Study on the interchangeability between low calorific value coalbed methane blended with hydrogen, dimethyl ether and natural gas

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Abstract. China is rich in coal-bed methane resources, but the utilization rate is very low, especially the low calorific value coal-bed methane, because of its methane concentration cannot meet the requirements of direct utilization, it must be discharged into the atmosphere, resulting in serious energy waste and environmental pollution. In this paper, the interchangeability of hydrogen, dimethyl ether and low calorific value coalbed methane mixtures with natural gas, as well as the influence of blending proportion on the interchangeability were studied by AGA index method and Weaver index method respectively. The results show that: An increasing number of the blending proportion of hydrogen in low calorific value coalbed methane can promote the heat load index and air ejection index to meet the requirements of interchangeability, reduce the tendency of lifting and yellow tipping, increase the tendency of flashback and incomplete combustion; while increasing the blending proportion of methane in low calorific value coalbed methane can also promote the heat load index and air ejection index to meet the requirements of interchangeability, and at the same time, it reduces the tendency of lifting, but increases the tendency of flashback and incomplete combustion, and the possibility of yellow tipping. What’s more, because of the low calorific value of hydrogen, the heat load index is always unable to meet the interchange requirements, the dimethyl ether was introduced into the mixture, and the interchangeability between low calorific value coalbed methane blended with hydrogen, dimethyl ether and natural gas was studied as well. When the blending proportion of hydrogen is controlled at 20%, in order to meet the interchangeability requirements, the blending proportion of dimethyl ether should be controlled to 60%, but some measures should be taken to prevent flashback, such as appropriately reducing the diameter of fire hole.

1. Introduction
Coalbed methane, CBM for short, refers to hydrocarbon gas stored in the coal seam with methane as the main component, mainly adsorbed on the surface of coal matrix particles, and is partially free of coal pores or dissolved in coal bed water which is associated mineral resources of coal. Coalbed methane belongs to unconventional natural gas and is a clean, high-quality energy and chemical raw material that has risen internationally in recent decades. At present, the global coalbed methane reserves are about 124.8 trillion m³, 90% of which are distributed in 12 major coal-producing countries. China's coalbed methane reserves are about 30-35 trillion m³, ranking the third in the world.  

The development of coalbed methane resources is mainly divided into underground extraction and surface extraction. At present, the main method in China is underground extraction, supplemented with surface extraction. The concentration of coalbed methane extracted on the ground is about 95%.
while the methane concentration of underground coalbed methane is only 10%~30%, which belongs to low calorific value coalbed methane, and because the concentration of methane cannot meet the requirements of direct utilization, it must be discharged into the atmosphere, resulting in huge energy waste. Taking 2018 as an example, the annual coalbed methane extraction volume in China was 18.4 billion m³, with a utilization rate of 55.51%, of which the surface coalbed methane production was 5.4 billion m³, with a utilization rate of 90.52%, while the underground gas extraction volume was 13 billion m³, with a utilization rate of only 40.91%, the production and utilization rate of coal bed methane in China from 2012 to 2018 was shown in Table 1. Reasonable using coal bed methane, increasing the utilization rate of this high-quality clean new energy, and turning waste gas into a useful resource has an important significance on the optimization of energy structure, reduction exhausting of greenhouse gas, lightening the air pollution and fundamentally solving coal mine safety problems.

Table 1 production and utilization rate of coal bed methane in China from 2012 to 2018

| Year | CBM production (bcm) | Utilization rate(%) | Ground development (bcm) | Utilization rate(%) | Underground extraction(bcm) | Utilization rate(%) |
|------|----------------------|---------------------|--------------------------|---------------------|-----------------------------|---------------------|
| 2012 | 14.1                 | 41.13               | 2.7                      | 74.07              | 11.4                        | 33.33               |
| 2013 | 15.6                 | 42.31               | 3                        | 76.67              | 12.6                        | 34.13               |
| 2014 | 17                   | 45.29               | 3.7                      | 86.49              | 13.3                        | 33.83               |
| 2015 | 18                   | 47.78               | 4.4                      | 86.36              | 13.6                        | 35.29               |
| 2016 | 17.9                 | 49.16               | 4.5                      | 84.44              | 13.4                        | 37.31               |
| 2017 | 17.8                 | 52.31               | 5                        | 88.73              | 12.8                        | 38.2                |
| 2018 | 18.4                 | 55.51               | 5.4                      | 90.52              | 13                          | 40.91               |

Note: bcm is billion cube meters. Hydrogen Energy refers to the chemical energy released by the chemical reaction of hydrogen and oxygen. It is a clean secondary energy with the advantages of high energy density, zero pollution, and zero carbon emissions. It is known as the "the ultimate energy of 21st century". As a feasible technical route to promote the global energy transition, hydrogen energy has gradually become a hot topic in the world's energy field. From European and American governments to the International Energy Agency and other important international organizations, all have high hopes for the hydrogen energy economy. In the main tasks of the 2020 National Economic and Social Development Plan, China also proposed the formulation of a national hydrogen energy industry development strategic plan for the first time and many provinces have included hydrogen energy in the 14th Five-Year Plan.

