Experimental Study on the Feasibility of Compound Technique of Perforating in Coal Seams

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Abstract：Compound technique of perforating can effectively control the perforating direction and the fracturing expansion. The feasibility of this technique used in rupturing coal seams is analyzed. The experiments of perforating and fracturing are carried out on coal samples and the experimental effects are satisfactory. Compound technique of perforating and fracturing is promising in coal seams.

Key words：explosive mechanics；compound technique of perforating and fracturing；coal seam；fracturing；HEGF

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1　Introduction

Gas disasters are the main hidden dangers of coal mines. According to the theories and engineering experience，the ultimate means of problem-solving is pre-drainage. The drainage effect of methane in coal seam，whose pressure is not relived，depends mainly on the permeability coefficient[1] which judges the flowage of methane. At present，one of the key problems in gas excavation is how to improve the productivity or seepage velocity and recovery rate of coal seams with low permeability coefficient at home and abroad[2]，and special measures improving permeability of coal seams have been invented and developed [2~8] to improve drainage rate and shorten drainage period，such as hydraulic fracturing，hydraulic cutting，the drainage method of stress-relief，loosening blasting or controlled blasting（pre-split or directional split）in coal seams or rocks.

Although the drainage effects of these methods are satisfactory to some extent and the technique and technological parameters have been improved，a great breakthrough of methane drainage is not made yet in the coal seams with high gas and low permeability coefficient. The main reason is that the permeability coefficients of coal seams are increased limitedly.

2　Depiction of new technique

The compound technique of perforating and fracturing is used sophisticatedly in the petroleum and gas industry[6]. Compound technique combines perforating and fracturing，and perforating depends on cumulative energy jet formed and fracturing is finished by quasi-static rupture of explosion gas，i. e. high energy gas fracturing（HEGF）[6,7,9]. In the compound technique mentioned above，the fracturing of explosion gas on rock follows on the heels of perforating，thus its fracturing scope is much larger than that of HEGF. The coal strength is low，thus it is perforated easily and deeply by cumulative energy jet. In this paper the author plans to put the compound technique of perforating and fracturing into coal seams to improve the permeability of coal seams and solve the methane problems.

Whereas the mechanical property of coal is bad and the special safety requirements are in demand in the districts of underground coal mining，the multi-perforator cumulative loader designed in this paper（shown in figure 1）is different from the ones used in the petroleum and gas industry. The designed-perforator is an equilateral cumulative loader，propellants are rolled into the tailor-made booster tube by powder rolling，the equilateral cumulative loaders are connected in series by the booster tube in holes. The tube not only produces large amount of high energy gas but propagates detonation which effectively eliminates channel effect. Appropriate amount of total charge does not damage the roof and floor strata of coal

seams, but assure the conditions of safety in production. Charges are detonated at the center of charge, in order to assure the symmetry and synchronization of cumulative energy jets in the process of their formation and development, wave retardation is adopted. The gun perforators have advantages in simple construction, cheapness, safety, quickness, etc.
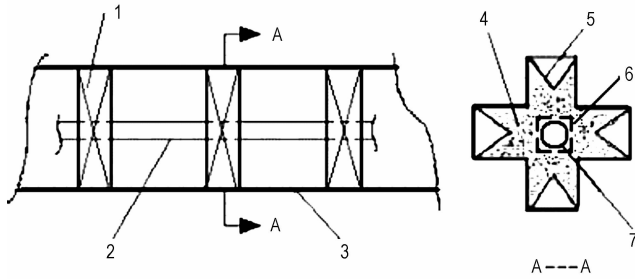

Fig. 1　Diagram of multi-perforator cumulative loader

1—gun perforator, 2—tailor-made booster charge, 3—wall of hole, 4—high explosive, 5—liner, 6—wave retardation, 7—lead hole

