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PRACTICE AND PROSPECT OF FULLY MECHANISED MINING TECHNOLOGY FOR THIN COAL SEAMS UNDER COMPLEX CONDITIONS IN CHINA

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ABSTRACT: In China, thin coal seam are rich in resources and complex in conditions, however, the characteristics such as narrow mining space, the low level of mechanised technology, bad working environment and the high cost of mining, directly restrict the development of mining safety and high-efficiency. In thin coal seams with hard gangue which contains concretions of pyrite, LS-DYNA is applied to calculate the rational blasting parameters and carry out the deep-hole pre-splitting blasting technology, the hard gangue is fractured effectively, hence advancing the productivity of thin coal seam mining. In addition, the mining rate is speeded up in thin protective layers in extreme close coal seams by enhancing the level of fully mechanised equipment and other effective measures. Safety and high-efficiency mining can be realised in the outburst coal seam. Thin coal seam mining technology faces many problems presently, i.e. the low level of equipment automation, the low advance rate of mixed coal-rock drift, and the big intensity of worker labour. By lowering the labour intensity, improving the efficiency by means of advancing mining automatic equipment and other measures, respectively, thus manless working faces can be successfully realised in thin coal seam mining.

INTRODUCTION

Thin coal seams, traditionally identified as less than 1.3 m of thickness, are rich in resources and widely ranging in China. The mineable reserve is 6 150 Mt of thin coal, accounting for 20.4% of the total coal resources (Chen, 2007). Simultaneously, the mineable reserve of 2 529 Mt and accounts for more than 85% of Chinese Key Coal Mines. Particularly, the thin coal mineable reserve is 1 800 Mt in the provinces and cities include Shanxi, Hebei, Sichuan, Inner Mongolia, Guizhou and Chongqing, furthermore, the mining bureaus of Xuzhou, Datong, Kailuan, and Pingdingshan, have 501 Mt of thin coal mineable reserves, which takes up 20.9% of these bureaus' total reserves (Liu and Liu, 2002; Yan, 2004). The mineable reserves of thin coal seam in provinces are listed in Table 1.

Table 1 - Statistics of thin coal seam mineable reserves in districts in China (Liu and Liu, 2002)

District	Hebei	Shanxi	Inner Mongolia	Liaoning	Jilin	Heilongjiang	Guizhou	Henan	Sichuan
Reserves /Mt	327	1380	197	198	65	44	464	524	1480
Proportion/%	16.8	17.6	15.1	12.9	18.3	1.35	37.2	12.3	51.8

Owing to the influence of narrow mining space, bad working environment, high drivage ratio, high labour intensity, low level of mechanised mining equipment, low safety factor, low work efficiency and high input-output ratio, the quantity of thin coal seams mined only accounts for 10.4% of the total product annually. The proportion between output and mineable reserves is serious out of balance in China, which shortens the mine service-life and seriously wastes the coal resources. The fundamental way of realizing safety and high-efficiency mining in thin coal seams is to employ advanced automatic mining equipment. Automatic operation and control request use of advanced hydraulic supports, mining machines and conveyors, which are adequate for the geological conditions of thin coal seams. Presently, the fully mechanised mining technology has improved by leaps and bounds, and has formed three main mining models as follows (Wang, 2009): shearer with matching hydraulic supports; plough with matching hydraulic supports and auger mining methods. As a result of the increasing mining intensity in the eastern coal mines and the aged coal mines in China, the mineable reserves of medium thick and thick coal seams have decreased year by year, and hence many key coal mines are facing the task of thin coal

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seam mining (Sheng, *et al.*, 2007; Ma, *et al.*, 2007; Zhao and Ma, 2009). Consequently, thin coal seam mining becomes an important task and has a promising future in China.

DEVELOPMENT STATUS OF FULLY MECHANISED MINING IN THIN COAL SEAMS

Development status overseas

Coal seams with thickness less than 2.0 m are named as thin seams in USA and other western countries, and the international definition is used for coal seams with thickness of 0.8-2.0 m. At present, longwall mining overseas for thin seams has two primary technological methods (Zhai, *et al.*, 2009): one is the fully mechanised mining method equipped with shearer, hydraulic support and scraper conveyer, the other is the fully mechanised mining method using plough, hydraulic support and scraper conveyer.

