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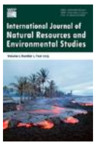

Calculation Method and Application of Methane Life Cycle Emission Reduction in Coal Mine

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ABSTRACT

The second largest greenhouse gas, methane (CH4), is mainly emitted from the coal industry. In order to propose targeted emission reduction measures, it is urgent to establish a refined emission accounting method. Based on the whole life cycle theory and carbon emission characteristics of coal mines, the mining and mining mines are divided into four stages: geological exploration, coal mining, post-mining activities and abandoned mines. The “IPC-2019 Guidelines” and “GB/T 32151.11-2018” established a method for accounting methane emissions during the whole life cycle of Jingong coal mines. Taking the methane emission of Fangzhuang Coal Mine in Jiaozuo, Henan Province from 2010 to 2017 as an example, it is calculated that the methane emission of coal mining stage in the whole life cycle accounts for about 80%, which is consistent with the historical methane emission law of coal mines in China revealed by the evaluation results based on T3 method. The establishment of this method can provide a theoretical basis for proposing effective measures to reduce methane emission and greenhouse effect in coal mines.

KEYWORDS

Full Life Cycle; Coal Mine Methane; Emission Accounting Method; Well Mining; Abandoned Mine.

1. INTRODUCTION

Coal is the main force of China 's energy production and consumption, and one of the main sources of carbon emissions. The largest proportion of methane emissions is underground mining[1-2]. With the increase of coal mining depth in China, it will lead to many disasters and disaster concurrent forms. Methane is the second largest greenhouse gas, and its comprehensive warming effect can reach 84 times that of carbon dioxide in 20 years[3,4].Meanwhile, it is also a clean low-carbon fuel and industrial raw material. Therefore, clarifying the critical path of methane emissions in the whole life cycle of coal mines can accelerate the promotion of China 's major strategic decision-making goals of ' carbon peak ' by 2030 and ' carbon neutrality ' by 2060.

The research system of coal mine methane emission can be divided into three core dimensions : emission source analysis, quantitative evaluation and emission reduction path. Li Xuewu et al.[5] established a model related to the output and emission by using the raw coal production method, so as to determine the methane emission factor in the coal mining areas of each province. Junlian Gao et al.[6] summarized the bottom-up estimation of methane emissions in China, and studied the type, emission coefficient and activity level data of methane emission sources. Scholars have proposed methods to estimate methane emissions from coal mining areas from multiple perspectives, but due to the objective differences in geological and mining conditions in China and the different methane treatment processes[7]. Improving the accounting method of coal mine methane emissions is still one of the urgent problems to be solved.

The whole life cycle assessment has been applied in the study of carbon emissions in the coal industry. Wang Xiaolin et al.[8] selected the coal mine of Panjiang Group as the research object, and systematically explained the core mechanism of carbon emission in the process of coal resource development by analyzing the structural characteristics of carbon emission sources in the whole life cycle of the mining area. Fan Jinlu et al.[9] analyzed and compared the utilization paths of different coal resources, and carried out research on carbon emissions in the whole life cycle. Cao Yuanguang et al.[10] studied the carbon emission characteristics of the whole life cycle of underground coal mining, and analyzed the main factors of greenhouse gas emissions from coal mining. Yuan et al.[11] innovatively constructed an integrated model of methane collection and accounting covering the whole process from exploration to pit closure, and systematically proposed a method system of methane emission in the whole life cycle. Although the above life cycle-based research has promoted the establishment of carbon emission accounting model in the coal industry, there is a certain lack of research on the specific classification of carbon emissions, and there is a lack of detailed research on methane emissions.

On the basis of clarifying the methane emission footprint of the whole life cycle of underground coal mines, the characteristics of methane emissions in each stage are comprehensively and systematically sorted out, summarized and analyzed, and different methods are used to calculate the methane emissions in each stage, so as to provide accurate reference for methane emission reduction and low-carbon development.

2. THE WHOLE LIFE CYCLE THEORY OF UNDERGROUND COAL MINE

The whole life cycle theory is a tool for evaluating factors related to products or services, which can summarize and evaluate the potential impact of the system from raw material acquisition, production, disposal after use and its input and output. The life cycle methane emissions of underground coal mines mainly come from four stages : geological exploration, coal mining, post-mine activities and abandoned mines. The main sources of methane in the whole life cycle of underground coal mines are summarized in Table 1.

