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Experimental research into the effects of abrasive characteristics on abrasive gas jet coal-breaking performance

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ABSTRACT

Based on the gas-solid flow theory, we analyzed the factors influencing abrasive gas jet (AGJ) velocity. On the basis of a certain nozzle structure, the influence of abrasive characteristics on the effect of coal-breaking was studied experimentally. Through theoretical analysis, it was found that the main factors affecting abrasive velocity wereabrasive density and abrasive grain size. The experimental results showed that when the jet pressure remained unchanged, the coal-breaking depth of the Brown corundumwasthe largest among quartz sand, garnet and Brown corundum, and the 120-mesh abrasive coal-breaking effect wasthe optimal one among the respective 80-mesh, 120-mesh, 200-mesh and 280-mesh abrasives. In terms of the effect of abrasive characteristics on abrasive gas jet coal-breaking performance, abrasive stiffness topped the list, followed by abrasive density. Through experimental research, we identified the best jet target distance (7cm) and the best coal-breaking abrasive (120-mesh Brown corundum abrasive).

Keywords: Abrasive Gas Jet (AGJ), Jet Coal Breaking, Abrasive Characteristics, Target Distance, Abrasive Mesh Number.

1. INTRODUCTION

Coal-bed gas is a kind of flammable and explosive gas, which seriouslythreatens the safety of any coal mine. At the same time, it is an excellent clean energy with high heat efficiency and low pollution, and thus provides energy for civil and industrial uses such as automobile fuel, electricity generation and the manufacturing of industrial products [1-2]. If the goal of further developing and utilizingcoal-bed methanecan be achieved, the energy structure will be optimized and energy utilization efficiency improved. Therefore, an inevitable trend of coal mine industry development in China will be the exploitation of coal mine gas to the maximum extent. China's coal-bed gas features high gas pressure, small coal-seam permeability and sophisticated operation of gas extraction and release [3]; present-day commonlyused methods to improve the efficiency of gas extraction include hydraulic punching, hydraulic cutting, water pressure cracking and abrasive water jet cutting [4-8]. However, these hydraulic measures, if used, will easily cause the borehole to collapse, affect the de-slagging process, and negatively incur water-induced premature termination of gas desorption [9,10].By displacing water with gas forpressure-relief and permeability-strengthened measures, the shortcomings of hydraulic measures can be overcome. Examples of the supplementary role of gases include liquid CO_2 phase-change fracturing technologies [11] and supercritical CO_2 jet coal-breaking shale technology [12]. However, due to the complexity of liquid CO_2 apparatus and techniques, there are constraints on these technologies in an underground coal mine. Such being the case, Liu Yong proposed the technology of high-pressure gas jet coal-breaking technology for pressure relief and permeability enhancement; however, owingto the low gas density and low coal-breaking efficiency of a pure gas jet,abrasive gas jet coal-breaking technology is discussedin this paper.

Abrasive gas jet coal-breaking can be realized becausethe abrasive particles are accelerated by high potential-energy gases at a velocity high enough to crush coal into pieces. There have been some research findings on the effect of different abrasives on the removal rate and surface roughness of sapphires obtained in abrasive-dependent sapphire polishing studies [13,14]. Numerous tests have been conducted by Sun Zengbiao et al. [15] under the principle of the action of SiO_2 / CeO_2composite abrasives on the surface of glassceramics, and the corresponding results reveal the maximum removal rate of SiO_2 / CeO_2 at different ratios. As can be seen from the above research, the effect of abrasive characteristics on abrasive gas jet crushing performance is strong. However, the effect of abrasive characteristics on abrasive gas jet coal-breaking performanceis rarely studied. Bearing in mindthis background, research was undertaken into the effect of different kinds of abrasives on coal-crushing, so as to determine the optimal coal-breaking abrasives and jet target distance.

2. FACTORS INFLUENCING ABRASIVE VELOCITY

The impact breakage of abrasives on coal is the major mode of abrasive gas jet coal breaking, and the interaction between abrasive particles and gas is one of the main dynamic characteristics in gas-solid flow. The abrasive particles' energy obtained in the gas phase flow field is the primary factor that influences the effect of coal breaking, especially the sub-factor of abrasive velocity. As abrasive energy is closely related to the force of abrasive particles, it is necessary to conduct the force analysis of abrasive particles in a high-pressure air flow, so as to further determine the factors influencing abrasive particle velocity. The corresponding results can be based on establishing the equation of the factors influencing abrasive particle velocity, which provides the theoretical foundation for subsequenttests and for the improvement of the abrasive gas jet coal-breaking effect.

According to the theory of gas-solid two-phase flow, abrasivesare principallyinfluenced by the force of resistance or drag force, pressure gradient force and virtual mass force in the airflow. Due to their small value, the thermal force and Basset force exerted on the flowing abrasive particles can be negligible.

