRYLAMIDE

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ABSTRACT

Rock drilling experiments with an Abrasive Suspension Swirling Jet (ASSJ) have been carried out under submergence. Results show that the ASSJ can improve rock drilling with 2.2 times increase in drilling-hole diameter and with 4-5 times increase in rock removal volume when compared with non-swirling jet drilling of rock under identical conditions. And with higher PAM concentration added to the fluid, the ASSJ can significantly increase drilling depth, especially when drilling at longer standoff distance. It is also shown that the mechanism of ASSJ drilling at medium pressure on hard rocks is the overall breakage of rock grains and the binding material, in which jetting abrasive particles play dominant roles. The bottom hole shape of rock drilling with the ASSJ under submergence looks like “V”. The higher rock drilling efficiency of the ASSJ results from the swirling of the jet.

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1. INTRODUCTION

Ultra-short Radius Horizontal Well Drilling is a newly developed promising technology in China to improve oil recovery and well productivity. In the well drilling, a kind of swirling water jet has to be used to successfully drill large diameter holes in oil formation such as in the well Jin 45-check 1 in Liaohe oil field, China. However, the swirling jet has not always been satisfactory in drilling rate of penetration, especially when drilling in hard formations. Thus, further research on improving the drilling capability of swirling jet has been necessary for great potential application of the URHWD to be extended to deep formations and to oil reservoirs with low permeability in China.

Based on high cutting ability of Abrasive Jets[1], an abrasive Suspension Swirling Jet (ASSJ) was brought forward in order both to drill large diameter holes and to increase drilling rates in hard rocks. And previous experiments, with Particle Image Velocimetry, on velocity fields of the ASSJ had been made and demonstrated that the suspension jet also has a much greater spreading angle than a non-swirling one[2,3]. So in this paper rock drilling experiments were further carried out to verify that the ASSJ can improve rock drilling ability and thus to provide a good guidance and basis to its applications in future URHWD in hard formations.

2. EXPERIMENTAL SETUP AND CONDITIONS

The experiments were made at High-Pressure Water Jet Research Center in China University of Petroleum. Figure 1 is a schematic of the experimental setup.

As shown in figure 1, a nozzle head and a rock block are both kept in submerged mode through filling a submerging tank with water in advance. The tank should be covered to keep drilling fully underwater. Two sorts of rock blocks of gray sandstone with different properties were drilled in the experiments. The rock mechanical properties are given in Table 1.

The ASSJ is produced, as shown in figure 2, with a swirling jet nozzle, in which the upper part is a set of flow conducting vane fixed into the nozzle body to create swirling of abrasive suspension, and the inner part of the contraction and the exit section is a lining of tungsten carbide to resist abrasive erosion. The exit diameter is 3 mm, and the initial swirling intensity of generated swirling jet is to be 1.19 at the nozzle exit. In experiment we got a non-swirling jet for drilling comparison when the flow conducting vane was taken out of the nozzle body.

Abrasive particles of arenaceous quartz with granularity of 0.2 - 0.4 mm were added to jet fluid on the high pressure pipe through a pressure vessel, i.e. the abrasive container in figure 1, and thus to form a uniform abrasive suspension during flowing in the transport pipe before jetting. There is an abrasive delivery valve under the container to open and close abrasive delivery. The mass percentage of abrasive particles in the suspension fluid in the experiments was remained at 16 percent that is generally considered as an appropriate value in well drilling application.

Two kinds of polyacrylamide (PAM) with different molecular weight range had been separately applied to water in order to make a better abrasive suspension. One is of molecular weight (20-24) $\times 10^6$, and another is (8-12) $\times 10^6$. The addition of PAM and the mixing was accomplished before pumping in a preparation tank as shown in figure 1.

Rock drilling was carried out with the jet head at a fixed position over top of the rock block. Jetting time was controlled with the abrasive delivery valve, and was preferably kept short in order to reduce the influence of the increasing standoff distance while drilling into the rock. As usual, the diameter, depth and removal volume of drilling-hole in the rock were measured to characterize jet drilling ability.

