A “Full Spectrum-Domain-Time” Coalbed Gas Utilization Model and Its Application in Mining area

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Abstract

Background: As an important energy source, coalbed gas (CBG) has been widely used. However, the allocation system of CBG resources is not perfect. During the utilization process, a large amount of CBG is discharged into the air, causing environmental pollution

Methods: In this study, we proposed a “full spectrum-domain-time” CBG utilization model, including full spectrum CBG utilization technology and full domain CBG supply. In addition, based on time series algorithms, real-time prediction of the demand for CBG, grasp the characteristics of time changes in demand, and scientifically allocate resources, that is, “full-time” regulation. Taking Yangquan Coal Group, Shanxi Province, China, as a case study, introduced the application of the “full spectrum-domain-time” utilization model in the enterprise, and at last assessed the achievement of the model application.

Results and Conclusions: The time series algorithm can be used to predict CBG demand in different regions of the mining area. Driven by this model, both the total CBG and low-concentration CBG utilizations in the Yangquan Coal Group increase year after year, making it promising to reach 77.15% of CBG utilization rate and indicating that application of the model has made great accomplishment.

1 Introduction

Coal mine gas disasters have always been a major problem for safe production of coal (Yuan 2016; Zhou et al. 2019; Wang and Du 2020). But at the same time, gas can also be used as a clean energy source (Tao et al. 2019; Zheng et al. 2019). Although extraction of gas can reduce the occurrence of underground gas disasters, exhaustion of a large amount of gas will lead to air pollution and aggravate greenhouse effects. Thus, it is necessary to reasonably utilize gas using reasonable methods. In addition, exploring coalbed gas (CBG) utilization model and its application become particularly important.

China's CBG reserve amounts to 36.8 trillion cubic meters, ranking the third in the world. According to the China's “13th Five-Year Plan” from 2015 to 2020 (Wen et al. 2019), in the year of 2020, the proven geological reserve of newly-increased CBG is 420 billion cubic meters, the extracted volume of CBG will reach 24 billion cubic meters, among which the extracted coal mine gas will be 14 billion cubic meters, and the utilization rate of CBG will increase to 50%. Figure 1 shows the coal mine gas extraction volume and utilization rate in China during 2012 and 2018. It is clear that although the utilization rate of CBG gradually increases, it is still very low, less than 42%. The main reason for such a low utilization rate is that the gas extracted from underground coal mines mostly has methane concentration $< 10\%$ and is massively released to the air rather than directly used for combustion, resulting in environmental pollution. Therefore, increasing the utilization rate of low-concentration gas is a key to increase the utilization rate of coal mine gas (Li et al. 2020; Yuan et al. 2020). At present, China has initially formed a cascade utilization model for extraction and utilization of coal mine gas (Shen et al. 2015; Yao 2016; Xiong 2018). The technologies for extraction and utilization of high-concentration gas have been matured and the technologies for low-concentration gas utilization are still under development with the

focuses on low-concentration-gas-based power generation technology and methane condensation and purification technology. Moreover, lack of scientific management and regulation of CBG resources in its storage and allocation process as well as insufficient understanding of its temporo-spatial requirements have led to the waste of some CBG resources.

As a relatively independent unit, the mining area can use the extracted CBG to realize power generation, heating and other industrial uses. The CBG pumped by the coal mine is basically consumed by the mine's own mine. If the CBG is used in a reasonable way in the mine, the utilization rate of coal mine gas will be greatly improved. Therefore, the research proposed a “full spectrum-domain-time” model for comprehensive utilization of CBG, summarized the CBG stepwise utilization technology by taking Yangquan Coal Group, Shanxi Province, China, as an example, introduced in detail the promotion and application of our model in the group, and evaluated its application effectiveness.