Table 1. The main source of methane in the whole life cycle of Jinggong coal mine

Serial Number	Stage	Specific Stage	Specific Sources
1	Geological Exploration	Geological Exploration	Methane emissions from drilling holes for coal exploration purposes
2	Coal Mining	Extraction Emissions	Methane emissions from coal mine extraction systems
		Ventilation Emissions	Methane emissions escaping into the atmosphere from coal mine ventilation systems
3	Post-mining Activities	Post-mining Activities	Methane emissions generated during the washing, storage, and transportation of coal after mining
4	Abandoned Mines	Abandoned Mines	Methane emissions from abandoned underground coal mines

Methane emissions during the mining stage of the whole life cycle come from two parts (extraction system and ventilation system), and the accounting methods for methane emissions vary according to the characteristics of the mine at each stage. The methane emission footprint throughout the whole life cycle of underground coal mines is shown in Figure 1.

2.1. Methane Emissions from Geological Exploration

During coal exploration, vertical drilling is carried out from the earth's surface to detect the existence, occurrence depth, thickness, and other geological structures, ash content, moisture content, volatile matter (VM), fixed carbon (FC), and other resource and chemical characteristics of coal seams. When the drilling passes through gas-bearing formations such as coal and carbonaceous shale, a small part of the methane retained in the coal seam may be released and escape into the atmosphere during the drilling process, resulting in methane emissions. The methane emissions during the geological exploration stage depend on the number of exploration drilling holes.

2.2. Methane Emissions from Coal Mining

Methane emissions during coal mining mainly come from two links: the extraction system and the ventilation system. Therefore, the accounting of methane emissions at this stage includes ventilation methane and gas extraction methane emissions.

During coalbed methane extraction, there is no significant correlation between the emission scale and the actual output of the coal mine at that time. Therefore, an independent accounting mechanism needs to be adopted for measurement; most coal mines in China have installed digital coal mine gas monitoring and control systems, and anemometers are installed at the air drift or ventilator diffuser to measure air volume, basically realizing continuous monitoring of coal mine gas.

2.3. Methane Emissions from Post-mining Activities

Methane emissions from post-mining activities are generated during the treatment, processing, and transportation of coal after mining. Methane release is not only formed by coal fragmentation during the mining stage but also continues to be emitted at a slow rate after mining. Therefore, the emission factor method must be adopted to estimate methane emissions from post-mining activities.

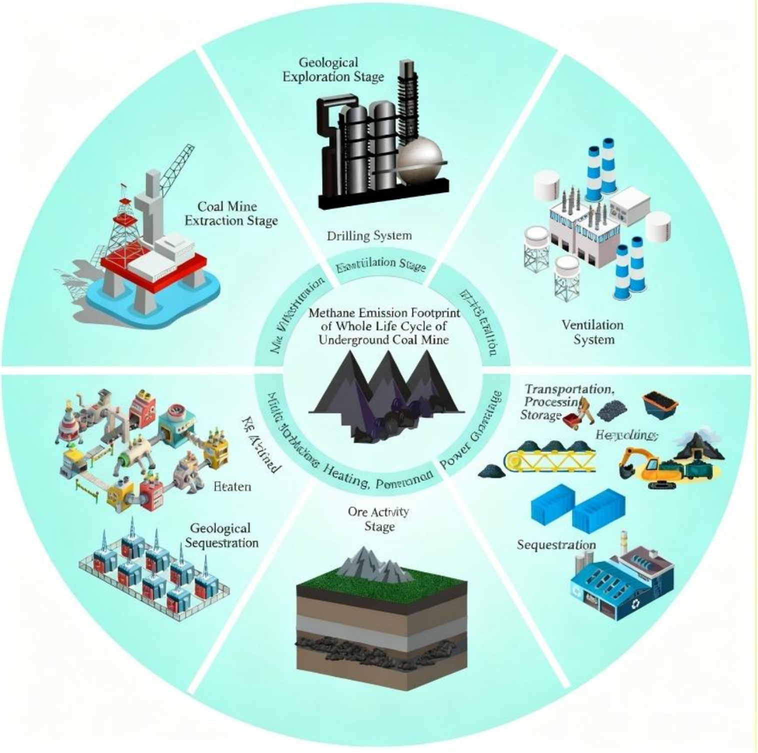


Figure 1 Methane Emission Footprint Map Throughout the Whole Life Cycle of Underground Coal Mines