In this paper, the AGA and Weaver index method are used to analyze the interchangeability of the mixture of low-calorific value coalbed methane blended with hydrogen and natural gas through theoretical calculation methods to study the influence of blending hydrogen in low calorific value coalbed methane on the interchangeability and provide theoretical foundation for the experimental study and utilization of the mixtures of coalbed methane with hydrogen. What's more, because of the low calorific value of hydrogen, the heat load index is always unable to meet the interchange requirements, the dimethyl ether was introduced into the mixture, and the interchangeability between low calorific value coalbed methane blended with hydrogen, dimethyl ether and natural gas was studied as well.

2. Gas interchangeability

Gas interchangeability means the ability to substitute one gaseous fuel for another in a combustion application without materially changing operational safety, efficiency, performance, or materially increasing air pollutant emissions. At present, the main methods used to predict gas interchangeability in China are index method, including AGA index method and Weaver index method. AGA index method includes three exchange indexes of lifting index $I_L$, flashback index $I_F$ and yellow tipping index $I_Y$, which was proposed by the American Gas Association (AGA) in 1946 and re-corrected by the American Gas Institute (GRI) in the 1980s; while the Weaver index method includes six determination indexes of heat load index $J_H$, air ejection index $J_A$, flashback index $J_F$, lifting index $J_L$, CO emissions
index $J_I$ and yellow tipping index $J_Y$, which was proposed by Elmer R. Weaver combined AGA research method in 1951. The calculation method of each index and the exchange range concluded by comparing the experimental results and calculation results are shown in Table 2.

### Table 2 The AGA indexes and Weaver indexes

| AGA indexes | Calculation formula | Exchange range | Weaver indexes | Calculation formula | Exchange range |
|-------------|---------------------|----------------|---------------|---------------------|----------------|
| $I_L$       | $I_L = \frac{K_a}{f_a \log (100 / f_a)}$ | $< 1.0$        | $J_H$         | $J_H = \frac{W_a}{W}$ | $0.95 \sim 1.05$ |
| $I_F$       | $I_F = \frac{H_f}{K_f \sqrt{3.994}}$ | $< 1.18$       | $J_F$         | $J_F = \frac{S_n + 1.54 V_0 + 0.4}{V_0 \sqrt{H_s}}$ | $< 0.08$ |
| $I_Y$       | $I_Y = \frac{f_a Y_a}{s_a Y}$ | $> 1.0$        | $J_L$         | $J_L = \frac{S_n V_0 \sqrt{3.994}}{(100 - O_2)}$ | $> 0.64$ |
|             |                     |                | $J_I$         | $J_I = \frac{V_0 \sqrt{3.994} R - 0.634}{R_y}$ | $< 0$ |
|             |                     |                | $J_Y$         | $J_Y = \frac{V_0 S_n}{V_0 S_n + N_y - N_x - 110}$ | $< 0.14$ |

In the formula, $K$ is the lifting limit constant; $f$ is the primary air factor; $a$ is the theoretical amount of air consumed for each $105 KJ$ of heat released by the complete combustion of the gas fuel; $H$ is the high calorific value of the gas; $Y$ is the yellow tipping limit constant; $W$ is the Wobbe index; $V_0$ is the theoretical air volume; $s$ is the relative density; $O_2$ is the volumetric composition of oxygen in the fuel gas; $S_f$ is the flame speed index; $N$ is the number of carbon atoms that are easily precipitated when burning in every $100$ fuel gas molecules; $R$ is the ratio of hydrogen atoms in the fuel gas to the number of carbon atoms in the hydrocarbon. The subscripts $a$ and $s$ represent the reference gas and the replacement gas, respectively.

### 3. Results and discussion

The total amount of coal-bed methane resources in Guizhou Province is $3.15$ trillion $m^3$, accounting for about $10\%$ of China, ranking only second to Shanxi. CBM resources in Guizhou Province are mainly distributed in Liupanshui coal field, Zhina coal field, and Qianbei coal field, accounting for $92.8\%$ of the province’s CBM resources[14]. In this paper, a representative coal mine in Panzhou City, Liupanshui is selected as the object to investigate the composition of coalbed methane extracted from underground mines. The results are shown in Table 3. The high and low calorific values of coalbed methane are $11930 KJ/m^3$ and $10832 KJ/m^3$, respectively. Low calorific value coalbed methane. The civil natural gas in Guizhou area is mainly transported to various places by the Guiyang gas transmission station. According to the gas quality analysis report, the composition of natural gas is shown in Table 4.