Longwall mining with shearer and room-and-pillar mining with continuous miners have been applied in thin coal seams in the USA and UK; manless automatic mining has been carried out in Germany with plough and hydraulic supports by electro-hydraulic control. From 2004 to 2005, the USA had 52 longwall faces, of which 21 coal mines had thin seams with thickness less than 2.0 m, 20 coal faces with shearer and only one with plough. The average work efficiency was 35.3 t/d per miner, and the largest and average output of coal faces with shearer were 9.3 Mt/a and 4.5 Mt/a, respectively. The output with plough was 1.6 Mt/a and the work efficiency was 18.7 t/d per miner (Chen, 2007; Bi, 2007). From the conditions of their services, both shearer and plough have achieved great economic results, however, each mining machine has certain advantages and disadvantages in adapting to different geological conditions.

Development status in China

The mining technology of thin coal seam has experienced five development stages in China as follows:

- During the fifties of the 20th century with blasting method;
- In sixties using deep coal cutter to blasting coal;
- During the period of 1970-1980, the machine unit had a big development, the thin coal seam shearer named BM-100 was manufactured in 1974; various ploughs were developed later;
- From 1990 to 2000, efficiency was increased by means of imported foreign advanced fully mechanised mining equipment employed in thin and extremely thin coal seam with complex geological conditions, and
- From 2000 with the shearer of high-power and highly reliable homemade mining equipment, the level of mechanization conspicuously improved.

In 2003, Jinhuagong Coal Mine of Datong Coal Mine Group employed a domestic MG200/450-WD shearer for thin coal seam mining, the output of the coal face was 6766 t/d, and annual output was 1.0 Mt, which created a new record for similar geological conditions (Chen, 2007). In 2006, based on the geological conditions of thin seam with dip angle 3-6°, average thickness 1.3 m and Protodyakonov coefficient f=1.6, Binhu Coal Mine in Zaozhuang City employed the following coordinating equipment: MG340-BWD1 shearer, ZY2400/0.9/2.0 hydraulic support and SGZ-730/320 scraper conveyer. The average yield of coal face was 80 000 t per month and the maximum yield was 3504 t/d. Under the coal seam conditions of average thickness 1.3 m, both Daizhuang Coal Mine in Zibo City and Tongjialiang Coal Mine in Datong City achieved average yields of 68 000-80 000 t per month by Chinese shearer of MG series, the two legged hydraulic shield support and associated equipment (Zhang, *et al.*, 2002; Zhai, *et al.*, 2009). According to the geological conditions of thin coal seam with average thickness 1.3 m and dip angle 5-8°, Tiefa Coal Mine Group Xiaoqing Coal Mine applied W1E-703 plough in the coal face with strike length of 905 m, through the automation, it had achieved profit of 28.5 RMB/t, produced 0.6 Mt in nine months, and created immediate economic benefit of 17.2 million RMB (Liu and Liu, 2002; Yan, 2004). The mines in Jixi Coal Mine Group with 77% of mineable reserves in thin coal seam had an annual output of 1.85 Mt of which 17% come from thin coal seam in 2006. Pinggang Coal Mine with an average thickness of 1.3 m and dip angle of 33-35°, where MG132/310-BW shearer, BY200-06/15 shield hydraulic supports and SGW-15C scraper conveyer were employed and efficient measures were used to prevent the slipping and falling of equipment, produced a yield of 50 000 t per month.

FIELD APPLICATIONS IN THIN COAL SEAMS WITH COMPLEX CONDITIONS

Deep-hole pre-splitting blasting in thin coal seams with concretions of pyrite gangue

Thin coal seams with hard gangue accounts for 52.8% of the total thin coal seam mineable reserves in Shandong Province, and the hard gangue has severely restricted the high performances of fully mechanised mining equipment. As an example, Geting Coal Mine of Zibo Coal Mine Group has abundant thin coal seam resources, the average thickness of the NO.16 coal seam is 1.3 m, and there is a hard gangue layer in the coal seam. According to the geological conditions, a high-power shearer, matching powerful drum and enhanced point-attach picks were employed for the thin coal seam mining, which was supported by Kennametal Co., Ltd. Table 2 shows the coordinative equipment.

