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Drainage and utilization of Chinese coal mine methane with a coal–methane co-exploitation model: Analysis and projections

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ABSTRACT

Coal mine methane (CMM) released during coal mining attributes to unsafe working conditions and environmental impact. China, the largest coal producer in the world, is facing problems associated with CMM such as fatal gas accidents and intense greenhouse gas emission along the path to deep mining. Complicated geological conditions featured with low permeability, high gas pressure and gas content of Chinese coal seams have been hindering the coal extraction. To solve these problems, a model of coal–methane co-exploitation is proposed. This model realizes the extraction of two resources with safety ensured and has been successfully applied in Huainan coalfield, China. The current situation of drainage and utilization of CMM in China are diagnosed. Connections between the coal production, methane emissions, drainage and utilization are analyzed. Estimations of future coal production, methane emissions, drainage and utilization are made in a co-exploitation based scenario. The emitted, drained and utilized CMM are projected to reach 26.6, 13.3 and 9.3 billion m^3, respectively by adapting the assumption of 3800 million metric tons of coal production by 2020.

Introduction

Powered by robust economic development, China has become the world's second largest energy producer and consumer (NBSC, 2009). Coal, as a primary energy source, accounts for 70% of the nation's total energy supply (BP, 2010). The Chinese coal production has increased significantly from 1299 million metric tons (Mt) in 2000 to 3050 Mt in 2009, an annual growth rate of 10% (BP, 2010). It is foreseen that coal will still play a leading role in the energy structure of China for a long time.

While the contributions from coal mining industry to Chinese energy supply are irreplaceable, the conditions for coal exploitation are deteriorating. With the continued dependence on coal production, coal extraction is expected to become increasingly challenging as shallow reserves are exhausted and deeper and more gassy seams are mined (U.N. ECE and M2M, 2010). The deeper mining levels are increasing the emissions of coal mine methane (CMM), which could lead to serious mining accidents like outbursts.

The CMM involved accidents are the dominant cause that is threatening mining safety. They account for 45.8% of severe coal mine accidents where there are more than ten fatalities, according to the 2010 China's coal mine accidents report (SACMS, 2011). Typical CMM accidents in China include gas explosion, gas outburst, gas ignition and suffocation due to a high gas concentration.

Although it poses a major threat to coal mine safety, methane is also a clean and high-efficiency fuel (Flores, 1998). The energy released in the combustion of 1 m^3 of methane is 35.9 million Joules, equivalent to the combustion of 1.2 kg of standard coal. In the mean time, methane is also an intense greenhouse gas (GHG) with a Global arming Potential (GWP) of 25, i.e. 25 times of the environmental impact over carbon dioxide, in a 100-year span (IPCC, 2007).

Therefore, measures to control CMM in China bear the multiple purposes of promoting mining safety, recovering the methane resource and abating the emission of GHG. Chinese government now plans to use the recovery and utilization of CMM as the core stimulus of CMM control. By spurring methane drainage through increasing the utilization of CMM, the administration expects to promote mining safety and reduce greenhouse methane emissions (Cheng et al., 2011).

This paper gives an analysis of the drainage and utilization of CMM in China by analyzing the methane-involved problems with coal mining and raises a solution of coal–methane co-exploitation model. Projections of future drainage and utilization based on this model are made while China climbs to its coal peak.

Problems with coal mining in China

Low permeability, high gas pressure and gas content of Chinese coal seams are hindering the development of coal mining in China. From the geological view of methane drainage conditions, most of

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China's coal took shape over the Carboniferous–Permian time period. After that the coal went through a number of strong tectonic movements that destroyed the original cracks in coal seams. As a result, the coal became soft, high-ranked, construction-complicated and less smooth for the gas flow. Due to this unique geological condition, CMM in China is characterized by poor drainability, low drainage efficiency, and high maintenance (Cheng et al., 2011). A recent paper by Karacan et al. 2011 gives more detailed analysis for the difficulties of CMM projects in China.