2 Full Spectrum-domain-time Model For Cbg Utilization

2.1 “Full spectrum” CBG utilization

Coal mine gas of different sources has different methane concentrations. Methane accounts for > 90% volume of the gas pre-extracted from ground wells of the original coal mines, 50%–90% volume of the gas extracted from the ground wells in the mining and goaf areas and more than 30% volume of the high-concentration gas captured from underground wells. The above-mentioned CBG with methane concentration > 30% is widely used as a fuel for heating and power generation. Due to technology maturation, their utilization would not result in resources extravagance and environmental pollution. However, for the low-concentration gases including that captured from underground with a methane concentration < 30% and ventilation-exhaust-air, which account for a majority of the coal mine gas, due to imperfective utilization and generalization technologies, most of them are poorly utilized. Especially, those with volumetric methane concentration < 0.75% are directly discharged into the air from coal mines, resulting in massive extravagance of these valuable methane resources. Therefore, in order to achieve the full spectrum CBG utilization, it is necessary to enhance utilization of these wasted low methane concentration gases.

First, CBG extracted from coal mines with 80% methane concentration can be directly used as a fuel for power and heat generation, as well as for chemical industry and the like. This part of gas only accounts for 1% of the total extracted gas amount. Second, CBG with 30%–80% methane concentration can be used for power generation, gas boilers, as well as preparation and purification of liquefied natural gas (LNG) and compressed natural gas (CNG), etc. This part of gas accounts for ~5% of the total amount of gas extracted from coal mines. Third, CBG with 20%–30% methane concentration can be first converted to gas with 90% methane concentration using pressure swing adsorption method and then used to prepare LNG and CNG (Zhen et al. 2010; Yang et al. 2016; Li 2018). In addition, gas with >10% methane concentration can be used for power generation using low-concentration gas power generation technology and gas with <10% methane concentration can be used for power generation using low-

concentration gas power generation as well as regenerative oxidation and shaft heating technologies (Zhen et al. 2010; Yang et al. 2016; Li 2018).

The principle of ventilation-exhaust-air thermal-storage oxidation power generation technology is as follows: 1) increase methane concentration to 1.2% by mixing the ventilation air with gas of low methane concentration in the pumping station, 2) instantly and flamelessly oxidize the gas mixture with very low-concentration methane to water and carbon dioxide after injecting it into the reaction chamber of a thermal-storage high-temperature oxidation device. The system could consume more than 95% of total methane and simultaneously release large amount oxidation heat. All the thermal energy except for a small portion used to maintain the reaction temperature will be output to the residual heat boiler for heat exchange with water, which produces over-heated high-pressure water vapor to drive the turbine to generate electricity.

2.2 “Full domain” CBG utilization

The full domain CBG utilization refers to the realization of the entire network CBG supply within the whole coal mine and meet the electricity demand of the whole coal mine area by generating power using the high/low-concentration gas power generation technology and meet the heating demand of the coal mine area by generating heat using CBG as the fuel. In addition, the remaining CBG can also be used for shaft heating, coal slime drying, alumina roasting, and other engineering projects.

2.3 “Full time” CBG utilization

The rational use of CBG resources relies, on the one hand, on expanding its utilization concentration range so as to reduce unnecessary extravagance, while on the other hand, on scientific management means to reduce CBG extravagance in the resource allocation process.

The full time CBG utilization is proposed to realize the reasonable allocation of CBG resources. In detail, that is under the premise of ensuring the normal supply of CBG resources, using data prediction method to real-time analyze the supply and demand relationship of CBG resources in the coal mine area and dynamically predict the variation trend for gas demand so as to take reasonable resource allocation measures. Because the current demand for CBG in the coal mine area is mainly for power and heat generation, which has an obvious time effect. For example, in winter, with the weather gradually turning cold, the demand for electricity and heating grows clearly, thus the demand for CBG also increases greatly. By contrast, in spring and fall, the demand for electricity and heating decreases, so for CBG resources. Thus, one can use the data prediction method to find the gap between the supply and demand of CBG resources, thereby taking rational management measures to balance the demand and supply.

Based on this, a time series algorithm prediction model is used to predict the coalbed methane demand in mining area. The realization of prediction depends on the built-in exponential smoothing model of SPSS

(including Winters addition model and Winters multiplication model) and ARIMA model. According to the expert modeler in the software, the appropriate prediction model can be automatically selected, and the periodicity of the time series can be considered. And determine the parameters of the model.

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The “Full Spectrum-Domain-Time” CBG utilization model is shown in Fig.2.

