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Patterns of powder transport by spiral drill pipes at different powder inputs and rotation rates

In order to obtain the relationship between powder input, rotation rate, capacity of powder exhaust, power consumption, vibrational disturbance during normal operation of a spiral pipe, experiments of powder transport with different powder inputs (88-91, 133-137, 176-182g/s) and rotation rates (240, 300, 360, 420, 480, 540, 600rpm) are carried out. The results show that with the powder input remaining constant and the rotation rate increasing, the amount of powder residue obeys an exponential distribution and decreases gradually, and that the power consumption and vibration acceleration increase linearly. The results indicate that: (1) the capacity of powder exhaust is positively related to the rotation rate and (2) the higher the rotation rate is, the lower will be the marginal increment of powder exhaust. Through comparison of the images captured by a high-speed camera, the powder being transported falls within two flow regimes: (1) depositing and moving axially, and; (2) being stirred and moved spirally. Based on the comparison of the curves of powder residue, power consumption and vibration acceleration, a conclusion is drawn that the rotation rate of the spiral drill pipe in soft coal bed shall be controlled strictly and shall be neither too high nor too low.

Keywords: *Spiral drill pipe, powder transport, flow regime, vibrational disturbance, drilling parameter.*

1. Introduction

In China, coal serves as the most basic and important energy source (taking up 66% of the energy consumption). Due to the complicated geological evolution such as excessive coalification and large amounts of faults, gas content and pressure in coal beds are higher than expected (the standards are 8m^3/t and 0.74Mpa, respectively). Coal mine gas explosions cannot be eliminated, which affects the normal operation of coal mines, and what is worse, leads to casualties.

The spiral drill pipe, as one of the gas extraction tools to prevent gas disasters, is widely utilized in most coal mines. Underground at coal mines, spiral drill pipes are used to bore holes of different lengths and diameters into coal beds for further gas extraction. Due to the effects of some geological processes like faults, the mechanic strength of some coal bed is always insufficient and that is the so-called soft coal bed. The fineness of coal cuttings produced by a drill bit there is 3~6 times that of normal cuttings [1] in ordinary mines, indicating that the powder transport in a soft coal bed is more complicated and requires more thorough study.

Besides being utilized in the coal mine industry, the spiral structure (like screw conveying) is also commonly used in other industries such as agriculture, building construction, chemical, process and food industry [2,3]. Therefore, the research on spiral drill pipes is also helpful to other fields and industries that adopt spiral structures.

Due to the spiral structure, increase in the rotation rate would enhance the drill pipe's capacity of powder exhaust. However, there have been a few reports on the quantified data and the flow regime of coal powder has not been thoroughly studied. The following part presents a few valuable researches in the field.

In terms of experiments, Ye [4] carried out a research on the powder transport by spiral drill pipes with a simulation system, in which he used spiral pipes with different pitches and different heights of spiral bands for comparative study. The results show that the longer the pitch is and the higher the spiral band is, the more efficient will be the powder transport. However, the test samples were not sufficient and he did not give the quantified curves of the parameters either. Zareiforoush [5] did a research on the effects of the rotation rate, auger dimension and inclination on the performance of a spiral pipe. He chose volumetric output and volumetric efficiency as the indices. According to his report, with the increase of the rotation rate, the volumetric output will reach a peak while the volumetric efficiency is decreasing linearly. Yu [6] gave a theoretical model on the torque requirement for a single-screw feeder. The calculated values of the model are basically in consistent with the experimental values.

With regard to numerical simulations, Liu [7], based on ANSYS, did research on the fluid-solid coupling process of a screw conveyor. In the paper, he studied the stress

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distribution and deformation under different working conditions and loads. The results show that the effects of centrifugal hydraulic pressure is less than those of centrifugal force on the strength and deformation of a conveyor. Besides, the maximum equivalent stress occurs inside the powder inlet, while the maximum deformation occurs at the outer edge of the spiral band. Owen [2] employed the Discrete Element Method (DEM) to study the performance of a screw conveyor affected by rotation rate, inclination and volumetric filling rate. Besides, he introduced the index of energy dissipation into the experiment. Pezo [3] utilized the DEM approach to study the mixed operation of a screw conveyor. In the paper, he put fifteen horizontal single-pitch screw conveyors with modified geometries and different lengths in mixed operation. Based on the traces obtained by DEM software under different conditions, he selected the most efficient design. Talebi [8] used the CFD method to simulate soil movement in an earth pressure balance (EPB) screw conveyor. The results show that the stress and velocity fields simulated are highly consistent with the data obtained from actual operation.