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Rock Drilling Characteristics with ASSJ

Characteristics of the ASSJ drilling were investigated in contrast to the non-swirling jet. Drillings on rock block number 2 were kept on a common face in order to eliminate the error caused by inconsistency of the rock property, and jetting time lasted for 30 seconds for each drilling. The nozzle pressure drops were 10 MPa and 20 MPa. Figure 3 gives out the drilling hole diameter and depth resulting from the swirling and non-swirling jet drilling at varying standoff distances. In the diagram and hereafter, the hole depth, diameter and standoff distance are all dimensionless values relative to nozzle diameter. As in figure 3, the swirling jet drilling increases the hole depth 20-30 percent and remarkably the hole diameter 120-150 percent from those of non-swirling jet under common conditions. We also see that drilling depth of the swirling jet decreases with increase of standoff distance. While when standoff distance increases the drilling-hole diameter goes up first and then begins to drop at a critical distance that we may call optimum standoff distance. The drillings at different pressure show that the lower the pressure of drilling is, the shorter the optimum standoff distance will be.

Considering the application of the ASSJ in successive long hole drilling in oil formation, hole diameter is more fundamental and critical for drill pipe feeding and for oil production, and thus must be as large as possible. From figure 3, we can see that when the nozzle pressure drop is up to 20MPa, the preferable standoff distance is $20d_0 \sim 30d_0$ (d_0 is nozzle exit diameter), and the corresponding drilling-hole diameter is about $10d_0 \sim 12d_0$, which would completely meet the practical request in the applications of radial horizontal well drilling.

3.2 Rock Drilling Mechanism with ASSJ

Rock drilling mechanism with water jet is generally determined by magnitude and distribution of jet velocity. When drilling with swirling water jet under submergence, the shape of the bottom hole created in rock has been found like “W”[4]. The reason is that swirling jet with its higher velocity departed from jet centerline cut the rock near the circumference of impact area in advance, leaving a tapered portion in the center to be cut while nozzle further feeding. However, the bottom hole shape in rock was found changed when drilling with the ASSJ under submergence. The shape turned to be “V”, and there was no tapered center body left. The number 2 sandstone block and bottom hole shapes drilled with the ASSJ are shown in figure 4.

Changing jetting conditions to verify this change resulted that the bottom hole shape drilled with the ASSJ was not relative to nozzle pressure drop and standoff distance, but dependent on whether drilling process was in submerged mode or not. If kept in air, the drilling was quite efficient and the bottom hole looks like the shape of “W”. If submerged in water, the drilling became less efficient and the bottom hole took to the form like “V”.

To identify key factors affecting the drilling process, a drilling test on the same rock surface was carried out at 20 MPa in nozzle pressure drop with no abrasive delivery. No excavation was finally found except for a slight change in colour. The result indicates that the rock breakage by the ASSJ is only attributed to abrasive particles, and the jet pressure was too low for the water only to break the hard rock. The function of the fluid during ASSJ drilling process at this pressure range is merely carrying the abrasive particles to the bottom and further carrying cutting debris away from the bottom to keep the bottom hole clean.

From surface roughness of the bottom hole wall, it can further be found that the rock drilling mechanism of abrasive suspension jet is different from that of water only jet. When water jet impacting rock at medium pressure, the rock breakage process is generally characterized by the failure or fracture of binding material, and the cut or drilled wall surface generally rough[5,6,7]. The fact that the rock surface of the hole drilled with the ASSJ in the experiments is much smoother than normally fractured face indicates that the rock drilling process with the ASSJ is the overall breakage of rock grains and the binding material, and that the jetting abrasive particles play dominant roles in the drilling.

Based on this mechanism of abrasive jet drilling in hard rock, we can understand why the ASSJ is more efficient in the drilling rock than a non-swirling jet. Firstly, the ASSJ with its swirling movement velocity exerts shearing actions on its cutting surface of rock at shallower angles than the non-swirling jet. Thus the cutting and plowing actions of abrasive particles are more efficient than the mainly normal impact of non-swirling jet. Secondly, the back flow from the bottom hole after drilling is generally not stable in non-swirling jet drilling, and then inhibits the coming jet flow from reaching and impacting effectively on the very bottom hole of drilling. While in ASSJ drilling, because swirling flow is stable, the back flow is so steadily near to the wall of hole that the coming jet flow can easily reach the bottom of the hole with less energy loss than in non-swirling jet. Therefore the higher rock drilling efficiency of the ASSJ results directly from the swirling flow of the jet.