2.4. Methane Emissions from Abandoned Mines

The methane gas stored in underground coal seams or goafs within the area of abandoned mines is called abandoned mine methane. After mining, the remaining coal still adsorbs methane, so methane emissions still exist in abandoned underground coal mines until the mine is geologically and naturally sealed (flooded after closure) and no longer produced.

3. ACCOUNTING OF METHANE EMISSIONS THROUGHOUT THE WHOLE LIFE CYCLE

On the basis of clarifying the methane emission footprint at each stage of the whole life cycle of underground coal mines, and according to the characteristics of methane emissions at different stages, referring to the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and the national standard GB/T 32151.11—2018, a calculation method for coal mine methane emissions throughout the whole life cycle covering geological exploration, coal mining, post-mining activities, and abandoned mines was constructed.

$$E(\mathrm{CH}_4) = E_e + E_{sm} + E_{um} + E_{af} + E_{\mathrm{ab}} \tag{1}$$

In the formula:

$E(\mathrm{CH}_4)$ is the total emission of methane in coal mine, t; E_e is the amount of methane emitted by geological exploration escape, t; E_{sm} is the methane emission caused by extraction, t; E_{um} is the methane emission caused by ventilation, t; E_{af} is the methane emission caused by post-mine activities, t; E_{ab} is the methane emission of abandoned mines, t.

3.1. Methane Emissions from Geological Exploration

Methane emissions from geological exploration are equal to the number of drilling holes at this stage multiplied by the methane emissions per drilling hole. The calculation method is shown in Formula (2):

$$E_{\mathrm{e}} = A_{\text{number of coal boreholes}} \times EF_{\text{coal boreholes}} \tag{2}$$

In the formula:

$A_{\text{number of coal boreholes}}$ is the number of boreholes for exploration activities; $EF_{\text{coal boreholes}}$ is the methane emission factor of exploration boreholes.

Coal mines need to consider the acquisition of the number of drilling holes and the difference in methane emission factors during the exploration stage. Therefore, the accounting methods for methane emissions during the exploration stage are as follows:

1) Regional Estimation Method

$$E_e = \sum_{i=1}^{n} A_{si\ \text{drilling hole amount}} \bullet EF_{si\ \text{bore hole}} \bullet CF \tag{3}$$

In the formula:

n is the number of regional units in the geological exploration of the coal mine; $A_{si\ \text{drilling hole amount}}$ is the number of boreholes in the i th geological exploration area; $EF_{si\ \text{bore hole}}$ is the methane emission factor of the i th geological exploration area, which can be obtained by measuring a specific drilling in the area, m3/drilling; CF is the conversion factor, namely the density of methane, 0.67·10-6Gg/m3.

2) Average Estimation Method

$$E_e = \sum_{i=1}^{3} A_i \bullet EF_i \bullet CF \tag{4}$$

In the formula: A_1 is the increase of coal storage in the range of the depth of the first coal seam in a certain period of time; EF_i is the methane emission factor in the depth range of the ith coal seam, m3/t (the depth of the first coal seam is 0~600 m, then = 0.01 m3/t; the second coal seam depth is 600~1200 m, then = 0.03 m3/t; the third coal seam depth is > 1200m, then = 0.05m3/t).

3.2. Methane Emissions from Coal Mining

Methane emissions during the mining stage come from the extraction system and the ventilation system, so the accounting of methane emissions at this stage is divided into two parts.

