Prospect analysis of high temperature air combustion technology for low calorific value coalbed methane in Liupanshui area of Guizhou province

Yu Zhou¹, Xiaowei Ji¹ and Jie Tang¹

1 Liupanshui Normal University, College of Electrical Engineering, Department of Energy and Power Engineering, Liupanshui
E-mail: zhu_yu_86@163.com/86_zhyu@tongji.edu.cn

Abstract. China’s coalbed methane resource is abundant, which ranks third in the world. The total amount of coalbed methane resources in Guizhou Province accounts for about 10% of China, which ranks second in the country. However, the utilization rate of coalbed methane in Guizhou Province is not only low, but also relatively single, especially the low calorific value coalbed methane extracted from underground mines which has a methane concentration of only 10-30%. And the main method to deal with low calorific value coalbed methane is discharging directly, which caused a huge waste of energy. High temperature air combustion technology (HTAC), which expands the utilization range of low calorific value fuels, has attracted wide attention due to its characteristics of extreme recovery of waste heat and ultra-low NOx emission. In this paper, the characteristics of high temperature air combustion of low calorific value coalbed methane are analyzed by theoretical and numerical calculation based on combustion theory and CFD method.

1. General situation of low calorific value coalbed methane in Liupanshui area
Coalbed methane (CBM), commonly known as "gas", refers to hydrocarbon gas [1-2], which is stored in coal seams, mainly composed of methane, adsorbed on the surface of coal matrix particles, partially free from coal pore or dissolved in coal seam water. It belongs to unconventional natural gas, and is a clean, high-quality energy and chemical raw material rising internationally in recent decades. At present, the global CBM reserves are about 124.8 trillion m³, 90% of which are distributed in 12 major coal-producing countries. China's CBM reserves are about 30-35 trillion m³, ranking third in the world [3-5]. The total amount of CBM resources in Guizhou Province is 3.15 trillion m³, accounting for about 10% of the country, ranking the second in the country, after Shanxi [6-7]. Coalbed methane resources in Guizhou Province are mainly distributed in Liupanshui, Zhiba and Northern Guizhou coalfields, accounting for 92.8% of the total coalbed methane resources in Guizhou Province [8-9].

According to statistics, the total amount of gas extracted from underground coal mines in Guizhou in 2009 is 674 million m³, of which 83.92 million m³ is used for power generation and as civil fuel. The utilization rate of gas in Guizhou Province is only 12.4%, most of which are discharged into the air as exhaust gas. In 2011, the utilization rate of Coalbed methane in Guizhou Province is 16% [10]. In 2016, the gas extraction rate in Guizhou Province is 231311.91 million m³, and the utilization rate is 78711.34 million m³. The utilization rate is only 34%, of which the utilization of gas power generation is 76726.83 million m³, accounting for 97.5% [11] of the total utilization. From the above statistics, not only the utilization rate of CBM in Guizhou Province is low, but also the utilization form is
relatively single, the main way of utilization is gas power generation, a small amount of which is used for civilian use.
At present, the way of CBM exploitation in Guizhou Province is mainly underground extraction, supplemented by surface extraction [12-13]. The concentration of methane in underground extraction CBM is only 10-30% which cannot meet the requirements of direct utilization, so it must be discharged into the atmosphere, resulting in huge energy waste. Take 2016 as an example, the annual CBM extraction volume in China is 173 billion m$^3$, of which underground gas extraction is one. With a utilization of 128 billion m$^3$ and a utilization of 48 billion m$^3$, the utilization rate is 37.5%, while the surface coalbed methane production is 45 billion m$^3$ and utilization of 42 billion m$^3$, the utilization rate is 93.3%. Therefore, it is of far-reaching significance to study how to utilize the low calorific value coalbed methane extracted from underground mine, improve the utilization rate of coalbed methane and turn waste gas into useful resources to alleviate the current energy shortage and optimize the energy structure.

2. High temperature air combustion technology
High temperature air combustion technology, also known as regenerative combustion technology, is a new type of combustion technology widely applied in developed countries since 1990s. Fig. 1 illustrates the principle of HTAC technology. The system consists of a pair of burners, regenerators, reversing valves and corresponding control systems. When the combustion-supporting air is fed by B burner, the air at ambient temperature is heated by the preheated high-temperature regenerator in B burner, then injected into the furnace and combusted with gas. After heat exchange in the furnace, the combustion-supporting air is discharged by A burner, the regenerator in A burner is heated at the same time. After appropriate time, through the switching function of the reversing valve, the combustion-supporting air is supplied by A burner, and the smoke is exhausted by B burner, so that the heat storage and heat release process can be completed again and again.