This paper focuses on the experimental study and quantitative analysis on the relationship between powder input, rotation rate, capacity of powder exhaust, power consumption and vibrational disturbance. Additionally, in this paper, images are captured to investigate the flow regimes of powder under different conditions.

2. Experimental system and design

2.1 Experimental system

The experimental system is designed based on [9-16]. The whole system, as shown in Fig.1, consists of three major parts, which are the visible pipe section, the power supply and the powder feeder, respectively.

For the visible pipe section, in order to obtain visual information, the test pipes are made of acrylic material. The lengths of two pipes are both 1m, and the inner and outer diameters are 50mm and 60mm. The two spiral drill pipes are both 0.9m long with the outer diameters of the central rod and the spiral band being 22mm and 42mm, respectively. The cross sectional size in the experiment is in strict accordance with the requirement for underground use in coal mines. One end of the acrylic pipe is designed with a circular powder inlet with a diameter of 25mm and the other end is equipped with a 50mm*20mm rectangular powder outlet. The iron board at the bottom functions as a fixed base on which the pipe collars are welded, supporting all pipes.

The power supply consists of an electromotor (YS90L-4 by Xiushi Corporation) with a rated power of 1.5kW and a frequency converter (ZVF330 by Chziri Corporation) with a power of 2.2kW. The converter controls the rotation rate of the motor by adjusting the output frequency and the motor drives the drill pipes to rotate. The output parameters can be read out from the converter, such as frequency or power.

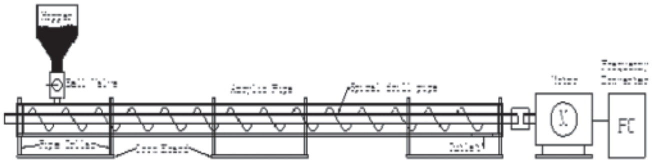


Fig.1 Schematic diagram of the experimental system

In the powder feeder, the graduated ball valve is the most important device, which is manufactured specially to adjust the flow rate to scale. An iron hopper with an inner diameter of 25cm and a height of 30cm connects downward with the graduated ball valve and supplies powder. The powder used in this experiment is fine sand with a size of 0.3-0.7mm. The sand exhausted from the outlet is collected for cycle use.

The system mentioned above is established specially for the experiment. However, measurement instruments are also needed. A digital tachometer (DT-2234B by Lutron Corporation) is employed to measure the rotation rate. The relationship between the output frequency and the rotation rate is determined: 1hz basically corresponds to 30rpm. During the experimental process, vibrations of the acrylic pipes are measured by a vibration meter (VM-63A by Rion Corporation). The powder residue in the acrylic pipes is collected and weighed by a Sartorius BSA2201 electronic balance.

2.2 Experimental design

In the experiment, this paper designs 3 levels of flow rates and 7 rotation rates for powder input. The 3 levels of powder input are determined by the balance, which are low (88-91 g/s), medium (133-137g/s) and high (176-182g/s) input. The 7 rotation rates are designed based on the actual conditions underground, which are 240rpm (8Hz), 300rpm (10Hz), 360rpm (12Hz), 420rpm (14Hz), 480rpm (16Hz), 540rpm (18Hz) and 600rpm (20Hz), respectively. The experiment is designed as follows.

(1) Compare the capacity of powder exhaust at different powder inputs and rotation rates. In each test, powder is input continually and is transported and exhausted for 45 seconds (the flow of the powder transported reaches a steady state in no more than 10 seconds). Then the remaining powder is exhausted and collected, which lasts for 3min. After that, the collected powder (residue) is weighed on the balance. The powder residue indicates the filling rate of the borehole and indirectly reflects the capacity of powder exhaust at different rotation rates.

(2) Measure the output power and vibration during the experiment and analyze the relationship between the capacity of powder exhaust, power consumption and vibrational disturbance.

