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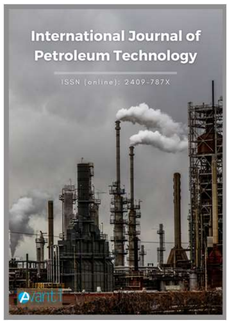

Analysis of Enhancing Coalbed Methane Recovery and Improving Coal Mining Safety by CO_2 Injection: Model of the Critical CO_2 Volume Fraction

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ABSTRACT

Coalbed methane (CBM) is produced before coal mining at the Qinshui Basin in China to utilize CBM and reduce CH_4 volume fraction for coal mining. However, the volume fraction of CH_4 often reaches the range between lower and upper explosion limits after CBM production, which is a great threat to coal mining safety. In previous work, we analyzed the feasibility of injecting CO_2 into coalbeds to control CH_4 volume fraction for mining safety and simultaneously enhancing CBM recovery. In this paper, we extended our work to propose a model to calculate the critical CO_2 volume fraction for CO_2 injection. We simplified the gas mixture during coal mining as the CO_2/CH_4/air mixture. The model of the critical CO_2 volume fraction was then built based on the explosion limit formula for the CO_2/CH_4/N_2 mixture. The formula for the critical CO_2 volume was derived using the critical CO_2 volume fraction. The model of the critical CO_2 volume fraction was applied in a CBM reservoir at the South Shizhuang Block in the Qinshui Basin. The CO_2 injection rate for this block was optimized to obtain the highest CBM recovery using the reservoir simulation method. Results show that the critical CO_2 volume fraction is 7.97%, which makes the CH_4 volume fraction out of the explosion limits. The optimum CO_2 injection rate for this block is 8000m^3/d which improves the CBM recovery up to 86.24%.

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1. Introduction

The Qinshui Basin is the largest coal-producing area in China, which is located in the southeast of Shanxi Province. It is also a black spot of gas explosion in coal mines [1]. To reduce gas explosion accidents and make full use of CBM (coalbed methane) resources, CBM is usually produced before coal mining to avoid unexploited CH_4 emissions into the atmosphere during coal mining. However, the conventional dewatering method for CBM development fails to achieve high recovery. For example, the average CBM recovery in the Qinshui Basin is lower than 55% [2], which tends to induce the CH_4 volume fraction between CBM explosion limits (upper explosion limit and lower explosion limit) [3,4] and leads to a gas explosion in coal mines. To solve these problems, we proposed to use CO_2 injection to prevent a gas explosion and simultaneously enhance CBM recovery in this work [5].

Present explosion prevention technologies include passive explosion prevention technology and automatic explosion prevention technology. The former technology uses rock powder, water mist, porous material, etc., which cannot predict gas explosion and blast waves [6-8], because it works by responding to gas explosion waves. And its fire barrier materials need to be replaced periodically which is severely limited by environmental factors. The latter technology is easily affected by the environment and causes misoperation. It can only separate flame from combustible materials but cannot reduce the pressure and destructiveness of the blast waves [9-11]. Overall these technologies only provide countermeasures when a small-scale explosion has already occurred. They cannot substantially prevent an explosion.

Previous researches showed that CO_2 can reduce flame temperature and combustion velocity of the combustible gas mixture when an explosion occurs [12-17]. So CO_2 can prevent gas explosion when its volume fraction reaches a specific value in CO_2 and CH_4 mixture [18-21]. This CO_2 volume fraction can be acquired through the experiment at different temperatures and pressures, and several researchers have already got their values under different experiment conditions [22-25].

In addition, CO_2 has a strong sorption capability [22,23]. The sorption capacity ratio of CO_2 to CH_4 is typically between 2 and 10 in coalbeds, depending on the thermal maturity of coal [26,27]. During CBM production, due to CO_2 preferential sorption ability, CH_4 is displaced from the coal matrix after CO_2 injection. Meanwhile, the desorption and production of CH_4 are improved due to this replacement process [28-30], which causes the CH_4 volume fraction to be lowered and CBM recovery is enhanced. Besides, CO_2 capturing technology is also one of the most effective measures to control CO_2 emissions. Injecting CO_2 into coalbeds helps to reduce the greenhouse effect.

In this work, we aimed to control CH_4 volume fraction out of explosion limits by injecting CO_2 during CBM production based on CO_2 abilities of explosion prevention and preferential sorption. The model of the critical CO_2 volume fraction was built using explosion limit formulae of $CO_2/CH_4/N_2$ mixture derived by Wang *et al*. [21]. Then we derived the critical CO_2 volume formula using the model of the critical CO_2 volume fraction. In order to achieve the peak CBM recovery during CBM production in the case study, the optimum CO_2 injection rate was determined through the reservoir simulation method.