Table 1 lists the permeability of raw coal seams in typical coal mine areas in China, United States and Australia. The permeability of Chinese coal seams is usually in the magnitude of 10^{-4}–10^{-3} mD, except for Jincheng, which is four orders of magnitude lower than the U.S. and three orders of magnitude lower than Australia.

In addition, the deeper level of coal mining also challenges the feasibility, cost and performance of CMM drainage. The shallow coal reserves in China have been exhausted by a fast coal producing rate and Chinese coal mining level is deepening at an annual rate of 10–20 m (NDRC, 2005). The average mining level of Eastern China's mines has reached −720 m. Thirty-two mines have been extended beyond −1000 m. In the case of Huainan and Huaibei coalfields, 85% of the known coal reserve is located at a depth of 800–2000 m underground, and the average mining level reached −850 m by 2009.

Table 1
Comparisons of permeability of raw coal seams in typical coal mine areas in China, United States and Australia.

Coalfield	Permeability (mD)
Huainan	0.00028
Huanibei	0.00121
Tianfu	0.00106
Yangquan	0.00037
Zhengzhou	0.00118
Shenyang	0.00035
Yaojie	0.00244
Jincheng	1.55
San Juan (U.S.)	10–100
Bowen (Australia)	1–10

Several attempts have been made to deal with the problems described above. Technologies such as hydraulic permeability-increasing, enhanced underground boreholes and surface drilling have been successfully applied in some mines. However, wider and further applications are restricted due to complicated process, massive workload and poor drainage performance. It should be noted that lack of knowledge, experience and adequate training of Chinese mining engineers also contribute to the unsuccessful application of the advanced technologies.

A coal–methane co-exploitation model and the applications

A coal–methane co-exploitation model

Chinese known coal reserve is 5.57 trillion metric tons, 63% of which is located at a depth of 800–2000 m. 70% of Chinese coal is featured with multiple-seam existence. There are two kinds of resources in Chinese low-permeability and high-gas-pressure coals seams: coal and methane. If only methane resource is exploited, then low permeability would restrict the methane drainage; and if only coal resource is exploited, the risks involved could lead to gas explosions or outbursts. Furthermore, if methane is not recovered, it is released into the atmosphere thus having a larger climate change impact.

A tentative solution to this dilemma is a coal–methane co-exploitation model. A coal seam with relatively lower gas risks should be selected as an initial mining seam. Through mining this seam, the gas pressure in the adjacent seams (top and below) are relieved and thus permeability increases, facilitating a good condition for high-efficiency methane drainage. Effective methane drainage in the adjacent more gassy seams could turn them into less gassy seams thus realizing the objective of extraction of both coal and methane in a safe environment (Cheng et al., 2009, 2003; Cheng and Yu, 2007; Liu et al., 2009; Yu et al., 2004).

The coal–methane co-exploitation model could solve the gas problems in coal mining, and recover methane, thereby reducing the GHG emissions. It is especially useful in the condition of multiple coal seams, which dominates the existence of coal reserve in China. The model for multiple gassy coal seams is illustrated in Fig. 1.