The principles of gun perforators are as follows: There is a great difference of reaction velocity between main charges (shaped charge) and propellants. When shaped charge is detonated in hole, the multiple cumulative energy jets form and develop in microseconds and perforate the coal seam, then the propellants are ignited in milliseconds and large amount of high pressure gas from the ignition of propellants, will subsequently fill the perforating holes which formed by jets. The pulsed extrusion of the high pressure gases on coal seam along the perforating holes makes the holes bigger and deeper and large numbers of crannies and fissures will be formed. Because of blast vibration and gas dilatancy, the large-scale networks of crannies and fissures emerge. As a result, the scope of unload pressure becomes larger and the permeability coefficient of coal seam is improved, and the methane can flow more easily in coal seam.

3　Experimental

In order to study the feasibility of utilizing the compound technique in coal seams, the coal properties and special safety requirements were taken into account when choosing the type of explosive and designing the charge structure, and the technique with reliability of course ra-

tionality of sealing holes is indispensable. For the convenience of experiment, experiments of perforating and HEGF were carried out respectively.

3.1　Perforating experiment

It is a contrast experiment. That is to say, damage capability of charge with shaped liner is compared with that of charge without liner. The two charges are the same size, so the type of explosives is not considered.

3.1.1　Preparation of coal samples

Coal samples were pressed into steel pipes. The curing age of coal sample is 30 days at normal temperature. The steel pipe is 1000 mm in length, its inner diameter is 106 mm, and the wall thickness of steel pipe is 2 mm. The main property indexes of coal sample are as follows: density is $1.34\ \mathrm{g \cdot cm^{-3}}$, Young modulus is 1.78 GPa, Poisson ratio is 0.26 and its compressive strength is 1.97 MPa.

3.1.2　Preparation of charges

The main charge for experiment is the permitted explosive for colliery (NH_4NO_3 based-explosives). For the convenience of experiment performance, the designed gun-perforator (the equilateral cumulative loaders) was treated as four parts, i. e. one part with one shaped liner which is made of copper powders. The parameters of shaped liner and charge are shown in Table 1.

Table 1　Parameters of charges and shaped liner

parameters	charge				conical liner (copper powder)		
	density /g · cm⁻³	length /mm	diameter /mm	mass /g	thickness /mm	outer diameter/mm	cone angle /(°)
with liner	1.60	80	50	60	2	50	53
without liner	1.59	80	50				

3.1.3　Experimental results

Generally, the penetration capability of the shaped charge is made the most of its optimal stand-off. The penetration depth increases with the increase of stand-off when the stand-off ranges between 0 and the optimal stand-off. However, if the stand-off is larger than the optimal stand-off, the penetration depth of the shaped charge will reduce obviously because the formed jet becomes divergent[9]. In practical application, the stand-off of shaped charge is limited by the explosive mass and hole's diameter. In general, the stand-off is chosen from 0 to the optimal stand-off and the lower value is better.

All the experiment explosives are initiated by electric detonators. The steel tube (coal sample) was put vertically and charge was on top of it, their symmetry axes were uniform, as shown in Fig. 2. Fig. 3 and Table 2 shows the experimental result.
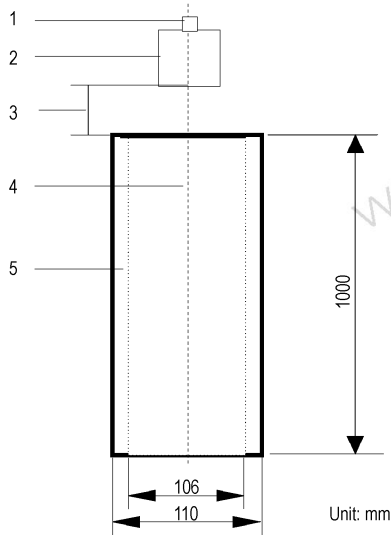

Fig. 2　Diagram of charge and coal sample
1—detonator, 2—charge, 3—stand-off,
4—coal sample, 5—steel tube