**Figure 1** Schematic diagram of regenerative combustion technology
HTAC technology alternately stores heat and exhausts smoke through pairs of regenerative burners. The high temperature flue gas is strongly disturbed in the furnace and constantly changes its direction, which makes the temperature distribution in the furnace very uniform and avoids the appearance of local high temperature. At the same time, due to the regenerator's regenerative effect, the limit recovery of waste heat and the preheating of air are realized, the preheated air temperature usually can reach 1000 ~ 1400°C, which can save nearly 50% of the fuel [14] compared with the traditional combustion mode. In addition, in industrial furnaces using HTAC technology, fuel is burned in combustion-supporting air with oxygen concentration less than 21% through the organization of combustion conditions, thus reducing the production of NOx and environmental pollution.

3. Combustion theory calculation
3.1. Composition of coalbed methane

Based on the investigation of CBM storage status in southwestern Guizhou, this paper chooses several typical areas such as Jinjia mining area, Songsha mining area and Xingyi Chaoyang mining area for calculation and analysis. Among them, Jinjia mining area and Songsha mining area belong to Liupanshui. The composition of CBM in each area is shown in Table 1. The calculation results of low calorific value and high calorific value are also listed in the table. It can be seen that the coalbed methane in the above areas belongs to low calorific value fuels.

|                       | Jinjia Mining Area | Songsha area | Chaoyang Mining Area, Xingyi |
|-----------------------|--------------------|--------------|------------------------------|
| **CH₄**               | 20%                | 25%          | 30%                          |
| **N₂**                | 63%                | 61.5%        | 45.86%                       |
| **CO₂**               | 10.5%              | 2.2%         | 11.24%                       |
| **C₂H₆**              | 2.5%               | 3%           | 2%                           |
| **C₃H₈**              | 1.5%               | 0%           | 1.5%                         |
| **C₄H₁₀**             | 1%                 | 0%           | 0%                           |
| **CO**                | 0%                 | 6%           | 0%                           |
| **O₂**                | 0%                 | 0.6%         | 0%                           |
| **Other**             | 1.5%               | 1.7%         | 1.5%                         |
| **Hᵢ (kJ/m³)**        | 10831.5            | 11099        | 12519                        |
| **Hₘ (kJ/m³)**        | 11930              | 12200.6      | 13789                        |

3.2. Explosion Limit

Explosion limit means that combustible materials and air must be uniformly mixed in a certain concentration range to form premixed gases and explode when confronted with fire source. The explosion limit is calculated by the following empirical formula.

\[ L_{\text{lower}} = \frac{100}{4.76(n-1)+1} \times 100\% \]  \( (1) \)

\[ L_{\text{upper}} = \frac{4 \times 100}{4.76n+4} \times 100\% \]  \( (2) \)

In which: \( L_{\text{lower}} \) -- the lower explosion limit for combustible mixtures;
\( L_{\text{upper}} \) -- the upper explosion limit for combustible mixtures;
\( n \) -- number of oxygen atoms required for complete combustion of 1 mol combustible gas.

The explosion limits of coalbed methane in Jinjia mining area, Songsha mining area and Chaoyang mining area in Xingyi are calculated. As shown in Table 2, the concentration of methane in low calorific value coalbed methane ranges from 20% to 30%, the explosion limit ranges from 11% to 48%, the explosion range is large. The explosion limit range is the smallest when the concentration of methane in coalbed methane is 25%.

|                       | Jinjia Mining Area | Songsha area | Chaoyang Mining Area, Xingyi |
|-----------------------|--------------------|--------------|------------------------------|
| **L_{\text{lower}}**  |                    |              |                              |
| **L_{\text{upper}}**  |                    |              |                              |
3.3. Calorimeter temperature

A certain proportion of gas and air combustion, the heat includes two parts: one is the physical heat of gas and air (enthalpy of gas and air); the other is the chemical heat of gas (calorific value). If the combustion process is carried out under adiabatic condition, the two parts of heat are all used to heat the flue gas itself, the temperature that the flue gas can reach is called calorimeter temperature, and is calculated by formula (3).

$$t_\alpha = \frac{H_f + (c_g + 1.266c_{H_2O}d_g)T_g + \alpha V_a(c_a + 1.266c_{H_2O}d_a)T_a}{V_{H_2}c_{H_2} + V_{H_2O}c_{H_2O} + V_{N_2}c_{N_2} + V_{O_2}c_{O_2}}$$  (3)