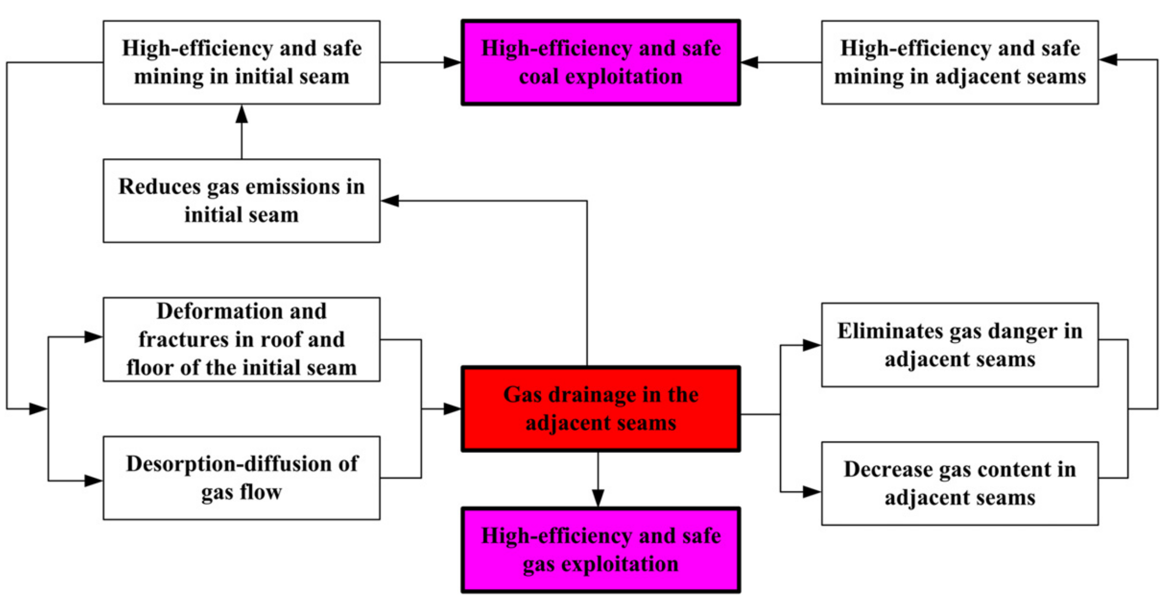

Fig. 1. A coal–methane co-exploitation model for multiple gassy coal seams under the coal–methane co-exploitation model.

Techniques for CMM drainage under the coal–methane co-exploitation model

A top–bottom sequence of coal mining is usually adapted for multiple coal seams in traditional mining methodology. This sequence has to be redesigned in a coal–methane co-exploitation model, as a relatively less gassy seam, i.e. the initial seam, is not necessarily the top seam. The extent of pressure-relieving and gas flow in adjacent seams varies with their distance from the initial seam. Thus, the corresponding drainage techniques are different based on the distance from the initial seam. The philosophy of the coal–methane co-exploitation model is to integrate the various techniques of gas collection (mostly by drainage) according to the different locations of coal mining, and thus to promote a reciprocal exploitation of coal and gas. By employing this philosophy, the drainage techniques can be classified based on the distance between the drainage engineering and the mining face, as summarized in Table 2.

Although Table 2 covers most of the drainage techniques during coal mining, there are certainly other methods of collecting gas, especially for the unmineable seams. Compared to the techniques involved in the coal–methane co-exploitation model, these methods are either at safety risk or costly due to the complicated engineering work. Some special techniques like injection of CO_2 or N_2 in to coal seams are successful in the practice of Enhance Coal-Bed Methane (ECBM). It is, however, only applicable in the coal-bed methane recovery industry, which does not regard coal as a primary resource.

Applications of coal–methane co-exploitation in Huainan coalfield

The Huainan coalfield took shape over the Carboniferous–Permian time period and is featured with multiple coal seams. The seams are numbered from bottom up and categorized into three groups: groups A, B and C. The total mineable coal thickness is up to 36 m. The gas pressure and gas content increase with deeper mining level and most of the coal seams have become outburst-prone seams. The problem of CMM is now the biggest obstacle in the coalfield.

There are 13–16 seams in the Xinzhuangzi Mine. The major mineable seams C13, B11b, B10, B8, B6, B4b and A1 are outburst-prone seams, as shown in Fig. 2. Seam B10 is less than 1.85 m thick with an average thickness of 0.9 m, at a distance of 30 m from the upper seam B11b and 40 m from the lower seam B8. The gas hazard in this seam is relatively lower than other seams.

Two mines located in this coalfield, the Xinzhuangzi Mine and the Panyi Mine, are selected as case studies to illustrate the application of the coal–methane co-exploitation model.

The characteristics of seam B10 makes it suitable for an initial seam in a coal–methane co-exploitation model. The mining of seam B10 results in the deformation of roof and floor, thus relieves the gas pressure and increases permeability of the upper seam B11 and lower seam B8. The simultaneous methane drainage in the upper seam B11 and lower seam B8 turn these two outburst-prone seams into slightly gassy seams. To mine seam C13 above seam B11, the then-slightly gassy seam B11 could be selected as # 2 initial seam to relieve pressure and increase permeability of seam C13. The simultaneous methane drainage for seam C13 eliminates its gas danger before mining. For the coal seams below B8, this technique of mining the upper seam to relieve pressure and increase permeability can be applied successively.