2.4 CBG utilization technology and its application in Yangquan Coal Group

Overview of Yangquan Coal Group

Shanxi Yangquan Coal Group currently has 40 production and infrastructure coal mines distributing in Taiyuan, Yangquan, Jinzhong, Linfen, Xinzhou and Shuozhou, Shanxi Province, China. Among them are 9 outburst mines, 16 high gas concentration mines, and 15 low gas concentration mines. A total of 54 sets of main ventilators are installed with a total installation power of 102 million kW and the actual ventilation volume of $\sim 640,400 \text{ m}^3/\text{min}$. A total of 157 extraction and discharge pumps are installed in 34 ground pumping stations with installation power of 130,000 kW and installation capacity of 98,000 m^3/min .

Yangquan Coal Group started utilization of CBG in 1958 and established a specialized CBG branch in 1984. Since 1986, it has safely supplied a total of 6.55 billion cubic meters of commercial gas. At present, it has built a complete CBG storage and utilization system and formed a new pattern of large-scale CBG utilization in civilian and industrial power generation, purification and liquefaction, and similar fields.

3 Application And Verification Of The Full Spectrum-domain-time Cbg Utilization Model

3.1 Application of the “full spectrum-domain” CBG utilization model in Yangquan Coal Group

As shown in Fig. 3, Under the “full spectrum” utilization model, Yangquan Coal Group could process and utilize CBG with methane concentration $\geq 0.2\%$ under the promise of ensuring normal apparatus operation which basically achieved joint recovery of coal and gas, reduced extravagance of resources and occurrence of disasters, thus ensuring the safe coal mine production. Mine exhaust air with methane

concentration < 1% is used for power generation after mixed with CBG or for heating after mixed with air. Similarly, CBG with methane concentration of 1–10% is also used for power generation after mixed with CBG with higher methane concentration or for heating after mixed with air. Gas with methane concentration of 10–20% is used for power generation using related technologies for low-concentration gas and for production of pipeline network gas after purification. Gas with methane concentration of 20–30% is used to produce compressed natural gas and liquefied natural gas using pressure swing adsorption and purification technology. Gas with methane concentration of > 30% is used for high-concentration-gas power generation, urban pipeline network gas supply, as well as production of compressed natural gas and liquefied natural gas using cryogenic liquefaction purification technology.

Under the full domain utilization model, Yangquan Coal Group currently has established 14 gas storage and distribution stations, 3 gas relay pressurization stations, and 154 pressure regulation stations with total storage/distribution capacity of 360,000 m³, total installed capacity of 16762 kW, more than 590 kilometers of laid low- and medium-pressure pipeline networks, and up to 1,379 square kilometers of pipeline network coverage areas. Thus, the group has realized to full supply of CBG for the entire mining area. Figure 4 shows a schematic diagram of the supply pipeline network of high-concentration gas with the methane concentration > 30%.

3.2 Application of the “full time” CBG utilization model

Based on the realization of both full spectrum utilization and full domain supply of CBG, proposed the full time utilization model to complete a reasonable allocation of CBG resources, that is, to manage CBG demand from both temporal and spatial angles, and predict the evolution trend of CBG demand using the time series forecast algorithm as well as historical CBG production and usage data in the future. This study uses short-term forecasts of CBG demand in different regions from the data from January 2017 to December 2019 using four gas supply centers in the Laoqu, Wukuang, Xiyang and Shouyang. The usage data comes from the coalbed methane utilization branch of Yangmei Group. Figure 5 is a sequence diagram of the raw data for 35 months.

Then the above four sets of data were imported into SPSS, and the variable attributes and dates are defined. An expert modeler was used to automatically select an exponential smoothing model or ARIMA model to fit and predict the data based on the characteristics of the data and taking into account seasonality and periodicity. The forecast data is set to the gas consumption data from December 2019 to June 2020. Figure 6 shows the predicted results of gas consumption in four different regions. The parameters of the prediction model are shown in Table 1.