In which: $H_f$--Low calorific value of gas, kJ/m$^3$ (dry gas);
$\alpha$--Excess air coefficient;
$c_g$, $c_{H_2O}$, $c_a$, $c_{N_2}$, $c_{O_2}$--The average volume constant pressure heat capacities of gas, H$_2$O, air, triatomic gas, N$_2$ and O$_2$ from 0 to $t_f$℃, kJ/(m$^3$·k), respectively.
$t_g$, $t_a$--Gas and air temperature, ℃;
$V_0$--Theoretical air requirement, m$^3$ (dry air)/m$^3$ (dry gas);
$V_{H_2}$, $V_{H_2O}$, $V_{N_2}$, $V_{O_2}$--The volume of triatomic gas, water vapor, N$_2$, O$_2$ produced by fully burning 1 m$^3$ dry gas, m$^3$/m$^3$ (dry gas);
$d_a$, $d_g$--The moisture content of air and gas, kg/m$^3$ (dry air).

If the moisture content of air $d_g$=10g/m3 (dry air), and the moisture content of coalbed methane is not counted. The calculating results of calorimeter temperature after complete combustion of coalbed methane at air temperature 1073K, 1173K and 1273K in three regions are shown in Table 3.

| Air temperature (K) | Jinjia Mining Area | Songsha area | Chaoyang Mining Area, Xingyi |
|---------------------|--------------------|--------------|-----------------------------|
| 1073                | 2260               | 2314         | 2321                        |
| 1173                | 2263               | 2369         | 2381                        |
| 1273                | 2385               | 2427         | 2439                        |

From Table 3, when the combustion-supporting air temperature is 1023K, the calorimeter temperature of low calorific value coalbed methane in three mining areas can reach more than 2000K. With the increase of air temperature and methane concentration, the calorimeter temperature shows an upward trend, and the influence of air temperature on combustion temperature is more obvious of methane concentration.

4. Numerical simulation and comparative analysis with the theory calculation

The combustion process of low calorific value coalbed methane is simulated by CFD method. Assuming that the fuel is burned in a circular tube, the diameter is 200 mm, the length is 600 mm, the size of the gas and air inlets are 10 mm and 20 mm respectively, the air inlets are evenly arranged around the gas inlets, and the wall condition is adiabatic, the model is simplified to two-dimensional. The geometric structure and meshing of the model are shown in Figure 2. The model is meshed with structured grid, the mesh of air and gas inlets are partially densified.
Taking Jinjia Coal Mine as an example, assuming that the inlet temperature of air is 1073K, the velocity is 2 m/s, the inlet temperature of gas is 300K and the velocity is 5 m/s, the steady-state numerical simulation of combustion process is carried out by using Eddy-Dissipation combustion model. The numerical results of combustion temperature, CH$_4$, O$_2$ and CO distributions are shown in Fig. 3-5 respectively.

From Fig. 3, the outlet temperature of flue gas is 2180 K, the theoretical calculation value is 2260 K, and the error is 3.5%. The numerical simulation results are in good agreement with the theoretical calculation results. The numerical simulation results are slightly lower than the theoretical calculation values. The main reasons for the error are: (1) the loss of chemical incomplete combustion and the decomposition of flue gas components at high temperature are neglected in theoretical calculation; (2) The combustible components other than methane such as ethane in coalbed methane are neglected in numerical simulation.

From Fig. 4 to Fig. 5, the concentration of CH$_4$ and O$_2$ at the exit are close to 0, indicating that CBM and air are close to complete combustion, so does the CO concentration in Fig. 6.
Similarly, the numerical results of low calorific value coalbed methane in Songsha area and Chaoyang mining area in Xingyi are shown in Table 4, the numerical simulation value is always lower than the theoretical calculation value. The cause of the error has been analyzed in the previous part, and it will not be mentioned here. In addition, the higher the methane content in coalbed methane, the smaller the error between calculated and simulated values, and the error is within the allowable range.

Table 4 Comparison of theoretical and simulated combustion temperatures.

|                | Theoretical calculation value | Numerical simulation | relative error |
|----------------|-------------------------------|----------------------|----------------|
| Jinjia Mining Area | 2260K                         | 2180K                | 3.5%           |
| Songsha area    | 2317K                         | 2274K                | 1.8%           |
| Chaoyang Mining Area, Xingyi | 2326K                       | 2304K                | 0.9%           |

5. Conclusion

In view of the present situation of rich CBM resources but low utilization rate, especially low calorific value CBM in Guizhou Province, combined with the characteristics of high temperature air combustion technology, the feasibility of applying high temperature air combustion technology to low calorific value CBM is analyzed theoretically and numerically in this paper.