3.2.1. Methane emissions from mine extraction

The methane emissions during the mine extraction stage can be accounted for according to the following three situations:

(1) According to the Basic Indicators for Coal Mine Methane Extraction

$$E_{\mathrm{sm}} = \sum_{i=1}^{n} \frac{K \times L_{1i} \times L_{2i} \times M \times \gamma \times X \times \eta}{365 \times 1440t} \times CF \tag{5}$$

In the formula:

$K \times L_{1i} \times L_{2i} \times M \times \gamma \times X \times \eta$ is the methane reserve coefficient of adjacent layer and surrounding rock, $K = 1.2$; L_{1i} is the length of the i th working face, m; L_{2i} is the strike length of the i th working face, m; M is the average thickness of coal seam, m; γ is the bulk density of coal, t/m3; X is coal seam methane content, m3/t ; η is methane extracti on rate; t is the extraction time, a;

(2) Taking reducing the coal seam methane content to 8 m^3/t as the inspection critical value

$$E_{\mathrm{sm}} = (1 - M_{\mathrm{drawing}}) \times CF \times W_{\mathrm{raw\ coal}} \times \left(\frac{abp}{1+bp} \times \frac{100 - A_d - M_{ad}}{100} \times \frac{1}{1 + 0.31 M_{ad}} + \frac{10\varphi p}{\gamma} \right) \tag{6}$$

In the formula:

$W_{\mathrm{raw\ coal}}$ is the raw coal output, t; p is the absolute methane pressure of coal seam, MPa; a is the methane adsorption constant, m3/t; b is the methane adsorption constant, MPa-1; φ is the porosity of coal; A_d is the ash content of coal, %; M_{ad} is the moisture of coal, %; M_{drawing} is the utilization rate of underground methane extraction, %.

(3) High-yield and High-efficiency MinesFor such mines, the underground extraction area should be divided into blocks according to geological conditions and production plans to calculate methane extraction emissions. Combined with the corresponding situation, the accounting model for mine methane extraction emissions can be derived as follows:

$$E_{sm} = \left(\sum_{i=1}^{n} \lambda \times t_i \div 100 \times W_i \times m_i - Q_{0i} \times C_i\right) \times CF \tag{7}$$

In the formula:

n is the number of extraction blocks; t_i is the annual methane extraction time of the block i, month; W_i is the original methane content of the coal block i, m3/t; m_i is the coal reserves of block i, t; Q_{0i} is the limit maximum air volume of block I, m / min; C_i is the average concentration of methane in the roadway of block i, %.

3.2.2. Methane emission of mine ventilation

The choice of accounting method for methane emissions depends on whether continuous methane monitoring conditions are available.

(1) With Continuous Methane Monitoring Conditions

The following formula can be used to calculate the methane carrying capacity of the return airway monitored every hour:

$$E_{\mathrm{um}} = W \times C \times T \times (1 - M_{\mathrm{ventilation}}) \times CF \tag{8}$$

In the formula:

W is the roadway exhaust volume, m3/min; C is the average concentration of methane in the roadway, %; T is time, min; $M_{\mathrm{ventilation}}$ is ventilation methane utilization rate, %.

(2) Without Continuous Methane Monitoring Conditions

The following formula can be referred to calculate the methane emission volume through ventilation:

$$q_{\mathrm{CH_4\text{-}wind\ row}} = \frac{1}{N} \sum_{n=1}^{N} \left(Q_{\mathrm{return\ air}} \times C_{\mathrm{return\ air-CH_4}} \right)_n \tag{9}$$

In the formula :

$q_{\mathrm{CH_4\text{-}wind\ row}}$ is the measured monthly average per minute of methane wind displacement, Nm3/min; N is the number of monthly measurements, three-shift mine N = 9, four-shift N= 12; n is the measured serial number, three-shift mine N = 1,2,..., 9, four-shift N = 1,2,..., 12 ; $Q_{\mathrm{return\ air}}$ is the air flow in the return airway of Class n, Nm3/min; $C_{\mathrm{return\ air-CH_4}}$ is the volume concentration of methane in the airflow of the nth return airway, dimensionless, and the value range is 0 ~ 1.

Calculate the monthly methane emission volume according to the actual working days of the mine in the current month, and sum them up to get the total annual methane emission volume through ventilation of the mine:

$$E_{um} = \sum_{m=1}^{12} \left(q_{\mathrm{CH4\text{-}wind\ row}} \times d \right)_m \times 60 \times 24 \times 10^{-3} \times CF \tag{10}$$

In the formula:

m is the number of months, m = 1,..., 12; d is the actual number of working days in the month of the mine, d.