As shown in Fig.2, 7 points are selected for measuring vibration. Compared to other positions (radial vibration), position 1 (P1), reflects the axial vibration. P4 and 5 are both situated in the middle of the pipes, but powder is distributed

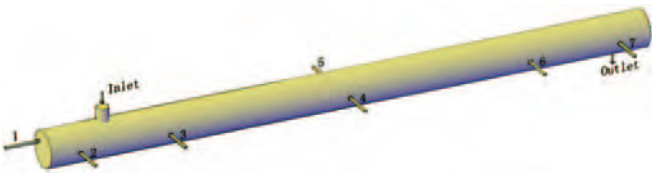


Fig.2 Distribution of the points for vibration measurement

more at P4 than P5 due to the circumferential stirring of the spiral pipes. P2, 3, 6 and 7 are arranged symmetrically.

3. Experimental results and analyses

3.1 Capacity of powder exhaust

In Fig.3, the X-axis refers to the rotation rate of the drill pipe; the Y-axis refers to the powder residue collected in the pipe. The test is repeated twice and each set of data indicates one kind of powder input. Obviously, under the same powder input, less residue means lower filling rate and higher capacity of powder exhaust.

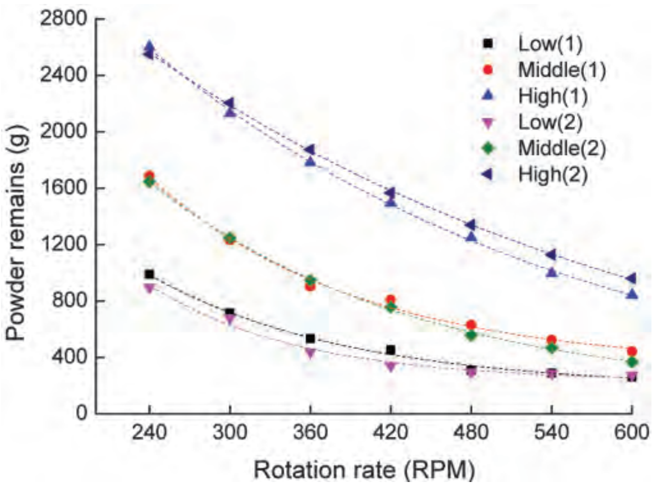


Fig.3 Powder residue curves

We can see that the data from the former and latter tests are fairly close, which means the data is reliable enough. At the same powder input, a higher rotation rate can significantly increase the capacity of powder exhaust. By fitting the data, this paper finds that all the data obey an exponential distribution very well and that the highest R2 value is over 0.999. In the left part (at a low rotation rate), the slope of curve is steep. Oppositely, the slope in right part is more horizontal. In other words, the marginal increment of powder exhaust is decreasing gradually along with the increase of the rotation rate. Besides, at the same rotation rate, the slope under lower input is more horizontal than that under higher input.

3.2 Curve of power consumption

In Fig.4, the power consumption data is compared to one of the powder exhaust curves. It shows that with the increase of the rotation rate, the power consumption of the electromotor increases linearly, and the slope of the powder residue curve decreases. Therefore, in actual work, due to the linear increase of power consumption, unlimited increase in the rotation rate is not desired for larger capacity of powder exhaust.

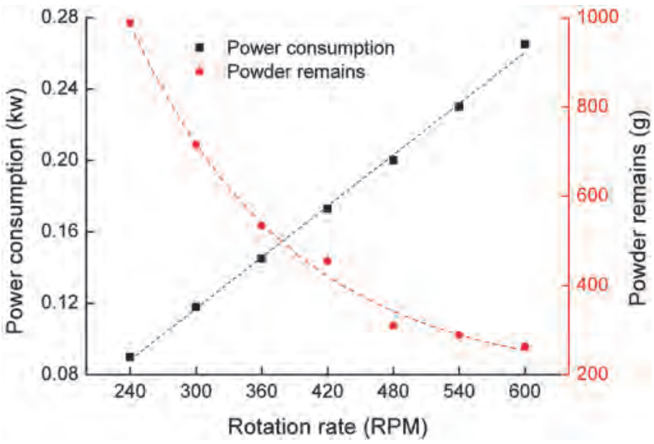


Fig.4 Comparison of power consumption curve and powder transport curve

3.3 Vibrational disturbance

Fig.5 shows the comparison of radial and axial vibration accelerations under different rotation rates. Apparently, the acceleration reflects the vibrational force. “1” and “4” in the legend represent P1 and P4 (mentioned in Fig.2), respectively. As can be seen, radial vibrations are substantially stronger than axial ones whatever powder input is chosen, which means that the rotation of drill pipes would bring more impact in the radial direction than in the axial one. With the increase of the rotation rate under the same powder input, the vibration acceleration is rising quickly. Meanwhile, it can be seen that along with increase of powder input, the vibration polyline moves downward entirely, especially under the high powder input and 240rpm, where the vibration is reduced to a very low level.