The lower seams benefit most in this repeated coal–methane co-exploitation technique. Taking seam B4 as an example, besides seam B6, mining of seams B8 and B7 also relieves the pressure and increases the permeability of seam B4.

The practices in these two mines have produced significantly improved conditions for gas drainage and coal mining. The details of the results are shown in Table 3.

Current state of the drainage and utilization of CMM in China

CMM emissions in China

With the increasing mining depth and steady growth of coal output, CMM emission has been on the increase in China. The Chinese safety code *Specification for identification of classification of gassy mines* (SAWS, 2006) requires all coal mines in China to be classified on gas hazard. The classification categories based on the methane emission rate are listed as: (1) slightly gassy mines, (2) highly gassy mines, and (3) very gassy mines (coal/rock and gas outburst-prone mines). Reports from State Administration of Coal Mine Safety reveal the CMM emissions as raw data for the mine classification (SACMS, 2008, 2009, 2010). The coal mine emissions from 2007 to 2009 are listed in Table 4.

Table 2
Drainage techniques and application performance for multiple gassy coal seams under the coal–methane co-exploitation model.

Drainage zone	Technique	Source of gas	Method	Application coalfield	Performance assessment
Upper pressure-relieving zone	Near-distance drainage	(1) Virgin sub-layer of the mining seam (2) Remnant coal in goaf (3) Coal seams in collapsing zone (4) Coal seams with great floor deformation (5) Coal seams in fracturing zone (6) Some coal seams in bending zone	Roof seam-penetrating boreholes	Huainan, Huaibei, Tiefa, Pingdingshan	Good
			Roof in-seam long boreholes	Huainan, Yangquan	Fair
			Roof drainage roadway	Huainan	Fair
			Buried pipes in goaf	Fushun, Pingdingshan	Fair
	Medium-distance drainage	(1) Coal seams in fracturing zone (2) Some coal seams in bending zone	Roof drainage roadway	Yangquan, Panjiang	Good
			Surface well drilling	Yangquan, Huaibei, Huainan, Tiefa	Fair
	Far-distance drainage	Coal seams in bending zone	Upward crossing floor seam-penetrating boreholes	Huainan	Good
			Surface well drilling	Yangquan, Huaibei, Huainan, Tiefa	Fair
Lower pressure-relieving zone	Distance irrelevant drainage	Coal seams in lower pressure-relieving zone	Upward crossing floor seam-penetrating boreholes	Huainan, Tianfu	Fair