Table 2 - Scheme of coordination equipment in Getting Coal Mine

Equipment	Type	Number	Main technical specifications
Double-drum shearer	MG200/456-QWD	1	Cutting power 2×200 kW, Mining height 1.15~2.20 m
Hydraulic support	ZY2800/09/18	22	Effective resistance 2800 kN, Support height 0.9-1.8 m
Scraper conveyer	SGZ730/2×132	1	Installed power 264 kW, Delivery capacity 600 t/h
Bridge conveyer	SZZ630/75	1	Installed power 75 kW, Delivery capacity 600 t/h
Belt conveyer	SSJ1000/132	1	Installed power 132 kW, Delivery capacity 630 t/h

The field trial demonstrated that many shearer picks were damaged while cutting hard gangue, and this slowed the advance rate. To ease the situation, a seismic method of exploration was adopted to explore the distribution regularity of gangue in the thin coal seam, and the partial graph of 100 m length is shown in Figure 1. Hard gangue is mainly distributed below the roof around 0.34 m, the height is 0-0.4 m, and the height between 0.2 to 0.4 m accounts for 29%, the Protodyakonov coefficient of pyrite is *f*=11. Pyrite presents as stratiform and nonuniform distribution, concretions of pyrite are similar to cobblestone, and most of them distributed in the gangue.

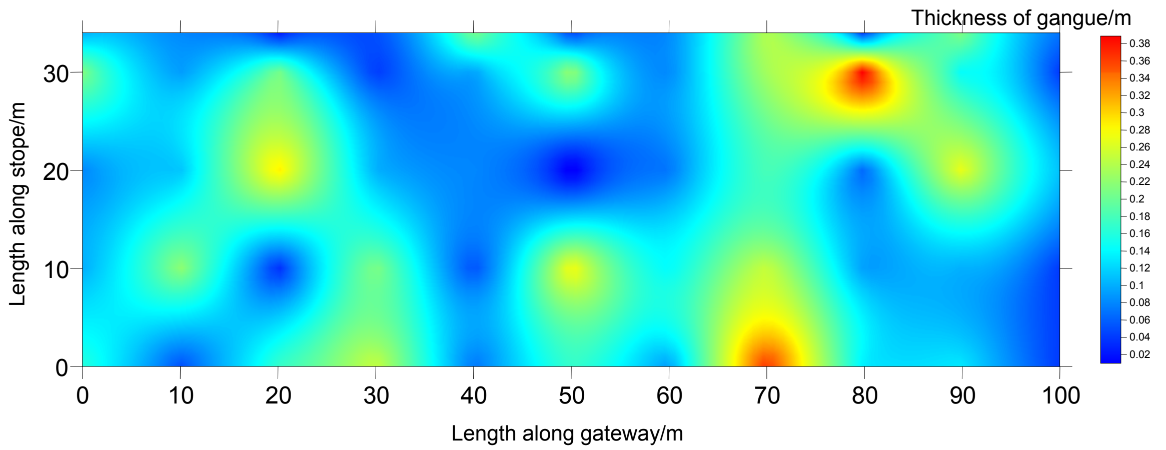


Figure 1 - Distribution regularity of hard gangue in thin coal seam

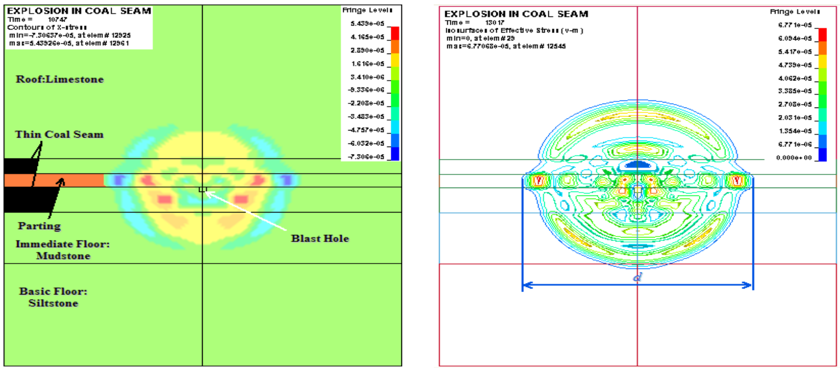
In order to reduce equipment consumption, prolong the service life of equipment and speed up the advance rate, deep hole pre-splitting blasting along gateway was obliged to be carried out in the area, where thick hard gangue were distributed. Based on the geological conditions, theoretical calculation and numerical simulation were used to provide rational blasting parameters.