Fig.6 shows the comparison of vibration accelerations measured at different positions and different rotation rates (under medium powder input). Apparently, in every single

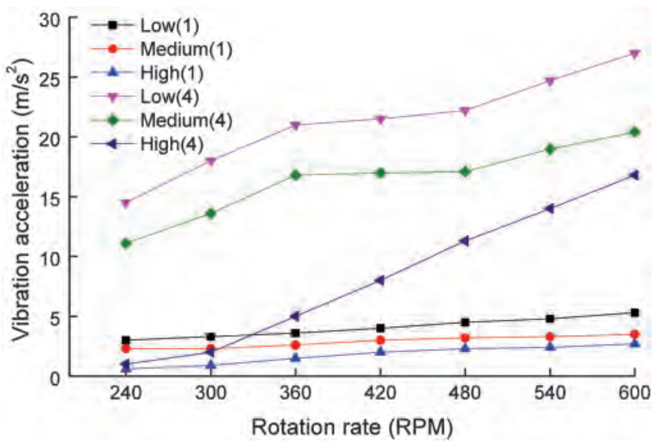


Fig.5 Vibrations at different rotation rates

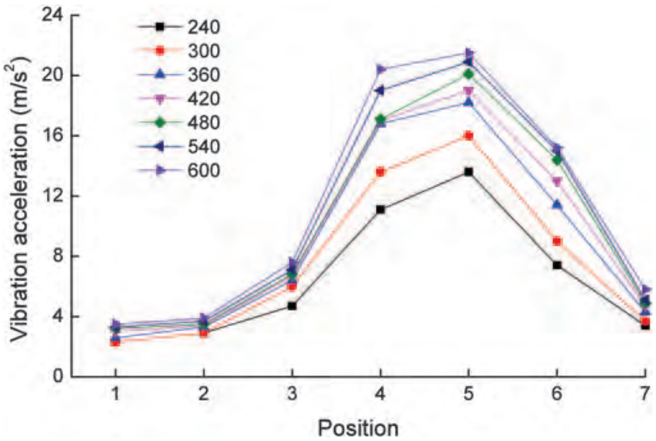


Fig.6 Vibrations at different positions

polyline, vibration acceleration at P1 is the lowest and reaches the peak in the middle of the pipe.

It is worth noting that P3 and P4 are lower than P6 and P5, respectively. As can be seen in Fig.2, near the powder inlet, the filling rate at P3 is higher than that at P6. The more powder there is, the higher will be the shock buffer to the pipe. Therefore, values at P3 are basically lower than those at P6. Similarly, as is mentioned above, powder accumulates more at P4 than P5. So, the vibration force at P4 is reduced a lot.

4. Discussions

4.1 Flow regimes of powder transport

In Fig.3, the capacity of powder exhaust increases along with the increase of the rotation rate as we expect. However, why are data points more fitted to an exponential curve than a line? In other words, why does the marginal increment of powder exhaust decrease gradually while the rotation rate increases constantly?

In order to find out the major cause of this phenomenon, a high-speed camera (GX-3 by Nac Corporation) is employed to capture videos in front and at the back of the acrylic pipe. Additional tests under medium powder input and 120, 240, 360, 480, 600 rpm are also carried out. Figs.7 and 8 show the static and dynamic comparison of flow regimes, respectively.

As shown in Fig.7(a), the filling rate in one pitch decreases from 120rpm to 600rpm. When it reaches 600rpm, it can be seen that the powder is stirred heavily. This phenomenon becomes more apparent in Fig.7(b). From the left enlarged image (240rpm) in Fig.7(b), it can be seen that the powder is depositing and seldom stirred (Fig.8(a)). Under this condition, although the powder is subject to the friction applied by the spiral band, the upward force is counter-acted by the gravity force. Therefore, the work applied by the drill pipe is mostly utilized for the forward movement of powder. With the increase of the rotation rate, the ratio of the stirred powder to the depositing powder goes upward apparently. When it reaches 600rpm (see the right enlarged image), the