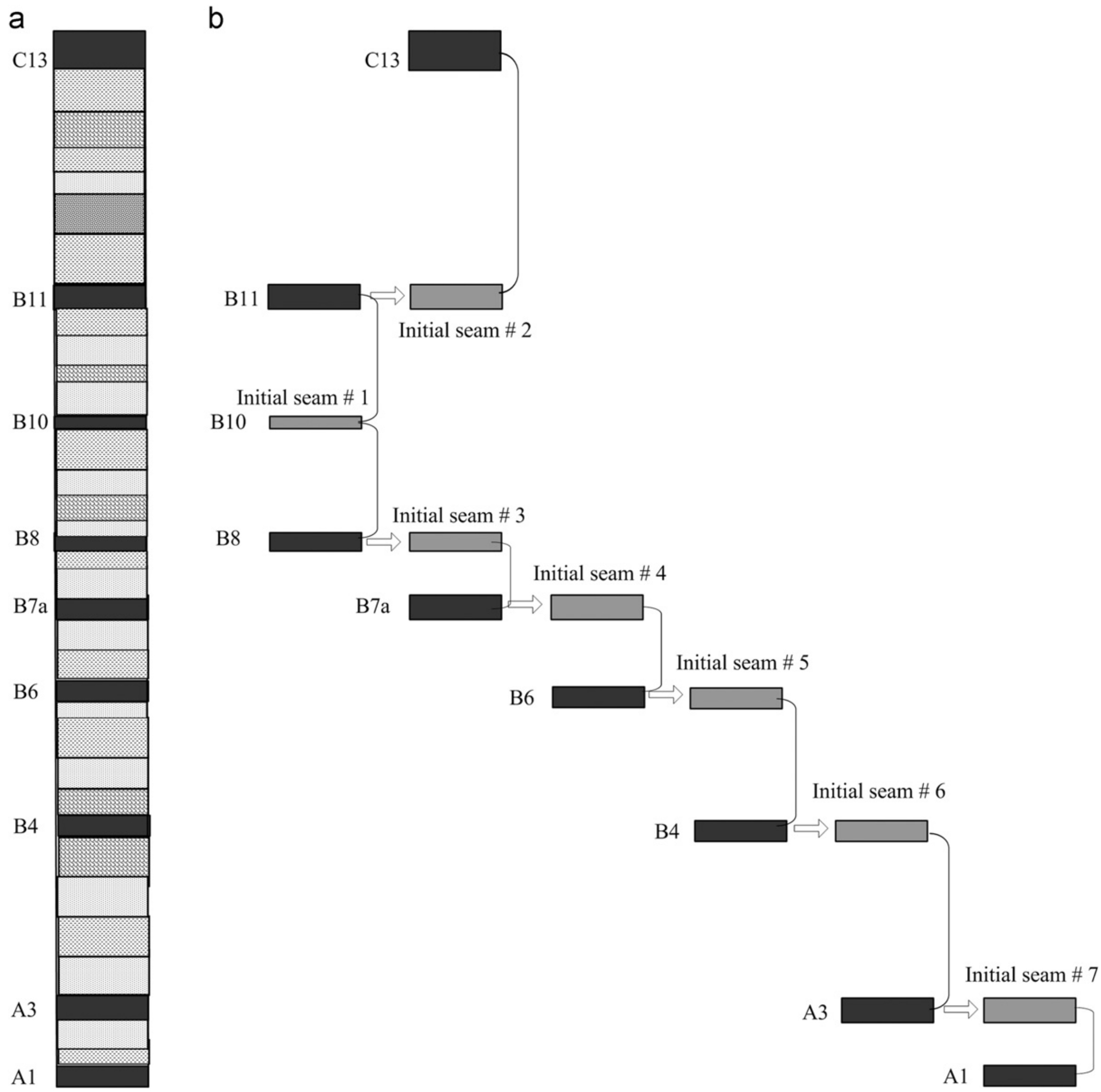

Fig. 2. The application of a coal–methane co-exploitation model in the Xinzhuangzi Mine, Huainan coalfield, China. The coal seams from top (seam C13) to bottom (A1) are mined in a sequence in which successive initial seams (#1–#7) are mined to relieve the gas pressure of adjacent seams.

Table 3
Results of the case studies by employing the coal–methane co-exploitation model.

Parameter considered	Performance/Improvement
Maximum relative expansion	26.3%
Permeability	Increased by 2880 times
Methane drainage rate	60%
Gas content	From 13 to 5.2 m^3/metric ton
Gas pressure	From 4.4 to 0.4 MPa
Monthly work face advancing rate	From 40 to 200 m

Table 4
Coal mine methane emissions in China, 2007–2009.
Source: State Administration of Coal Mine Safety (SACMS, 2008, 2009, 2010).

Year	Total emission (billion m^3)	Emission from highly gassy and outburst-prone mines (billion m^3)	Emission from slightly gassy mines (billion m^3)
2007	19.3	14.5	4.8
2008	20.2	15.2	5
2009	21.3	15.9	5.4

Based on the classification, the highly gassy mines and outburst-prone mines account for about three quarters of the total CMM emissions, even though the number of mines in these two categories are less than slightly gassy mines (Cheng et al., 2011). This is due to the rich gas content and better drainage infrastructure in the former two kinds of mines.