According to the theory of rock blasting mechanism and the rule of stress wave produced and weakened in the rock blasting process (Song, 1989), the radius of crack zone R_p can be calculated by the formula:

$$R_p = \left[\frac{\nu P S_t}{1-\nu}\right]^{\frac{1}{a}} r_b = 2.54 \tag{1}$$

Where, P is the initial radial stress peak of stress wave, $P = \rho_0 D_t^2 \left(\frac{r_c}{r_b}\right) n/8$; a is the attenuation value of of stress wave, a=(2-v)/(1-v); D_t is detonation velocity, 3650 m/s; ρ_0 is explosive intensity, 1050 kg/m^3; r_c is radius of cartridge bag, 0.025 m; r_b is radius of blast hole, 0.045 m; S_t is the tensile strength of rock mass, 3.6 MPa; *v* is Poisson's ratio, 0.2; *n* is the stress intensification factor, 10. The calculation is R_p=2.54 m, which provide a theoretical reference for the later test.

Blasting effectiveness and the stress wave development process can be analysed and simulated by the software of LS-DYNA (LSTC, 2003), Figure 2 indicates the regulation of stress distribution.



(a) X-Stress distribution (b) Von Mises distribution

Figure 2 - Regulation of stress distribution for blasting hard gangue

The numerical model has analysed the process of smashing rock near the explosion source by shock wave and stress wave. As shown in Figure 2(a), the X-Stress wave velocity in coal is faster than in the rock mass, the stress wave distribution forms a flat "O" shape; it contributes to the pre-splitting blasting of the hard gangue and lessens damage to the roof. As shown in Figure 2(b), the radius of the crack zone *d* is around 5 m, The Von Mises wave spreads farther along hard gangue than intruding into the roof and floor, which is more beneficial to the mining, and the result agrees with the previous theoretical calculations. The results of both the theoretical calculation and numerical simulation provide the rational blasting parameters for the field experiment.

The field investigations show that the safety and high-efficiency mining in thin coal seam with hard gangue has been achieved by the pre-splitting blasting technology. Blasting and coal mining operated separately, which improves the efficiency of fully mechanised mining equipment. As a result, the operation ratio of shearer is more than 71.4%, and the output of coal face is 11 65.2 t/d, the working environment has an apparent improvement, and economical profit of 29.4 million RMB has been achieved annually.

Safety and high-efficiency mining in the protective coal seam

At present, gas explosions cause the highest proportion in coal mine accidents in China. There were 182 coal mine explosion accidents in 2008, with a death toll 778, so preventing gas accidents shoulders heavy responsibilities (Fang, *et al.*, 2009). Protective coal seam mining is the most effective and economical regional gas control technology (Liu, *et al.*, 2009). The mineable reserve of thin coal seams is more than 102.7 Mt in Huaibei Coal Mine Group. To protect the subjacent outburst coal seam, the overlying 7_1 thin coal seam was mined in Qinan Coal Mine. This is the first study of mining in thin protective coal seam close to an outburst coal seam in China and abroad.