The drag force exerted on the abrasives in the abrasive gas jet is:

$$F_D = \frac{1}{8}\pi d_s^2 \rho^* C_D (u_q - u_s)^2 \tag{1}$$

where F_D is the resistive or drag force of airflow, d_s is the diameter of abrasive particles, $\rho*$ is the fluid density, C_D is the resistance coefficient, u_q is the fluid velocity, and u_s is the kinematic velocity of abrasive particles.

Assuming that the gas is ideal gas, and we refer to aerodynamics to obtain the following formula:

$$\rho^* = \frac{P^*}{R_g T} \tag{2}$$

where $P*$ is the stagnation pressure, 25MPa; T is the absolute temperature of the ideal gas, 298K; R_g is a constant, and here we have $R_g=1.4$.

The abrasive high-speed movement is a movement of a large Reynolds number. When the Reynolds number falls within the range of $800\sim2\times10^5$, the resistance coefficient is basically constant, and its value is:

$$C_D = 0.44 \tag{3}$$

The pressure gradient force is:

$$F_p = -\frac{\partial p}{\partial x} 4\pi a_p^3 \int_0^{\frac{\pi}{2}} \cos^2\theta \sin\theta d\theta = -\frac{4}{3}\pi a_p^2 \frac{\partial p}{\partial x} \tag{4}$$

where a_p is the abrasive's radius $a_p=0.5d_s$.

The virtual mass force is:

$$F_a = \frac{1}{2}(\frac{4}{3}\pi a_p^3)\rho_p \frac{d(u_q - u_s)}{dt} \tag{5}$$

where ρ_p is the abrasive particles' density.

Thus, the force exerted on the abrasive is:

$$F = \frac{4}{3}\pi a_p^2 \frac{\partial p}{\partial x} - \frac{2}{3}\pi a_p^3 \rho_p \frac{d(u_q - u_s)}{dt} \pm \frac{1}{2}\pi a_p^2 \rho^* (u_q - u_s)^2 \times 0.44 \tag{6}$$

According to the force analysis of the abrasive particles, the major factors that affect the velocity of the abrasive particles include gas velocity, gas jet pressure gradient, the particle size of the abrasive grain, and the density of the abrasive. It can be seen that under the same conditions of jet pressure, different abrasives have different final speeds, resulting in different jet erosion effects. Therefore, it is necessary to study the effect of the abrasive properties on the coal-breaking performance.

An abrasive is a granular or powdery mineral material with a certain hardness and tenacity. Usually the abrasive indices include density, hardness and particle size. Qualified abrasives should be accessible, cost-efficient, and pollution-free. Considering different densities, particle size and hardness, we selected three abrasives - quartz sand, garnet and brown corundum, each of which has four grain sizes (i.e. 80 #, 120 #, 200 #, and 280 #). The basic parameters of the abrasives are listed as follows:

Table 1. Basic parameters of the abrasive

Name	Density (kg/m^3)	Stiffness (Moh's hardness)	Key component
Quartz sand	2660	7	SiO_2
Garnet	4100	7.9	A variety of minerals
Brown corundum	3950	9	Al_2O_3

3. THE CPAL-BREAKING EXPERIMENT OF AN ABRASIVE GAS JET

3.1 Experimental system

The experimental system device consists of an air compressor, high pressure cylinders, abrasive cans, protective boxes, a console, high pressure hose, measuring instruments and other components. The upper-limit exhaust pressure of the air compressor is 40MPa, and its maximum suction capacity is 2m^3/min. The nozzle type is convergent. The system is connected as shown in Figure 1 and 2. The jet pressure in the experiment is chosen as 25MPa. The source of our coal is the Jiaozuo Jiuli Hill coal mine. The coal is shaped asΦ50mm×100mm coal samples to measure its mechanical properties. The basic physical parameters of the coal samples are shown in Table 2.

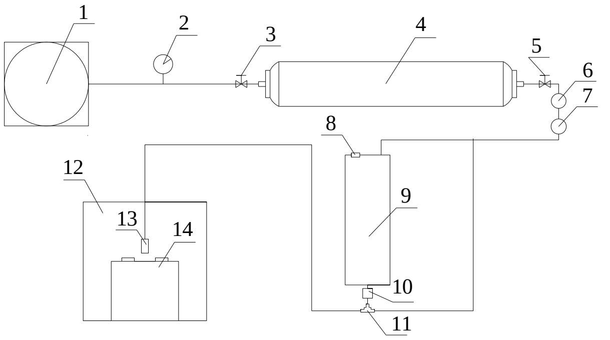

Figure 1. Schematic diagram of the experimental device: 1—Air compressor, 2—Pressure gage, 3—Pressure valve a, 4—High-pressure gas cylinder, 5—Pressure valve b, 6—Pressure sensor, 7—Temperature sensor, 8—Abrasive inlet, 9—Abrasive jar, 10—Spherical valve, 11—Three-way valve,12—Shield tank, 13—Laval nozzle, 14—Control console