(1) Through the investigation of Jinjia mining area, Songsha mining area and Xingyi Chaoyang mining area, most of the coalbed methane content is below 30%, which belongs to low calorific value fuel.

(2) When the concentration of methane in low calorific value coalbed methane ranges from 20% to 30%, the explosion limit ranges from 11% to 48%, the explosion limit range is large, and the explosion limit range is the smallest when the concentration of methane in coalbed methane is 25%.
(3) The theoretical calculation and numerical results of combustion of low calorific value CBM in high temperature air state are similar. When the temperature of combustion-supporting air is 1073K, the calorimeter temperature of combustion of low calorific value coal bed methane in three mining areas can reach more than 2000K. With the increase of air temperature and methane concentration, the calorimeter temperature shows an upward trend, and the influence of air temperature is more significant with the increase of the concentration of methane.

(4) The application of high temperature air combustion technology in the utilization of low calorific value CBM in Liupanshui area of Guizhou Province has a very broad prospect.

6. References

[1] Xie Wei, He Ting, Yang Ming, et al. Features and recovery technology of coal-bed gas in Guizhou[J]. Drilling and Production Technology, 2011, 34 (3): 58-60.
[2] Li Bobo, Yuan Mei, Ma Kewei. The utilization of methane and the analysis of influencing factors in Guizhou province [J]. Coal Mine Modernization, 2009 (5): 4-5.
[3] Tao S, Pan ZJ, Tang SL, Chen SD. Current status and geological conditions for the applicability of CBM drilling technologies in China: A review[J]. International Journal of Coal Geology, 2019.
[4] Qin Y, Tang X Y, Jian-Ping Y E, et al. Characteristics and Origins of Stable Carbon Isotope in Coalbed Methane of China[J]. Journal of China University of Mining & Technology, 2000, 29(2):113-119.
[5] Fu H, Tang D, Hao X, et al. Geological characteristics and CBM exploration potential evaluation: A case study in the middle of the southern Junggar Basin, NW China[J]. Journal of Natural Gas Science & Engineering, 2016, 30:557-570.
[6] Li S, Tang D, Pan Z, et al. Evaluation of coalbed methane potential of different reservoirs in western Guizhou and eastern Yunnan, China[J]. Fuel, 2015, 139:257-267.
[7] P Ren, H Xu, D Tang, Y Li, Z Chen, et al. Pore structure and fractal characterization of main coal-bearing synclines in western Guizhou, China[J]. Journal of Natural Gas Science and Engineering, 2019.
[8] Zhang Chunpeng, Wu Caifang, Li Teng, et al. Principal Component Analysis Method applied to evaluation on coalbed methane block selection [J]. Coal Science and Technology, 2016, 44 (08): 137-142.
[9] Gao Di. The prospect of 3 trillion cubic meters CBM development in Guizhou Province is vast [J]. Contemporary Guizhou, 2010 (20): 68-69.
[10] Huang Pei. Geological conditions and development and utilization situation of coal bed methane in Guizhou Province[J]. Clean Coal Technology, 2011, 17 (5): 104-105.
[11] Tang Yong. Present Situation and Foreground of Development and Utilization in Coalbed Methane in Guizhou [J]. Chemical Industry, 2017, 35 (5): 43-45.
[12] Yuan Mei, Li Xijian, Li Bobo, et al. Discussion of present situation of exploitation and utilization of coal bed gas resource in Guizhou Province [J]. Mining and Processing Equipment, 2008 (20): 11-13.
[13] Ma Shu, Luo Yong, Han Shixin, et al. [J]. The analysis of the situations and patterns of ground gas drainage of coal mine in Guizhou of China [J]. China Coal, 2016, 42 (3): 92-96.
[14] Zhou Yu, Qin Chaokui. Application Prospect of Natural Gas Regenerative Combustion Technology in Small-Size Heating Furnace [J]. Industrial Furnace, 2016 (6): 13-15.

Acknowledgments

Financial support for this work was provided by the Guizhou Provincial Education Department Foundation Project: Application study on High Temperature Air Combustion Technology in Low Calorific Value Coalbed Methane in Liupanshui Area (No. Qianjiaohe KY Zi[2018]373) and Research Initiation Fund of Liupanshui Normal University (LPSSYKYJJ201815) and (No.LPSSYKYJJ201814).