Figure 5 is rock drilling efficiency contrast of the ASSJ to the non-swirling jet at common pressure 20 MPa. It shows that the rock removal volume of ASSJ drilling decreases slightly with standoff distance in range of $5d_0$-$20d_0$. The ASSJ can gain 4-5 times increase in rock removal volume than the non-swirling jet under common conditions. The specific energy consumption of the swirling jet is much lower than that of the non-swirling jet.

3.3 Effect of PAM on Rock-Drilling

Referring to the application of Super-Water in jet cutting[8], effect of Polyacrylamide (PAM) on improving rock drilling of the ASSJ was experimented with PAM concentration being 0.1 percent in contrast to abrasive water swirling jet (AWSJ). The molecular weight of PAM is (8-12) $\times 10^6$. Rock block number 2 was drilled at nozzle pressure drop 25 MPa for 30 seconds. Abrasive and the concentration remained unchanged from previous drilling test. The results are plotted in figure 6.

As illustrated in figure 6, addition of PAM to jet makes no intrinsical change to the general tendency of rock-drilling depth and hole diameter relative to standoff distance. However, it can indeed improve rock-drilling performance. The increment in drilling depth is not remarkable when drilling at shorter standoff distance, but becomes ever greater with standoff distance increasing, and is 80 percent more than that of the AWSJ when drilling at standoff distance of $30d_0$. Although the drilling hole diameter of the ASSJ at short standoff distance is, because of focusing effect of PAM polymer on jet flow, smaller than that of the ASWJ, when drilling at a great standoff distance the hole diameter does not decrease owing to addition of PAM, which presents the potential of PAM on improving jet velocity.

In order to identify effect tendency of PAM on drilling performance, drilling tests had been conducted with the ASSJ by varying PAM concentration in jet fluid from 0.04 to 0.1 percent. The reason for selecting 0.1 percent as an upper limit is that when PAM concentration is greater than that the fluid would be too viscous to suit for well drilling applications. PAM with molecular weight ranging (20-24) $\times 10^6$ was chosen, and rock block number 1 was drilled at $10d_0$ and $30d_0$ respectively. The drilling time lasted 15 seconds for each hole drilling at common nozzle pressure drop of 15 MPa. Abrasive concentration was the same as in previous tests. The drilling result was shown in figure 7.

As illustrated in figure 7, with higher concentration of PAM added to jet fluid, the ASSJ drills more effectively in the rock both in hole depth and in diameter. It can also be found that drilling performance improvement is more phenomenal when drilling at a longer standoff distance than at shorter one.

4. CONCLUSIONS

In contrast with the non-swirling jet, the ASSJ drilling in rock and the effectiveness of additive Polyacrylamide have been experimentally verified in order to give us some basic understanding of features of rock drilling with the ASSJ and some fundamentals for the application in URHWD in hard formations. From this experimental study we could conclude as follows:

1. In contrast to non-swirling jet, the ASSJ drilling under common conditions results in a higher rock drilling efficiency. The ASSJ can improve rock drilling with about 2.2 times increase in drilling-hole diameter and 4-5 times increase in rock removal volume over non-swirling jet, which shows its remarkable advantage and prospect in well drilling in hard formations.
2. It is shown that the mechanism of medium-pressure ASSJ drilling on hard rocks is the overall breakage of rock grains and the binding material, in which jetting abrasive particles play

dominant roles. The higher rock drilling efficiency and bigger drilling-hole diameter of ASSJ result from the swirling flow of the jet.

3. When PAM added to the fluid within the concentration limit of 0.1 percent, the higher the PAM concentration is, the more significantly the ASSJ will drill in rock, especially at longer standoff distance.