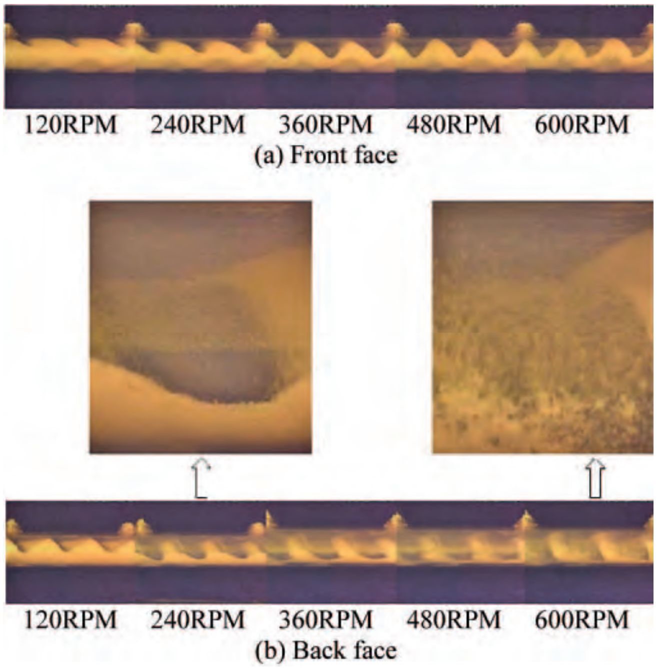


Fig.7 Static comparison from the front and the back
In order to show the different flow regimes of powder, two images from the back (images from the back are more representative) are partially enlarged

depositing powder can hardly be seen while the stirred powder fills the whole pipe (Fig.8(b)). Under this condition, the stirring force is enhanced substantially and exceeds the gravity force, forcing the powder in spiral movement. The work applied on the axial movement is sharply shunted away.

Based on the above, there exist two kinds of flow regimes during powder transport: (1) at a low rotation rate, the powder is depositing and moving axially as shown in Figure 8(a); and (2) at a high rotation rate, the powder is stirred and moving spirally as shown in Fig.8(b).

Therefore, in the left part of any curve in Fig.3, the flow regime is more inclined to be depositing and axial movement, and the work is more likely to be applied on the forward movement of the powder, which indicates a higher efficiency. In the right part, the flow regime turns to stirring flow and the work is largely applied on the stirring powder, which indicates a lower efficiency and reflects a lower slope. Additionally, the difference between flow regimes also explains another phenomenon: the slopes under the same rotation rate and different powder inputs are different. As shown in Fig.9, the filling rate under the low powder input is lower than that under the medium powder input. Powder with a smaller size is easier to stir and steps into the downward stage earlier.

4.2 Determination of reasonable rotation rate

Fig.10 shows the comparison between curves of powder residue, power consumption and vibration acceleration. Although a higher rotation rate reduces the filling rate in the borehole sharply, it brings a serious problem: despite the

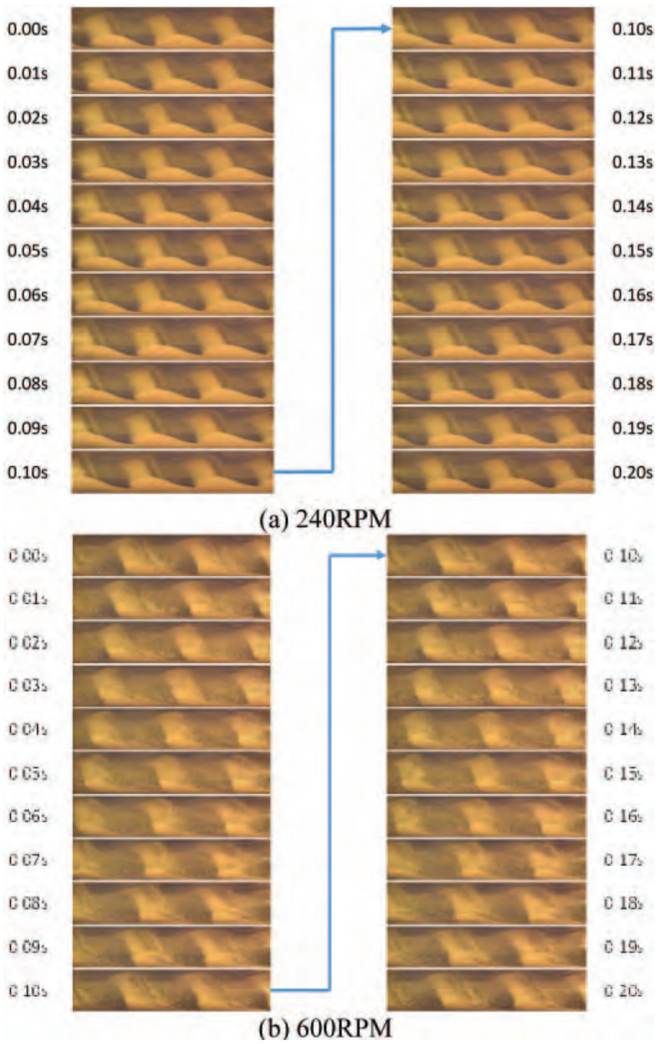
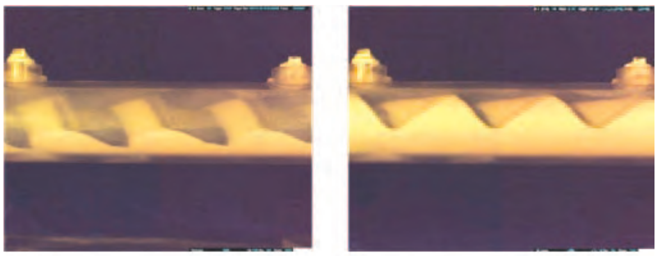