3.3. Methane Emissions from Post-mining Activities

The accounting method for annual methane emissions from post-mining activities of underground coal mines is as follows:

$$E_{af} = \sum_i AD_{\text{after the mine } i} \times EF_{\text{after the mine } i} \times 10^{-4} \tag{11}$$

In the formula:

i is the methane level of underground coal mines, including outburst mines, high methane mines and low methane mines; $AD_{\text{after the mine } i}$ is the sum of the annual raw coal production of all mines with methane grade, t / a; $EF_{\text{after the mine } i}$ is the post-mine active methane emission factor of mine with methane grade, m3 / t, outburst mine and high methane mine is 3m3/t; low methane mine is 0.94m3/t.

3.4. Methane Emissions from Abandoned Mines

The accounting of methane emissions from abandoned mines can be divided into the following two methods:

(1) Phased Calculation Method

The specific calculation is shown in the following formula.

$$E_{\mathrm{ab}} = \sum_{i=1}^{T} \max\{0, E_{abz} \times EF_{abi} - E_{arui}\} \tag{12}$$

In the formula :

T is the total number of years expected to be abandoned; E_{arui} is the amount of methane recovery and utilization in the ith waste year, t/a; E_{abz} is the total reserves of methane resources in the waste stage, t; EF_{abi} is the emission factor of methane in the ith abandoned year, a-1.

(2) Overall Estimation Method

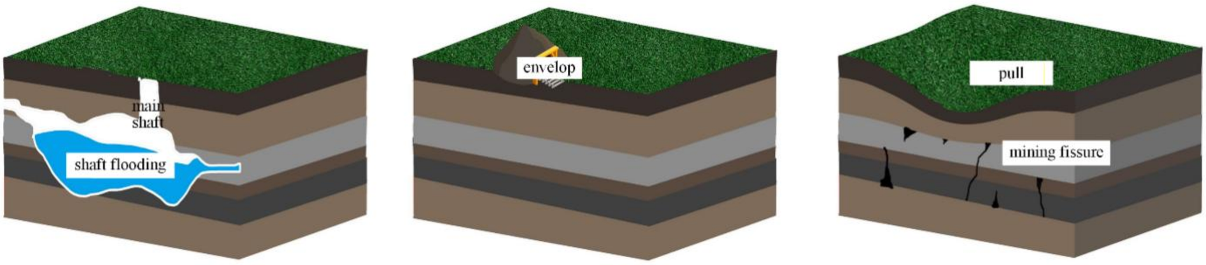
The residual methane content is determined by the residual methane content calculation method provided in AQ1018-2006, and the methane emissions from abandoned mines can be obtained:

$$E_{ab} = (Q_1 \times W_C + Q_2 \times W_0) \times \rho_{CH_4} \times \gamma \tag{13}$$

In the formula :

γ is the correction coefficient, dimensionless.

The value of the correction coefficient depends on the different conditions of the mine, and the specific value of can be divided into three categories. The specific classification of mines is shown in Figure 2.



(a)Shaft flooding

(b)The development degree of mining fracture is poor and the wellhead sealing is strict.

(c)There are obvious subsidence or cracks on the surface.

Figure 2. Schematic Diagram of Mine Condition Classification

1)Flooded Mines

After the mine is closed, with the shutdown of drainage and ventilation facilities, the internal environment of the mine pit gradually transitions from an oxidizing environment to a partially oxidizing and partially reducing system, and finally forms a fully reducing environment, as shown in Figure 2(a). At this time, the value of is 0.

2)Poor Development of Mining-induced Fractures and Tight Wellhead Sealing

Mining-induced fractures are caused by the abutment pressure in front of the coal wall, often forming 5~15 meters ahead of the coal wall, and are usually parallel to the working face direction and inclined to the coal wall[19]. When the working face advances towards the direction of the joint fractures, the pressure fractures often intersect with the joint fractures, as shown in Figure 2(b). Therefore, the value of is 0.

3)Obvious Surface Subsidence or Good Development of Mining-induced Fractures

Surface subsidence is the ground deformation caused by the caving of the roof of the underground goaf, as shown in Figure 2(c). The research results of scholars show that the methane emissions from abandoned underground coal mines should account for 1~2% of the total emissions. At this time, the value of is between 0.0017 and 0.0035, so the value is determined by the development degree of surface fractures.