5. ACKNOWLEDGEMENT

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7. NOMENCLATURE

ASSJ=abrasive suspension swirling jet;
PAM=polyacrylamide;
URHWD= Ultra-short Radius Horizontal Well Drilling;
d_0 = nozzle exit diameter;
AWSJ= abrasive water swirling jet.

Table 1. Mechanical properties and dimensions of rock block used in the experiments

No. of Rock Block	Compressive Strength / MPa	Porosity / %	Permeability / μm^2	Dimension / cm^3
1	61.2	8	32.83×10^{3}	60×60×50
2	53.81	9.21	39.66×10^{3}	60×60×60

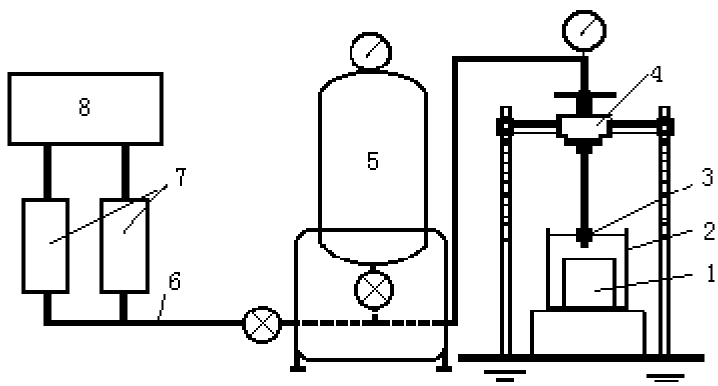


Figure 1. Experimental setup for rock drilling
1-rock block; 2- submerging water tank; 3- swirling jet nozzle head; 4-drilling rig; 5-abrasive container; 6- pipe; 7-pumps; 8- polymer solution preparation tank.