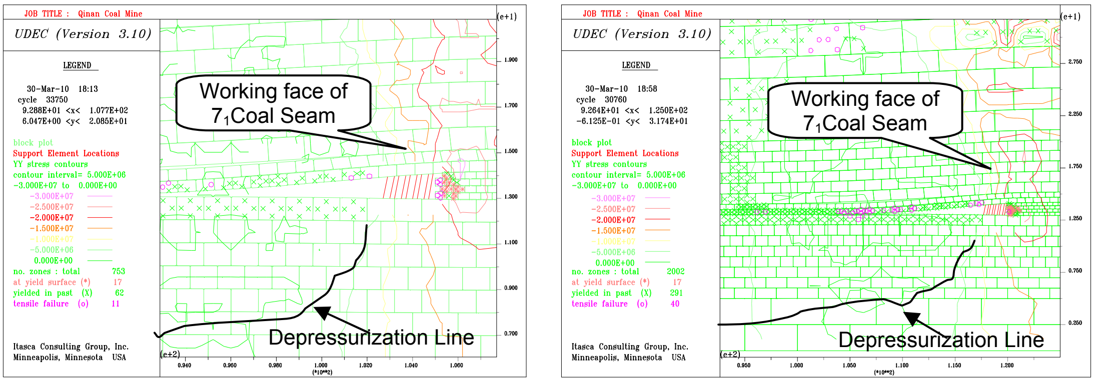
According to the geological conditions of 7_1 coal seam with average thickness 1.3 m and Protodyakonov coefficient *f*=0.2-0.3, coordinative equipment was designed and improved for the protective layer mining, the field experiment demonstrated that choosing and matching of coordinative equipment facilitated the realization of rapid advance in the thin protective seam. Table 3 lists the coordinative equipment applied in Qinan Coal Mine.

UDEC (Universal Distinct Element Code) is a two dimensional, discrete element numerical calculation program appropriate for non-continuum modelling. According to the geological conditions of thin protective coal seam, UDEC is employed to analyse the law of movement and fracture development in the 7_1 coal seam floor. Figure 3 shows the distribution of vertical stress and plastic zones.

Figure 3 (a) shows the distribution of vertical stress and plastic zones developing to the 7_2 coal seam while the excavation length of 75 m in 7_1 coal seam, and the overlying strata has fractured and sunk, the stress-relaxed area of the protected coal seam increases under the goaf. Meanwhile, the ground stress decreases and the seam permeability increases, then the effect of pressure-relief, increasing permeability and fluidity appears in the protected coal seam. When the working face advanced 90 m (Figure 3 (b)), the stress-relaxed area in the protected coal seam increases still further, the degree of pressure relief reaches its peak under the goaf. The range and degree of stress-relaxation increases further especially in the advanced direction and the seam permeability increases. The protective coal seam occurs stress-relaxation and volumetric expansion under the goaf, and emerges plenty of faulted joints and interlamination cracks, which promotes the efficiency of gas drainage and avoidable of the outburst risk.

Table 3 - Scheme of coordination equipment in Qinan Coal Mine

Equipment	Type	Number	Main technical specifications
Double-drum shearer	MG200/456-WD	1	Cutting power 2×200 kW, Mining height 1.25-2.50 m
Hydraulic support	ZY4000/09/20	83	Effective resistance 4000 kN, Support height 0.9-2.0 m
Scraper conveyer	SGZ-730/400	1	Installed power 400 kW, Delivery capacity 700 t/h
Bridge conveyer	SZZ-730/132	1	Installed power 132 kW, Delivery capacity 730 t/h
Belt conveyer	SDJ-150	1	Installed power 150 kW, Delivery capacity 630 t/h
Lotion pump	BRW-315/31.5	2	Nominal flow rate 315L/min, Nominal pressure 31.5MPa



(a) Excavation length of 75 m (b) Excavation length of 90 m

Figure 3 - The distribution of vertical stress and plastic zones

The average thickness of the 7_2 coal seam is 3.0 m, and the distance between the 7_2 and 7_1 coal seams is only 5.0 m, so it is an extremely close coal seam group. Coal samples were tested in the lab and the methane content is 12.3 m^3/t, which have the danger of outburst. The stress-relaxed gas of 7_2 coal seam easily swarm into the goaf and working face of the 7_1 coal seam through rock mass fracture, effective measures: speeding up the advance rate, drainaging the gas accumulated in the upper corner and goaf, enhancing the ventilation management and monitoring gas in real-time to avoid gas exceeding the limit. The field measurements indicate that the maximum gas concentration is 0.3% in the upper corner, and the working face advanced 16 cuts/d, the maximum monthly output of the coal face is 64 600 t. Safety and high-efficiency mining has been achieved.