Table 1
Predictive model statistics

Region	Prediction model	Stationary R^2	R^2	Standardized BIC	Ljung-Box Q(18)		
					Statistics	DF	Significance
Laoqu	Additive Holt-Winters	0.823	0.827	30.885	33.078	15	0.005
Wukuang	Simple periodic model	0.669	0.311	30.742	10.131	16	0.860
Xiyang	Simple periodic model	0.619	0.604	29.658	41.463	16	0.000
Shouyang	Simple periodic model	0.571	0.558	29.007	16.912	16	0.391

It can be seen from the prediction results that when considering seasonal periodicity, the Wukuang and Shouyang residual test results are Ljung-Box Q(18) = 10.131 ($P = 0.860$) and Ljung-Box Q(18) = 16.912 ($P = 0.0391$), P values are all greater than 0.05, the model information is sufficiently extracted and can be used for prediction. But Laoqu and Xiyang's residual sequence white noise test results are Ljung-Box Q(18) = 33.078 ($P = 0.005$) and Ljung-Box Q(18) = 41.463 ($P = 0.000$), indicating that the error terms are not random. The model's information extraction is insufficient. To this end, the expert modeler in SPSS is used to make predictions without considering seasonality. At this time, the best time series models suitable for Laoqu and Xiyang are ARIMA (0,0,2) and ARIMA (1, 0,0). Although the model's R^2 is not very high, both models can pass the series white noise test. The error terms are random and the model information has been fully extracted, which means that prediction can be made. Therefore, it is feasible to use time series to forecast the CBG demand in different areas of the mining area. According to the real-time forecast results, corresponding resource allocation measures can be taken and scientific management.

3.3 Application results and accomplishment

According to the industrial plan, by the end of the 13th Five-Year Plan, the total pure CBG production of Yangquan Coal Group will reach 2.2 billion m^3 . Among them, 1,677.4 million m^3 will be utilized, with utilization rate of 77.15%, which is far over the goal of 50% in the Five-Year Plan. Besides, Fig. 7 shows the situation of CBG utilization of Yangquan Coal Group from 2014 to 2019. It can be seen that the amount of CBG utilization shows a year-by-year increasing trend. Of them, power generation from low-concentration CBG also shows an increasing trend. Therefore, application of the "full spectrum-domain-time" CBG utilization model has achieved good results in Yangquan Coal Group as the consumption of low-concentration CBG increases annually and the utilization rate is far above the average in China.

4 Conclusion

Although extraction of CBG resource in China is increasing annually, its utilization rate has been very low. Therefore, developing CBG utilization technology and reasonable resource allocation model are of great significance to improve CBG utilization rate. In this study, we put forward a “full spectrum-domain-time” CBG utilization model, detailed the current CBG utilization technology, and promoted and applied the model in Yangquan Coal Group.

(1) Currently, Yangquan Coal Group can process and utilize CBG with methane concentration $\geq 0.2\%$ under normal operation conditions, which basically reaches the full spectrum gas utilization mode, and realizes the full domain supply of CBG.

(2) Using the time series forecast algorithm can predict changes in demand and spatially coordinate resource allocation to achieve the “full time” regulation of CBG. The prediction of CBG demand in four different areas of the mining area shows that time series can be used for prediction.

(3) So far, the utilization rate of high and low concentration CBG by Yangquan Coal Group has reached 77.15% and is increasing year by year, indicating that the application has made significant accomplishment.

Declarations

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Authors’ contributions

Linghu Jianshe: Paper writing; Chen Jinhua: Research ideas and methods; Zhou Jianbin: Research method; Jiang Wangang: Data collection

Availability of data and materials

Raw data from processed data will be made available by the authors, without undue reservation, to any qualified researcher on request.

Ethics approval and consent to participate

Not applicable

Consent for publication

All participants consented the confidential publication of their contributions in this study.

Competing interests

The authors declare that they have no competing interests.

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Figures

Figure 1

Coal mine gas extraction and utilization from 2012 to 2018 in China

Figure 2

The “Full Spectrum-Domain-Time” CBG utilization model in mining area

Figure 3

The “full-spectrum” CBG utilization model in Yangquan Coal Group

Figure 4

The “full-domain” CBG supply model in Yangquan Coal Group

Figure 5

Gas consumption data for 35 months in four different regions

Laoqu gas demand fitting and prediction results

Wukuang gas demand fitting and prediction results

Xiyang gas demand fitting and prediction results

Shouyang gas demand fitting and prediction results

Figure 6

Time series prediction results

Figure 7

Coalbed gas utilization in Yangquan Coal Group from 2014 to 2019