4. CASE APPLICATION

Fangzhuang Mine in Jiaozuo, Henan Province was closed in 2017. The mining area contains 16 coal seams with a total thickness of 12.33 m and a mineable coal seam thickness of 8.40 m. The main mineable and partially mineable coal seams in the area include No. 2-1 coal of the Shanxi Formation and No. 1-2 and No. 1-1 coal of the Taiyuan Formation. Among them, No. 2-1 coal is the currently mined coal seam in the mine. The burial depth of No. 2-1 coal seam is 50~796 m, the coal thickness is 1.50~7.12 m, with an average of 4.96 m. The coal seam is fully mineable. By 2017, when the mine was closed, the cumulative developed resource volume of the mine was about 9.5172 million t, the undeveloped resource volume was about 17.7058 million t, and the total remaining coal volume of the mine was about 2.3793 million t. The resource development status of Fangzhuang Mine is shown in Table 2.

Table 2. Overview of Resource Development in Fangzhuang Mine

	Cut-off Date	Resource Volume/10,000t	Recovery Rate	Output/10,000t	Remaining Coal Volume/10,000t
Developed	2009	780.4	75.0%	585.3	195.1
	2010~2017	171.32	75.0%	128.49	42.83
Undeveloped	2009	1941.9			
	2010~2017	1770.58			

No measurements were carried out in the drilling holes in the exploration area of Fangzhuang Coal Mine, so the average estimation method was used to calculate methane emissions during this stage; since the mine is not a high-yield and high-efficiency mine, the methane extraction emissions were calculated according to the formula in the Basic Indicators for Coal Mine Methane Extraction; the methane emissions from the ventilation system were accounted for according to the method with continuous methane monitoring conditions; during the resource survey process, no relevant tests were carried out in some goafs, and there were no measured data on methane-related parameters in the goafs, making it difficult to conduct an accurate assessment. Secondly, in the calculation of the goaf volume, without advance detection, it is difficult to judge the influence range of groundwater on the roadway, and it is impossible to accurately obtain its influence on the roadway. Therefore, the overall estimation method was adopted for the accounting of methane emissions from abandoned mines.

In summary, calculated by Formula (4), is 11.48 t; calculated by Formula (6), is 8660.6 t; calculated by Formula (8), is 9169 t; calculated by Formula (11), is 2152 t; calculated by Formula (13), is 257 t. Therefore, the total methane emissions from Fangzhuang Mine throughout the whole life cycle from 2010 to 2017 calculated by Formula (1) is 17745.99 t.

According to the whole life cycle theory, the proportions of methane escape in the four stages are 0.07%, 79.08%, 19.35%, and 1.5% respectively. The proportion of methane emissions is shown in Figure 3. Referring to the data on the proportion of coal mine methane emission sources in different years calculated by the T3 method, it is very close to the proportion of methane emissions at each stage obtained by this method. Among them, the coal mining stage is still the main source of methane emissions, accounting for about 80% of the whole life cycle of underground coal mines. Therefore, the mining stage is the key to promoting methane energy conservation, emission reduction, and low-carbon environmental protection. It further verifies the rationality of the calculation method for total methane emissions from coal mines throughout the whole life cycle, which is helpful for the refined accounting of methane emissions from underground coal mines.