### Table 3 Volume composition of coalbed methane in a mining area of Panzhou City, Guizhou Province

| Component | CH₄ | C₂H₆ | C₃H₈ | C₄H₁₀ | N₂ | CO₂ | Other |
|-----------|-----|------|------|-------|----|-----|-------|
| Volume composition(%) | 20  | 2.5  | 1.5  | 1.0   | 63 | 10.5| 1.5  |

### Table 4 Volume composition of natural gas in Guizhou

| Component | CH₄ | C₂H₆ | C₃H₈ | C₄H₁₀ | C₅⁺ | N₂ | CO₂ |
|-----------|-----|------|------|-------|-----|----|-----|
| Volume composition(%) | 96.7982 | 0.9374 | 0.1313 | 0.0233 | 0.0172 | 0.8075 | 1.2575 |
Table 5 shows the AGA and Weaver results of interchangeability of low-calorific value coalbed methane blended with hydrogen and natural gas. Whether it is the AGA index or the Weaver index, with the hydrogen blending proportion increase from 10% to 95%, the phenomenon of flashback occurs when the blended gas of CBM and H$_2$ is interchanged with natural gas, and the more the hydrogen blended, the more serious the phenomenon is. This is because the flame propagation speed of hydrogen is greater than that of methane, and it indicated the consistency of AGA index and the Weaver index on the other hand; at the same time, whether it is the AGA index or the Weaver index, with the hydrogen blending proportion increase from 10% to 95%, there is no yellow tipping occurs when the blended gas of CBM and H$_2$ is interchanged with natural gas, but the AGA index shows that the more difficult it is as the proportion of hydrogen blending increases, while the Weaver index does not change much or even shows the opposite trend. According to the property of hydrogen, the AGA index method is more accurate in the estimate of yellow tipping; while the blending proportion of hydrogen is small, the phenomenon of lifting occurs when the blended gas of CBM and H$_2$ is interchanged with natural gas. This is also due to the difference in flame propagation speed of hydrogen and methane. As we all known, the flame propagation speed of hydrogen is about 5 times that of methane. According to the Weaver index, when the hydrogen blending proportion reaches 45%, the lifting phenomenon disappears, while according to the AGA index it barely disappears until the hydrogen blending proportion increased to 80%, the AGA index is obviously harsher than the Weaver index in the estimate of lifting.

Compared with the AGA index, the Weaver index increases extra index which related to heat load, air ejection and incomplete combustion. With the increase of the hydrogen blending proportion, the heat load index also increases, this is mainly due to the blending of hydrogen in low calorific value coalbed methane and the reduction of the content of non-combustible nitrogen at the same time. However, the calorific value of methane is about 3 times that of hydrogen, the blended gas of low calorific value coalbed methane and hydrogen is still cannot interchange with natural gas; For natural gas, the theoretical amount of air required to release the same amount of heat during complete combustion is basically the same, so the primary air coefficient can be inversely proportional to the Wobbe number. Therefore, the difference between the air ejection index and the heat load index is very small. The air ejection index also increases with the increase of the blending proportion of hydrogen, but both are less than 1, indicating that the primary air coefficient increases after replacement. The reason is that the amount of air required for hydrogen combustion is 1/4 of the amount of air required for methane combustion, resulting in excess air; from the results of the incomplete combustion index, no matter what the blending proportion of hydrogen, there is no incomplete combustion occurs when the blended gas of CBM and H$_2$ is interchanged with natural gas.