Fig. 3　Comparison of effects of two charges

Table 2　Comparison of effects of perforating experiments

charges	charge mass /g	sample length /mm	stand-off /mm	penetration depth /mm
with liner	172.5	1000	55	540
with liner	170.1	1000	55	538
with liner	169.5	1000	0	723
without liner	222.5	1000	55	124
without liner	218.7	1000	55	117
without liner	220.0	1000	0	200

As shown in Table 2, the explosive mass of charge with liner is less than that of charge without liner, but the damage depth (penetration depth) of the former is more than three to five times of that of charge without liner, obviously, the result owns to the shaped liners.

Because the wall thickness of steel pipe is too thin, it cannot offer enough confining effect. When the shock wave and cumulative energy jet propagate along the central axis of the steel pipe (coal sample), the pipe is damaged firstly by the shock wave which cause the coal to fly in all directions and the rarefaction wave to emerge. Therefore, the energy of jet and the shock wave decrease greatly, the penetration depth decreases accordingly. Obviously, as long as the steel pipe strength is great enough, it is not damaged by shock wave and explosion gas, and the penetration ability of cumulative energy jet can not be affected. What's more, when the shock wave propagating in coal sample reaches the interface of coal and steel pipe, part of the wave reflects. The energy along the central axis of the steel pipe will greatly strengthen because of the pipe effect. From above analysis, if the confining effect is obvious enough, the damage and penetration depth will go beyond 536 ~ 723 mm.

3.2　Experiment of fracturing

3.2.1　Preparation of samples

The raw coal, which mixed with solidified agent, was pressed in six tailor-made cubic molds without covers. The molds are made of laths, and the molds are 600 mm × 600 mm × 600 mm. There is a prepared hole in coal sample, the hole is $\Phi 28$ mm × 400 mm (as shown in Fig. 4).
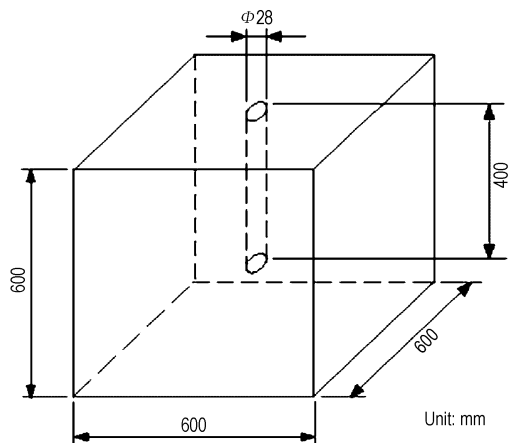

Fig. 4　Diagram of coal sample for experiment of fracturing

3.2.2 Experimental and results

Coal samples are constrained in wooden molds whose counter-failure ability is very limited, so the coal sample only can afford a low rupture stress. Therefore sandbags are tightly put around the samples. The propellants for experiment are permitted explosives for colliery. In order to find the safe and reliable range of the peak value of rupture stress, three values, i. e. 40 MPa, 60 MPa and 120 MPa, are chosen by borrowing ideas from the application experiences.

The powder chambers (holes) are sealed by cement. Suppose the space loaded explosives (powder chamber) is sealed. Based on powder and inner ballistic theories, the peak value of powder chamber's pressure is calculated by equation (1) [10]:

$$p = \frac{KF\rho}{1 - \alpha\rho} \qquad (1)$$

Where, K is coefficient of correction, 0. 1 ~ 0. 6; F is propellant force, J·kg^{-1}; ρ is charge density, kg·m^{-3}; $\rho = m/V_m$ is explosive mass, kg; V_m is volume powder chamber, m^3; α is characteristic factor of powder, m^3·kg^{-1}.

When calculating the peak value of powder chamber' pressure, the writer suppose $K = 0. 5$, $F = 9. 6 \times 10^5$ J·kg^{-1}, $\alpha = 9 \times 10^{-4}$ m^3·kg^{-1}. Table 3 shows the experimental parameters of models.