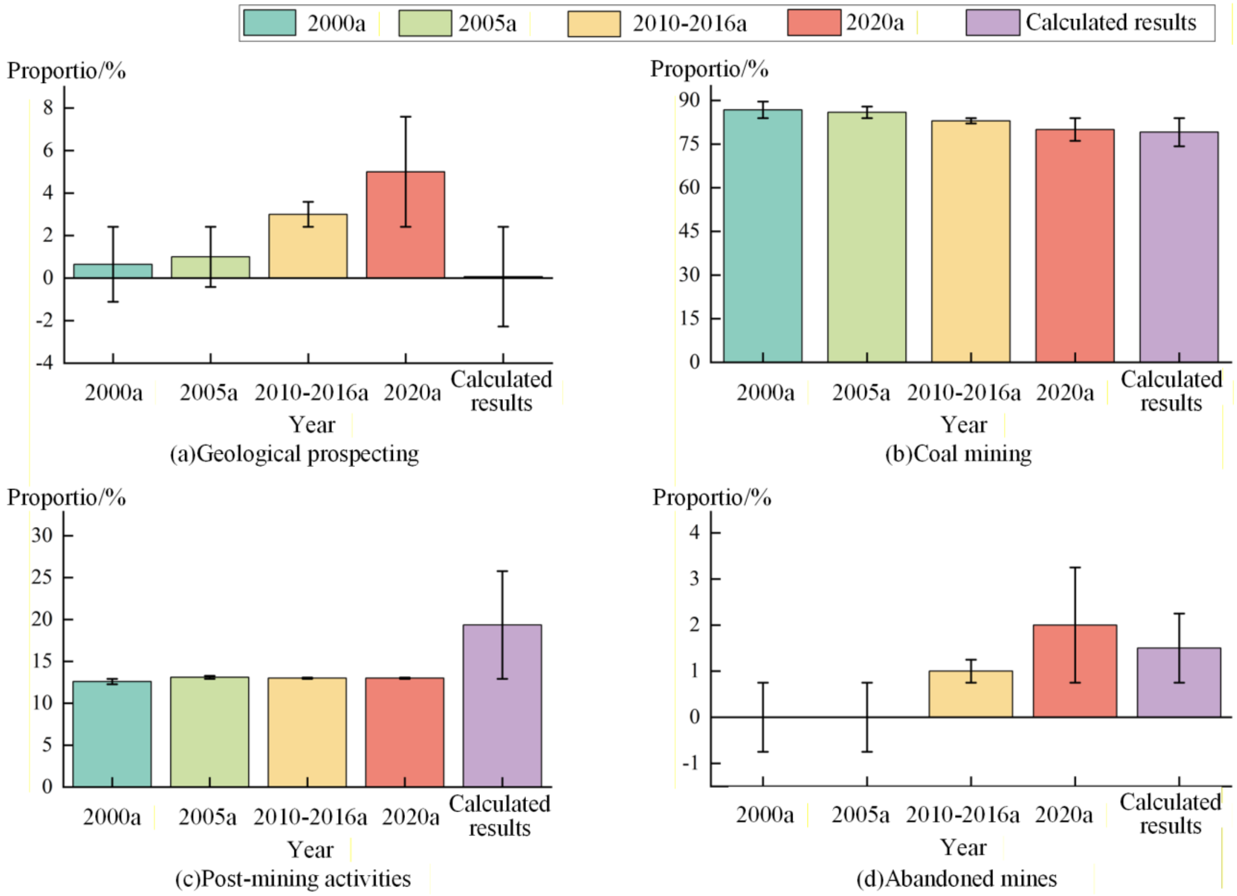


Figure 3. Comparison Chart of Methane Emission Composition of Fangzhuang Mine Throughout the Whole Life Cycle from 2010 to 2017 and Recent Data

5. CONCLUSIONS

(1) Based on the whole life cycle analysis framework and combined with the carbon source distribution characteristics of underground coal mines, a method for accounting methane emissions throughout the whole life cycle of underground coal mines from geological exploration, coal mining, post-mining activities to abandoned mines was constructed. According to the differences in the acquisition of the number of drilling holes and methane emission factors, the methane emission methods during the geological exploration stage are divided into two categories: regional estimation method and average estimation method; three methane accounting methods for the extraction system are proposed; the acquisition of roadway air volume data is the key to calculating methane emissions from the ventilation system; the overall estimation method for abandoned mines is optimized according to the classification of different mine conditions.

(2) The total methane emissions from Fangzhuang Mine in Jiaozuo, Henan Province throughout the whole life cycle from 2010 to 2017 were accounted for. The research shows that the methane emission from the coal mining link accounts for about 80% of the total emissions, which is consistent with the historical methane emission law of China's coal mines revealed by the evaluation results based on the T3 method. The new accounting model can more accurately quantify the methane emissions from underground coal mines throughout the whole life cycle.

(3) By establishing the accounting method for methane emissions throughout the whole life cycle of underground coal mines, it is shown that the mining stage is the main source of coal mine methane

emissions, and targeted measures for efficient methane emission reduction and greenhouse effect mitigation can be formulated.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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