Drainage and utilization of CMM in China

All underground coal mines in China are required to use ventilation systems to keep in-mine methane concentrations below explosive limits and to provide fresh air to the miners. Mines with methane concentration over 30% must augment their ventilation systems with drainage systems to remove methane. The CMM emitted is either drained or released by the ventilation system. Most of the utilized methane comes from the drainage system, while a small portion of it comes from the ventilation system.

Currently, civil consumption, power generation, industrial fuels, chemical industry and automobile fuels are major ways to utilize CMM in China. Civil application of drained methane accounts for 70% of total methane utilization and has been deployed to more than 870,000 families (Cheng et al., 2011).

China's Eleventh Five-Year Plan (2006–2010) set an objective of draining 5 billion cubic meters (Bm^3) of CMM, of which the utilization should reach 3 Bm^3. The drainage rate and the utilization rate should achieve 40% and 60%, respectively. In China, the "drainage rate" is defined as the quantity of methane drained from active underground mines as a percentage of the total methane liberated through drainage and ventilation systems. The "utilization rate" is the ratio of the methane used to the methane drained. By the end of this five-year period, this objective was partially fulfilled. The 2009 drainage and utilization amounts were 6.2 and 2.1 Bm^3, respectively. And the 2010 drainage rate and the utilization rate are 33.4% and 29.1%, respectively both short of the objective set in the 11th Five-Year Plan.

The unique condition of the Chinese coal seams is the main cause of poor utilization rates. The methane concentration for drainage methane in most Chinese coal mines is lower than 30%, the minimum concentration required due to safety concerns. It is internationally accepted that a factor of safety of at least two times the upper explosive limit (i.e., 30% or greater methane concentration) should be adopted when transport and use of mixtures of gas (U.N. ECE and M2M, 2010). China has used the same standard (State Administration of Coal Mine Safety, 2010). The low concentration imposes explosion risk for methane pipeline transportation and therefore some amount of drained methane has to be released, thus decreaseing the overall methane drainage rate. Though there are programs promoting the utilization of low-concentration CMM, the progress is still hindered by technology and profits.

Ventilation air methane (VAM) from coal mines has been released directly to the atmosphere without any utilization in China over a long time. This lack of utilization was due to its low concentration and the demanding technology required (Ning and Chen, 2005; Yuan and Naruse, 1999). Despite the great amount of the VAM, the particularly low methane concentration, usually lower than 0.25%, hinders the utilization, as most utilization technologies for VAM requires a minimum methane concentration of 0.5% for stable operation. The spread of the demonstration projects of VAM utilization in China requires technology advancement and profits stimulus as well (Cheng et al., 2011).

Projections of drainage and utilization of Chinese CMM

General outlook

It is inherently decided by the methodology of coal–methane co-exploitation that the recovery and utilization of CMM is equally important with the coal mining. The attention paid to the coal mining safety has been promoting the increase of the amount of drainage and utilization. However, there is still a development gap for the methane drainage and utilization given the vast coal production.

It should be noted that the pace of Chinese coal production is going to be stable as a result of the deeper mining level and adjustment of Chinese energy structure. The bottlenecks in technology, management and cost of methane drainage and utilization have been preventing the increase of drainage and utilization rate. Therefore, the increase of methane drainage and utilization is primarily relying on the rise of coal production. An accurate prediction of China's coal production is the basis of the projections of the drainage and utilization of Chinese CMM.

Prediction of Chinese coal production

More than 20 coal-producing countries in the world have reached peak production, while Chinese coal production is still climbing at an annual rate of 10%. Methods of Hubbert on predicting coal production have been widely adapted by institutes and individual researchers (Hubbert, 1956, 1959, 1974, 1976). However, most of the research focuses on the coal production of the U.S. or the total world (BP, 2011; Höök and Aleklett, 2009; Höök et al., 2010; Hubbert, 1976; Kavalov and Peteves, 2007; Laherrere, 2006; Milici, 2000; Milici and Campbell, 1997; Mohr and Evans, 2009; Patzek and Croft, 2010). Predictions on China's coal production from some organizations have been discrepant with the actual data, mostly due to the lack of the latest data of Chinese recoverable coal reserve (BGR, 2009; EIA, 2009; EWG, 2007; IEA, 2009; IPCC, 2000b; WEC, 1995). The latest research, with knowledge of accurate Chinese coal reserve data, show that China would reach its peak coal production of 3300–4200 Mt by 2020–2030 (Höök et al., 2010; Lin and Liu, 2010; Tao and Li, 2007). Although economic effect on the production was not considered in these predictions, they are believed to be the most accurate and reasonable.