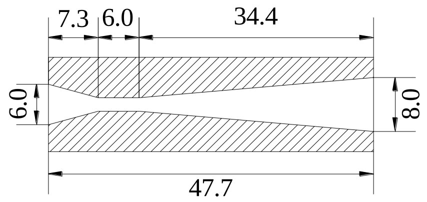

Figure 2. The structure parameter of nozzle (Unit: mm)

Table 2. Basic physical parameters of coal samples

Sampling site	Elastic modulus E/MPa	Bulk modulus K_s/MPa	True density /g·cm^{-3}	Apparent density /g·cm^{-3}	Poisson ratio μ
Jiaozuo Jiuli Hill coal mine	2590	2158	1.66	1.58	0.30

3.2 Analysis of experimental results

The test targets are three abrasives (i.e.quartz sand, garnet and brown corundum), each of which has four grain sizes (i.e. 80 #, 120 #, 200 #, and 280 #). The mass flow rate of the abrasives is 0.01kg/s and the erosion time lasts for 20s. On this basis, the abrasive gas jet coal experiment is carried out to study the effect of abrasive characteristics on the erosion effect and to determine jet target distance.

3.2.1 The test on abrasive properties

With variables of abrasive types and mesh numbers, the effect of abrasive properties on the erosion effect was analyzed in the abrasive gas jet coal-breaking test. The corresponding test parameters were: jet pressure 25MPa, jet target distance 7cm, and the mass flow rate of abrasives 0.01 kg/s. Part of the coal-breaking performance and the experimental data of crushing depth are shown in Figure 3 and Table 3.

Figure 4 reflects the depths ofquartz sand and garnet under four different meshes. With the increase in the mesh number, the depth of the broken coal increased initially and then decreased, reaching its highest pointat 120 mesh. When the abrasive type remained unchanged, the 120-mesh abrasive achieved ideal coal-breaking performance among the four mesh numbers (80 mesh, 120 mesh, 200 mesh, 280 mesh).

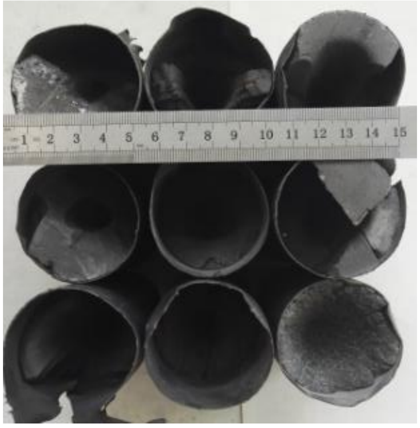

Figure 3. Experimental results of breaking coal

Table 3. Experimental data of breaking experiment

Mesh number(#)	Coal-breaking depth /cm	
	Quartz sand	garnet
80	6.230	6.181
120	7.642	9.326
200	7.321	8.388
280	6.185	5.633

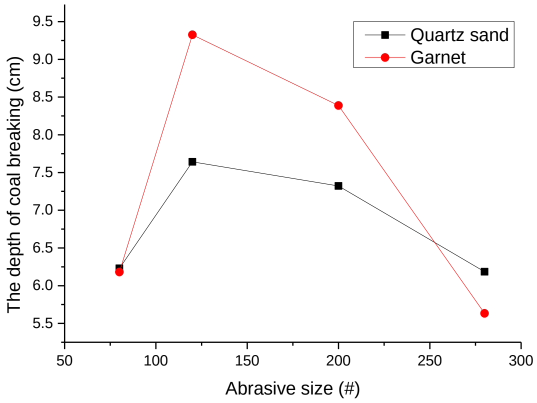

Figure 4. The coal-breaking depth under different meshes

In order to compare the effects of abrasive density on abrasive coal jet, three kinds of abrasive - quartz sand (2660 kg/m^3), garnet (4100 kg/m^3) and corundum (3950 kg/m^3) were selected herein to conduct the abrasive gas jet coal-breaking test at the fixed mesh number of 120. The depth of the broken coal are shown in Table 4.