EXISTING PROBLEMS AND PROSPECT FORECASTS

Main existing problems

At present, thin coal seam mining technology faces many problems, including:

- The level of equipment automation remains to be improved. A contradiction between installed power, machine height and delivery coal space is still the main technological problem of developing a high-power shearer in thin coal seams. Automatic control and fault diagnosis function for the shearer, and adaptability of hydraulic support to adjust to thin coal seam with complex geological conditions are required to improve rapidly. Meanwhile, the level of self-propelled control between hydraulic supports and conveyer remains to be developed.
- Advance rate of mixed coal-rock drifts needs to be accelerated. In general, coal seam thickness is less than 1.3 m while the roadways are higher than 2.5 m, and hence half of the drift section is

rock mass. The speedy drivage of mixed coal-rock drifts is a challenge, which directly influences the mining-drifting balance. Therefore, the development of a tunnelling and bolting integrated machine in the mixed coal-rock drift is a key to realizing efficient operation and speedy drivage.

- Working environment and less labour intensive effort is needed. The characteristics include narrow mining space, low level of mechanised mining technology and high cost of mining, which cause an intensity of worker labour and bad working environment. Particularly, the labour intensity is still greater in thin coal seams with complex geological conditions like hard gangue, faults and folds, large angles and great undulations.

Prospect forecasts

The development tendencies of thin coal seam mining technology are as follows:

- Evaluating and planning various geological conditions is an important foundational work in thin coal seam mining. According to factors such as coal seam thickness, seam inclination, structure, Protodyakonov coefficient, roof and floor conditions, faults and folds, gas outburst and water inrush, system analysis is needed to study the influence of factors and bring out a rational exploitation program.
- Improving the level of equipment automation and choosing and matching coordinative equipment reasonably are the trend of mining development. According to the evaluation system of geological conditions, there is a rapid change in designing the suitable mining technology and choosing and matching rational coordinative equipment. It is important to manufacture the electric traction shearer to adapt to geological conditions, develop reliability and cutting efficiency, and reduce the dust in the working space in China coal mines. Meanwhile, many advanced automatic machines and techniques have already emerged, e.g. automatic control and fault diagnosis systems, automatic adjustment of cutting height by means of automatic identification in coal and rock, self-control pulling speed through interchange frequency conversion electric traction, self-propelled hydraulic support and conveyer by means of infrared and electro-hydraulic servo valves.
- Developing the technique and equipment to speed drivage has a large market for drifting excavation of thin coal seams. Studying the rational technique and equipment of tunnelling efficiently and transporting in the underground environment quickly, loading and delivering of coal and waste rock separately, so as to realise speedy drivage in mixed coal-rock drifts.
- Realising manless working face in thin coal seams is the representation of scientific mining. According to the automatic monitoring technique, China has already experienced the technique of long distance bidirectional communication, telemeter and telecontrol between dispatch room and centralized control station in roadway and shearer, hydraulic supports, conveyer, etc. which has lessened the labour intensity, improved the safety conditions, and increased the production efficiency and contributed to realise manless working faces in thin coal seam mining.

CONCLUSIONS

Based on the geological conditions of thin coal seams, the main factors which restrict the realization of safety and high-efficiency mining were analysed. The conclusions are summarized as follows:

- Thin coal seams have various disadvantages: low mining height, low level of mechanised equipment, bad working environment, high drivage ratio, high labour intensity, low safety factor, low work efficiency and high input-output ratio, which restricts the development of safety and high-efficiency mining.
- High-performance of high-power coordinated equipment is restricted because thin coal seam contains concretions of pyrite gangue. Therefore, seismic methods of exploration were adopted to explore the distribution and regularity of gangue in thin coal seams. Theoretical calculation and LS-DYNA numerical simulation were employed to analyse the rational blasting parameters. Field experiment shows that by means of the technique of deep hole pre-splitting blasting along roadways, safety and high-efficiency mining can be successfully realised.
- Based on the geological conditions of the thin protective coal seams, which are extremely close to the below outburst coal seam, though advanced fully mechanised mining equipment and various

efficient measures separately, safety and high-efficiency mining was realised, and it provides great advantages to mine the outburst coal seam.

- The main problems of mining in thin coal seams include the low level of equipment automation, slow advance rate of mixed coal-rock drifts, big labour intensity and bad working environment. Manless working face mining in thin coal seams will be realised by means of improving the mining technology and automatic level of mining equipment.

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