In the report National Energy Development Strategy, released by (CAE, 2010), it is predicted that Chinese coal production will reach 3800 Mt by 2020. This outcome agrees with the predictions made above. In the following analysis, the coal production prediction from the Chinese Engineering Academy is adapted for the projections of methane drainage and utilization.

Projections of future drainage and utilization of Chinese CMM

International predictions on emissions of Chinese CMM are usually found falling behind the fast coal production. For example, the Environmental Protection Agency of the United States (EPA, 2006) predicted that the emission of Chinese CMM would reach 153.8 Mt CO_2-equivalent by 2010, which is 11.5 Bm^3, converted by using a GWP of 21 for methane as used in the Second Assessment Report of Intergovernmental Panel on Climate Change (IPCC). Actually, the emission of Chinese CMM has already exceeded 21 Bm^3 in 2009, according to the 2010 report from SACMS, (2010).

CMM emissions are closely related to coal production. The increased coal production in China inevitably leads to a rise of CMM emission. It is expected that the future methane emission can be estimated by employing the equation provided by IPCC(2006)

$$CH_4 \text{ emissions} = CH_4 \text{ emission factor} \times \text{Underground coal production} \quad (1)$$

However, there is no specific emission factor for China in the GHG inventories of IPCC (1997), (2000a, 2006). The Tier 1 approach from which China's methane emissions are calculated, gives only global average values for emission factor and the uncertainties of country-specific variables could be a factor of 2 IPCC, 2006).

Alternatively, a more reliable emission factor can be derived from available historical data of coal production and CMM emissions, as shown in Fig. 3. The emission factor over the past years has been a nearly constant value of 7 m^3/metric ton with slight fluctuations. Based on this value from Eq. (1), it could be estimated that the methane emission in 2020 could reach 26.6 Bm^3 based on an assumption of 3800 Mt of coal production.

The proportion of VAM can be a reference when estimating the amount of methane drainage as these two parts comprises the total emissions. According to the predictions of the total CMM emissions and the VAM in China made by EPA (2003, 2006) the proportion of VAM over the total emission would drop from 79% in 2000 to 68% in 2020. In another word, it was predicted that the drainage rate would reach 32% by 2020. Since the current drainage rate has already surpassed 32%, the predictions made in the past without expecting the drastic development of coal

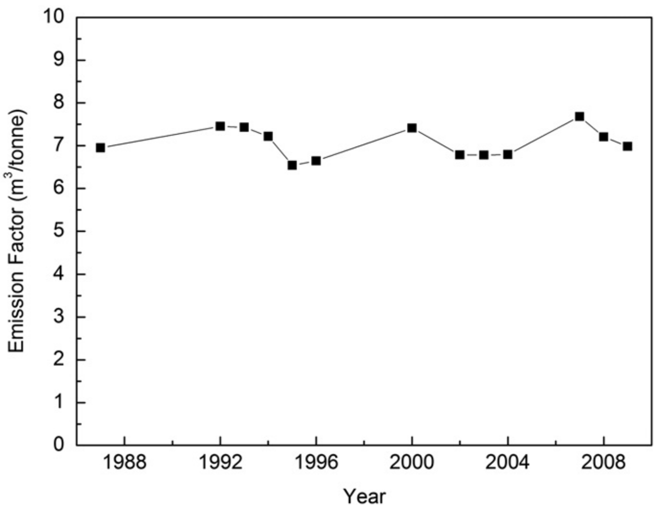

Fig. 3. Historical emission factors of Chinese coal mines, 1987–2009.
Source: State Administration of Coal Mine Safety (SACMS, 2010).