Table 4. The depth of the broken coal

Name	Mesh (#)	Abrasive density (kg/m^3)	Coal-breaking depth(cm)
Quartz sand	120	2660	7.642
Garnet	120	4100	9.326
Brown corundum	120	3950	10.975

By comparing the coal-breaking depth using the same mesh number, it was found that the depth of corundum was the largest, which means that the coal-breaking effect of brown corundum is the optimal one. The reason why different types of abrasives display different coal-breaking performance when other conditions remain the same lies in their abrasive properties. Specifically speaking, quartz sand has a density of 2,660kg/s or so, Moh's hardness of 7 and the smallest coal-breaking depth. Compared to the otherabrasives, the low density of quartz sand helps in obtaining high speed and high kinetic energy near the nozzle, but due to its low hardness, the final coal-breaking depth was reduced.Garnet has a density of 4,100kg/s or so and Moh's hardness of about 7.9, while brown corundum has a density of 3,950kg/s or so and Moh's hardness of 9. Through data analysis, we identified the better coal-breaking performance of brown corundum compared with garnet. Their similar densities allowed them to gain asimilar amount of energy near the nozzle, but the difference between their hardness led to different crushing effect. The comparison of their crushing effect under the same mesh number indicated that the factor of hardness exerted a greater effect on coal-breaking performance. In addition to the experimental results, we took into account the price and accessibility of different abrasives and accordingly determined that brown corundum is the best abrasive for abrasive jet coal breaking.

3.2.2 Determination of target distance

As jet erosion effect responds easily to jet target distance, it is thus an effective measure to determine the best jet target distance so as toensure ideal jet performance. In this paper, on the premise that the jet pressure is fixed, we undertook the abrasive gas jet coal-breaking test to determine the best target distance. Due to the longer length of the isokinetic core area of gasjet flow field structure compared to the traditional water jet flow field structure, we chose six different target distances (0.8cm, 1.2cm, 6cm, 7cm, 8cm and 14cm) to conduct the following experiment. The jet's gas pressure was set as 25MPa, and we used 120-mesh quartz sand abrasive at the mass flow rate of 0.01 kg/s and the erosion time of 20s. The experimental results are shown in Figure 5.

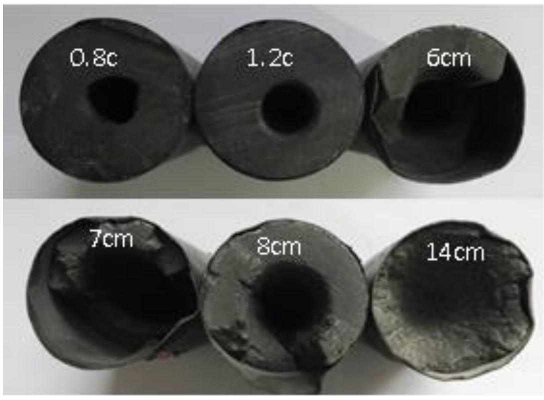

Figure 5. Coal-breaking effects at different target distances

From left to right are the coal-breaking effects at the target distances of respectively0.8cm, 1.2cm, 6cm, 7cm, 8cm and 14cm, and the coal-breaking depth is measurable (Figure 6). It can be found that when the jet pressure is fixed, with the increase in the target distance, the depth of the broken coal increases first and then decreases, and that the target distance has a relatively large influence on the depth of the broken coal. When the target distance is too small, the abrasive gas jet process will form an abrasive layer in the erosion pits, which blocks the otherwise smooth discharge of abrasives and further affects the abrasive crushing effect. For the abrasive gas jet, abrasives will diverge after being propelled out of the nozzle. As the target distance is enlarged, the distribution range of abrasives will further expand, and then the diameter of the crushing pits will increase as a response to the distribution range. The more divergent the abrasive is, the more widely distributed the coal-breaking energy is, and the larger is the diameter of the crushing pit. As a result, the coal-breaking depth plunges. Therefore, there exists an optimal jet target distance for abrasive gas jet flow. Through tests, we identified the optimal target distance of abrasive gas jet as about 7cm.

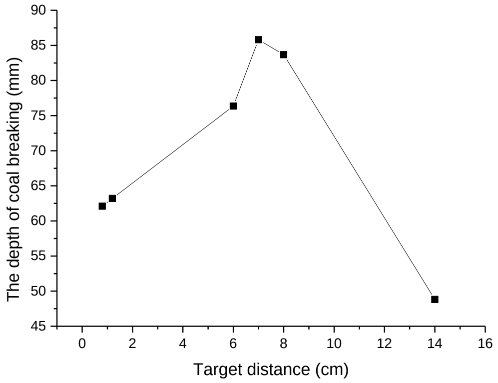

Figure 6. The coal-breaking depth under different target distances

4. CONCLUSIONS

(1) When the jet flow pressure is fixed, the factors influencing the abrasive velocity of anabrasive gas jet were analyzed and identified as abrasive density and abrasive grain size.

(2) We conducted experiments on the effect of abrasive characteristics on the coal-breaking performance, in which the 120-mesh brown corundum wasdetermined as the most suitable abrasive because of its optimal coal-breaking performance.

(3) By comparing the depths of broken coal reached by quartz sand, garnet and brown corundum, we analyzed the effect of respective abrasive hardness and abrasive density on the effect of coal-breaking. The analysis demonstrated that abrasive hardness exerted a stronger effect on coal-breaking performance, while abrasive density was a less influential factor.

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