| Blending proportion of H$_2$(%) | AGA index | Weaver index |
|-------------------------------|-----------|--------------|
|                               | $I_L$     | $I_F$ | $I_Y$ | $J_H$ | $J_A$ | $J_F$ | $I_L$ | $I_I$ | $J_Y$ |
| 10                            | 3.2079    | 1.5407 | 8.4575 | 0.2613 | 0.2540 | 0.8055 | 0.1933 | -0.7019 | -0.6896 |
| 15                            | 3.1045    | 1.5632 | 8.4792 | 0.2684 | 0.2580 | 0.9717 | 0.2407 | -0.6979 | -0.6894 |
| 20                            | 2.9943    | 1.5881 | 8.5058 | 0.2761 | 0.2625 | 1.1482 | 0.2928 | -0.6934 | -0.6888 |
| 25                            | 2.8767    | 1.6158 | 8.5384 | 0.2845 | 0.2674 | 1.3358 | 0.3504 | -0.6885 | -0.6877 |
| 30                            | 2.7515    | 1.6468 | 8.5789 | 0.2937 | 0.2729 | 1.5357 | 0.4143 | -0.6830 | -0.6861 |
| 35                            | 2.6180    | 1.6816 | 8.6295 | 0.3038 | 0.2791 | 1.7492 | 0.4856 | -0.6768 | -0.6838 |
| 40                            | 2.4760    | 1.7209 | 8.6932 | 0.3150 | 0.2860 | 1.9775 | 0.5657 | -0.6699 | -0.6807 |
| 45                            | 2.3251    | 1.7657 | 8.7744 | 0.3275 | 0.2939 | 2.2223 | 0.6565 | -0.6620 | -0.6767 |
| 50                            | 2.1648    | 1.8172 | 8.8791 | 0.3416 | 0.3029 | 2.4853 | 0.7601 | -0.6530 | -0.6716 |
| 55                            | 1.9950    | 1.8768 | 9.0159 | 0.3576 | 0.3133 | 2.7686 | 0.8795 | -0.6426 | -0.6651 |
Because of the low calorific value of hydrogen, the heat load index is always unable to meet the interchange requirements. The calorific value of dimethyl ether is higher than that of methane, which is about 1.7 times that of methane. The calorific value of mixed gas can be improved by mixing hydrogen and dimethyl ether. Figure 1 shows the influence of the blending proportion of dimethyl ether on the interchangeability when the blending proportion of hydrogen is 20%, the influence of methane concentration in the mixture is also shown in the figure.

Figure 1 Variation of interchangeability index with the blending proportion of dimethyl ether under different methane content in low calorific value coalbed methane (The abscissa is the blending proportion of dimethyl ether/%)

In the AGA index, when the methane concentration in the coalbed methane remains unchanged, with the increase of the dimethyl ether blending proportion, the lifting index and the yellow tipping index decrease, and the flashback index rises, which reduces the lifting tendency and increases the yellow tipping and flashback tendency. When the concentration of methane in coalbed methane increases, the lifting index, yellow tipping index and flashback index all show a downward trend, which reduces the lifting away and flashback tendency, but increases the possibility of yellow tipping.

In the Weaver index, when the methane concentration in the coalbed methane remains unchanged, except for the flashback index, the other indexes all increase with the increase of the dimethyl ether blending proportion, which is consistent with the influence of the methane concentration in the coalbed methane on the interchangeability. It can promote the heat load index and the air ejection index tend to meet the interchangeability requirements, while reducing the tendency to lifting, but increase the
tendency of flashback and incomplete combustion, and the possibility of yellow tipping. However, in the scope discussed, the incomplete combustion index and yellow tipping index always meet the requirements of interchangeability, but the flashback phenomenon cannot be significantly improved.

In conclusion, when the blending proportion of hydrogen is controlled at 20%, in order to meet the interchangeability requirements, the blending proportion of dimethyl ether should be controlled to 60%, but some measures should be taken to prevent flashback, such as appropriately reducing the diameter of fire hole. If the blending proportion of hydrogen is further increased, the blending proportion of dimethyl ether can be reduced.

4. Conclusions
(1) The AGA index is consistent with the Weaver index in the estimate of flashback, and the AGA index method is more accurate in the estimate of yellow tipping, while in the estimate of lifting, the AGA index is obviously harsher than the Weaver index.

(2) Increasing of the blending proportion of hydrogen in low calorific value coalbed methane can promote the heat load index and air ejection index to meet the requirements of interchangeability, reduce the tendency of lifting and yellow tipping, increase the tendency of flashback and incomplete combustion.

(3) Increasing the blending proportion of methane in low calorific value coalbed methane can also promote the heat load index and air ejection index to meet the requirements of interchangeability, and at the same time, it reduces the tendency of lifting, but increases the tendency of flashback and incomplete combustion, and the possibility of yellow tipping.

(4) when the blending proportion of hydrogen is controlled at 20%, in order to meet the interchangeability requirements, the blending proportion of dimethyl ether should be controlled to 60%, but some measures should be taken to prevent flashback, such as appropriately reducing the diameter of fire hole.

Acknowledgments
This work was supported by Guizhou Provincial Science and Technology Foundation under Grant No. Qiankehejichu-ZK[2021] yiban280; the Young Scientific Talents Growth Project, Department of Education of Guizhou Province under Grant No. qianjiaohe KY Zi [2018]373; the High-level Talents Fund of Liupanshui Normal University under Grant No.LPSSYKYJJ201815.

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