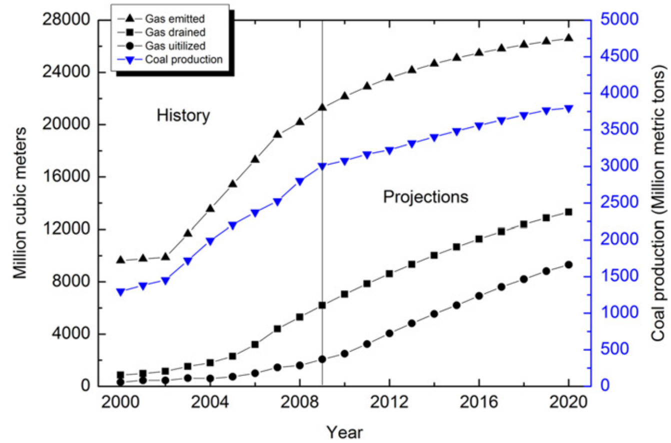

Fig. 4. Historical and forecasted coal production, emissions, drainage and utilization of coal mine methane in China, 2000–2020.
Source: State Administration of Coal Mine Safety (SACMS, 2010); BP (BP, 2010).

production and drainage technology advancement in China are not sound based to estimate the future CMM drainage.

Powered by technology advancement, administrative policies and profit stimulus, the methane drainage in Chinese coal mines will get substantially enhanced in the background of wider application of the coal–methane co-exploitation theory. However, it should be noted that the slightly gassy mines are not required to equip the methane drainage facilities according to the Safety Code for Coal Mines, 2010 (State Administration of Coal Mine Safety, 2010). It means 3/4 of the total emissions are not drainable. Therefore, it is expected that the drainage rate will level out after absorbing the increase by raised coal production and improved technology and management.

It is believed that the development of CMM utilization would follow the same pattern with that of the methane drainage, except that the current utilization rate is relatively low which allows more room for development. Factors like technology advancement, carbon financing, government's policies providing priority grid access and subsidies to CMM power will keep pushing up the utilization rate until it reaches the peak. A setback to this is that some mines have been releasing the methane from underground portable drainage system into the ventilation system, thus causing a resource waste.

The historical data and forecast of Chinese coal production, methane emissions, drainage and utilization from 2000 to 2020 are plotted in Fig. 4. The curve of the methane emission follows the same trend with the coal production as they are inherently correlated. The methane drainage and particularly methane utilization show steeper slopes, which is a result of their low bases. The projected peak drainage and utilization are 13.3 and 9.3 Bm^3, respectively if the forecasts of peak coal and methane emissions are accurate. A drainage rate of 50% will be achieved based on the scenario, which is comparable with the other major coal producers in the world. The utilization rate will reach 70% in an optimistic high-case projection.

Conclusions

As a by-product of the robust Chinese coal mining industry, the CMM plays multiple roles as a threat to mining safety, an intense GHG and a high-efficiency clean fuel. Traditional methodology on dealing with the CMM is no longer applicable when most of the Chinese coal mines are digging deep and encountering the problems of high gas pressure, high methane emissions and low permeability. A model of coal–methane co-exploitation offers a solution by placing equal emphasis on methane drainage and utilization as with coal extraction. Through different techniques aiming at different coal seam conditions, this co-exploitation model allows the recovery of both resources without compromising safety.

Coal production is expected to increase rapidly before it reaches the peak in 10–20 years. CMM emissions will keep increasing with the coal production. The coal–methane co-exploitation model will substantially promote methane drainage and utilization. Besides the rising coal production, the technology advancement and economic stimulus will also contribute to the increasing amount of methane drainage and utilization. Based on assumption of 3800 Mt of coal production by 2020, the emitted, drained and utilized CMM are projected to reach 26.6, 13.3 and 9.3 Bm^3 respectively. The corresponding drainage rate and utilization rate will reach 50% and 70%, respectively.

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