It is well known that if methane explosion happens, the following three conditions must be met: (1) methane concentration is within the range of explosion limit (5% ~ 16%), (2) oxygen concentration is more than 12%, and (3) the lowest temperature of mixed gas is over 650 ℃ (the lowest ignition temperature).

Table 3　Experimental parameters of models

No.	size of mold /mm	pressure /MPa	explosive mass/g	parameters of holes/mm		
				depth	diameter	sealed depth
1	600 × 600 × 600	40	13.9	400	28	150
2	600 × 600 × 600	40	11.1	400	28	200
3	600 × 600 × 600	120	49.7	400	28	150
4	600 × 600 × 600	120	39.8	400	28	200
5	600 × 600 × 600	80	30.3	400	28	150
6	600 × 600 × 600	80	24.2	400	28	200

In order to study whether or not methane explosion happen after the powder was ignited, the mixed gas which meets conditions (1) and (2) had been injected into powder chamber before the powder was ignited.

Six experiments were carried out according to the parameters in Table 3. For each experiment, there was only a deep-voiced detonation, and not a second detonation, which shows that the methane were not detonated. The experimental results demonstrate that the parameters of coal sample 6 are perfect. Some distinct cracks appeared on the surface of coal sample 6 after the powder was ignited. The cracks propagated almost from the hole to the boundary of coal sample. The biggest crack is 310 mm in length, which is more than 11 times of borehole diameter, the tightness of the hole is in good condition. From the profile section of coal sample 6 (as shown in Figure 5), it is found that the sample does not fall apart. Although the coal fissures around the hole, the shape of the hole holds the line and the diameter hardly becomes larger.

Fig. 5　Photo of experimental result

There are several distinct cracks on the surface of coal sample 5 after the powder was ignited. The sealing plug(cement) was damaged, which shows the sealing depth is not large enough.

Coal sample 4 was damaged badly by the explosion. When the mold was detached from the sample, the coal sample fell to pieces. It shows that the designed peak value is too high.

The sealing plug (cement) of sample 3 was destroyed by the explosion. The coal around the sealing plug collapsed, and there was a funnel. All show that the peak value is too high.

As for the sample 1 and sample 2, there were only two or three cracks on their surfaces, which show that the peak value is too low.

4　Conclusions

（1）For the perforating experiment, the damage depth (penetration depth) is increased more than four times because of the shaped liners; for the fracturing experiments, the biggest crack in coal sample is 310 mm in length, which is more than 11 times of borehole diameter. If the confining effect is obvious enough and cracking is added to perforating, the perforating and fracturing effect will be enhanced greatly.

（2）The perforating and fracturing in coal cannot induce methane explosion, which ensures the safety of blasting engineering. As long as the parameters of propellants are determined properly, the shape of the hole will hold the line and the cracks will not be compacted after the gas pressure disappears. The rupture effect is satisfactory and the permeability coefficient of coal seam is improved obviously.

（3）According to the experimental results, considering the confining effect of surrounding coal (rock) of boreholes, the peak value ranging between 80 MPa and 100 MPa is ideal when the technique is put into practical application.

（4）Considering the particularity and complexity of the experiment, the experiment conditions in the laboratory are limited. So in the laboratory, the experiment of compound technique of perforating and fracturing in coal seams cannot be carried out directly for the moment.

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复合射孔技术用于煤层致裂的可行性实验研究

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摘要：复合射孔技术能有效地控制射孔方向和压裂缝的扩展。借鉴石油工业中的复合射孔技术，对其应用于煤层致裂进行了初步的实验研究。针对煤层的特性，介绍了煤质模型的射孔与高能气体压裂（HEGF）实验的研究情况，结果表明，射孔和压裂效果良好。

关键词：爆炸力学；复合射孔技术；煤层；致裂；高能气体压裂（HEGF）

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