Fig.8 Dynamic comparison from the back for over 0.2s. The shooting frame rate is 500 frames per second, and the 21 frames in (a) and (b) are evenly selected from 100 frames in 0.2s

linearly increasing power consumption, the vibration acceleration is hugely increased from 1m/s^2 at 240rpm to 16.8m/s^2 at 600rpm, which is extremely critical to a borehole in a soft coal bed.

Fig.10 shows three images under three different conditions along with the powder residue curves. In the left image, the filling rate in the acrylic pipe is very high.



(a) Low powder input (b) Medium powder input

Fig.9 Comparison of filling rates at the same rotation rate

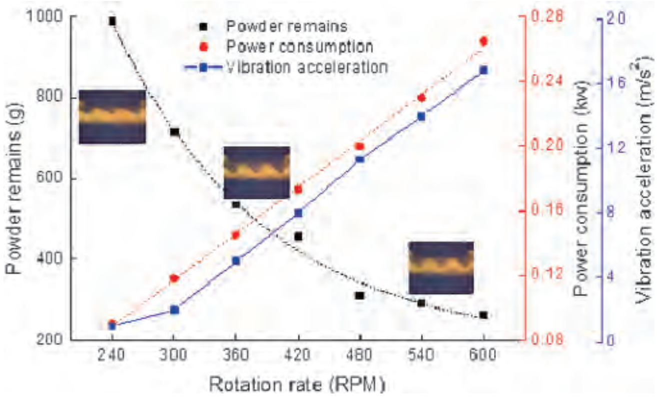


Fig.10 Comparison between curves of powder residue, power consumption and vibration acceleration

Although the normal transport of powder can be assured in the condition, its capacity to prevent hole collapses is the weakest because there is not much space to store such amount of powder. When the rotation rate is between 360~420rpm, the filling rate in the image is reduced significantly, which offers a better capacity to prevent hole collapses. On the right, when it reaches 480~600rpm, the filling rate does not decrease obviously due to the entire change of the flow regime, whereas the radial vibration is hugely increased to a high level.

Based on the analysis in Fig.10, the rotation rate shall be controlled strictly and shall be neither too low nor too high. In this experiment, 360~420 rpm might be the desired range.

7. Conclusions

Based on the experiment and discussion above, the following conclusions are drawn.

First, at a low rotation rate, the flow regime of powder is depositing and axial movement while at a high rotation rate, the powder becomes stirred and moves spirally. Under the constant powder input, the powder residue curve obeys an exponential distribution.

Second, even though a higher rotation rate brings a higher capacity of powder exhaust and less load on the drill pipe, the rotation rate shall still be controlled strictly. With the rotation rate increasing, the power consumption goes up linearly and the vibrational disturbance applied on the hole wall is enhanced substantially.

Acknowledgments

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STUDY ON THE APPLICATION OF DOUBLE CORRIDOR PROJECT IN MANAGING GEOLOGICAL DEFECTS AFFECTING TRANSMISSION LINES IN MINING AREAS

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