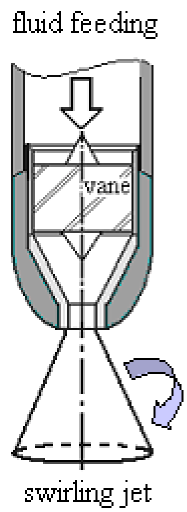


Figure 2. Schematic of swirling jet generation

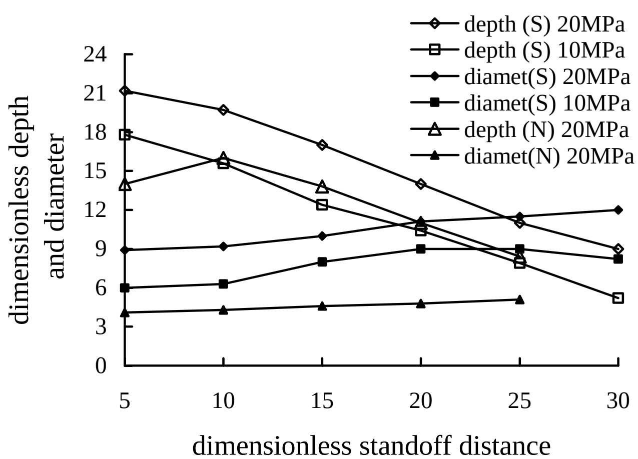


Figure 3. Drilling depth and diameter versus standoff distance

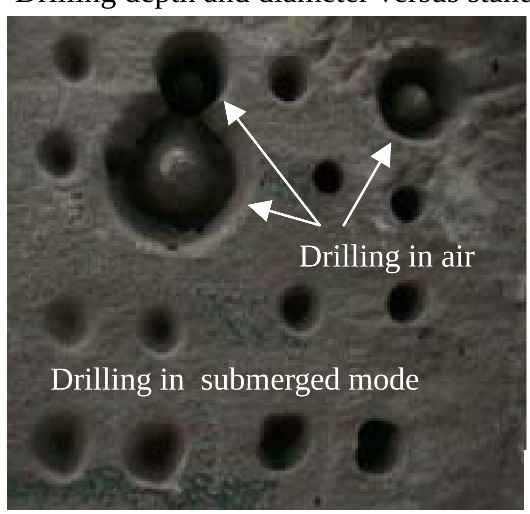


Figure 4. Bottom hole shapes drilled with ASSJ at different conditions

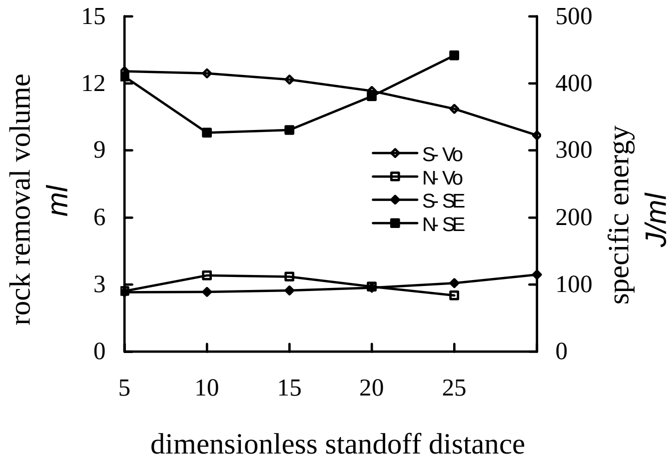
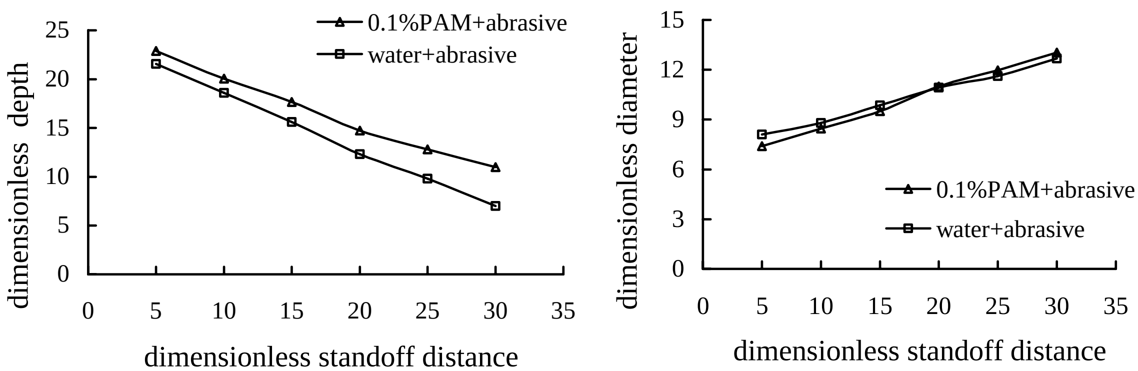


Figure 5. Rock drilling efficiency contrast of the ASSJ to the non-swirling jet



(a) (b)

Figure 6. Drilling performance contrast of the ASSJ to the AWSJ

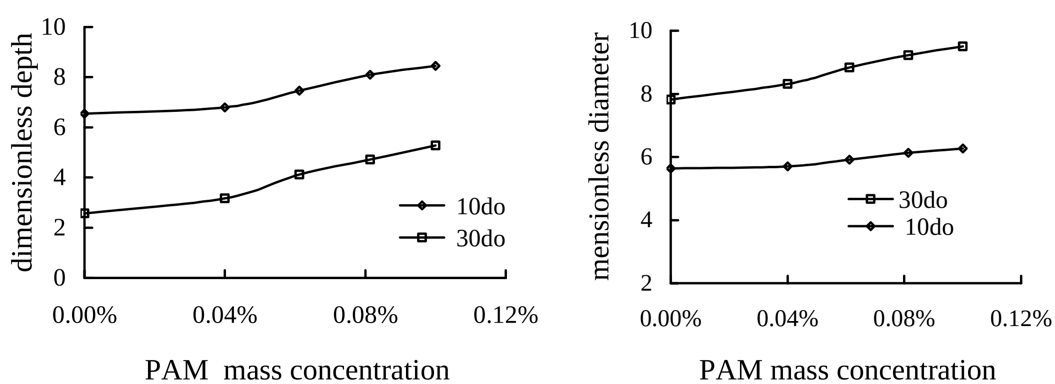


Figure 7. Effect of PAM on drilling performance