2. Model of the critical CO_2 volume fraction

To determine the injected CO_2 volume fraction for explosion prevention, CH_4 explosion limits undermining conditions need to be studied. We suppose:

(1) after injecting CO_2, a gas mixture in coalbeds only contains two components: CH_4 and CO_2; after coal mining, the gas mixture in coalbeds is the CO_2/CH_4/air mixture;

(2) injected CO_2 is totally adsorbed on the surface of coal matrix;

(3) the volume of CO_2 production from CBM wells can be ignored.

Wang *et al*. [21] studied the influence of N_2/CO_2 mixture on the explosion of CO_2/CH_4/air mixture. During their research, explosion limits of $CO_2/CH_4/N_2$ mixture were tested with different N_2/CO_2 ratios at 298.15K and 101325Pa. Regression equations for $CO_2/CH_4/N_2$ explosion limits are presented:

$$UEL = \frac{15-\varphi_c\left(\mathrm{CH_4}\right)}{55.75-3.48\varphi_c\left(\mathrm{CH_4}\right)}m+15 \tag{1}$$

$$LEL = \frac{\varphi_c\left(\mathrm{CH_4}\right)-5.3}{23.68\varphi_c\left(\mathrm{CH_4}\right)-130.25}m+5.3 \tag{2}$$

Where m is the volume fraction of N_2/CO_2 in the mixture, %; φ_c (CH_4) is critical methane volume fraction, which can be calculated by (Eq. (3)); *UEL* and *LEL* are the upper explosion limit and lower explosion limit of methane respectively, %.

$$\varphi_c\left(\mathrm{CH_4}\right) = 7.48417-0.01079\varphi\left(\mathrm{N_2}\right) \tag{3}$$

Where φ (N_2) is the N_2 volume fraction in N_2/CO_2 mixture.

Based on Wang *et al*. [21] research, we study the explosion limits of CO_2/CH_4/air mixture.

We suppose that the air volume fraction in CO_2/CH_4/air mixture is *n*, %. The air only contains two components: N_2 and O_2, whose fractions are 79% and 21% respectively. The φ (N_2) can be expressed as:

$$\varphi_c\left(\mathrm{N_2}\right) = 7.48417-0.01079\times\frac{0.79n}{m-0.79n} \tag{4}$$

Therefore in CO_2/CH_4/air mixture:

$$UEL+m+0.21n=100 \tag{5}$$

$$LEL+m+0.21n=100 \tag{6}$$

When the air begins to enter coal mines, the gas explosion can be prevented if the CH_4 volume fraction is less than *LEL*. In this work, we suppose that CH_4 volume fraction is *LEL* when the air starts to enter coal mines, and CH_4 burns completely when exploding (Eq. (7)):

$$CH_4+2O_2=CO_2+2H_2O \tag{7}$$

According to Avogadro law, the air volume fraction is derived based on (Eq. (7)):

$$n = 2\times LEL/0.21 \tag{8}$$

Combining Eqs. (2), (4), (6) and (8), we can obtain the values of φ_c (CH_4), *m*, *n* and *LEL* respectively.

We define the minimum required CO_2 volume fraction for explosion prevention as the critical CO_2 volume fraction. If the CO_2 volume fraction is below the critical CO_2 volume fraction at the end of CBM production, the gas explosion will not occur during the whole coal mining process. The critical CO_2 volume fraction at 298.15K and 101325Pa is expressed as:

$$\varphi_c\left(\mathrm{CO_2}\right) = \frac{m-0.79n}{100} \tag{9}$$

Based on the above equations, the critical CO_2 volume fraction is 7.97% at 298.15K and 101325Pa. The ratio of injected CO_2 volume to in-situ CH_4 volume is 91.2%. To verify the calculated result, we compare it with the experimental result reported by Gant *et al*. [12] from an explosion experiment of CH_4/CO_2/air mixture. Gant *et al*.

[12] investigated the effect of different CO_2 concentrations on the explosion behavior of CH_4/CO_2/air mixture. They found that a concentration of 70% CO_2 made the gas mixture inert and unable to maintain a stable flame. Experimental CO_2 concentration by Gant *et al*. [12] is lower than the calculated ratio of injected CO_2 volume to in-situ CH_4 volume (91.2%). However, in their experiment, air volume exceeded the required volume for explosion by 10%, while our calculation assumes that air volume is equal to the required volume for explosion (Eq. (7)), which is more in accordance with real conditions in coal mines. The air volume fraction in Gant *et al*. [12] experiments is higher than the assumption in our calculation. Because the specific heat of air is larger than CO_2, which induces the higher the specific heat of the gas mixture. Therefore, our results are in accordance with Gant *et al*. [12] experimental results.

During coal mining, the volume fraction of CO_2 changes dynamically and relevant CO_2 volume fraction is difficult to be calculated. But the result calculated in this work meets the requirement of explosion prevention at any air volume fraction. Moreover result from theoretical calculation also approximates the required CO_2 volume fraction in relevant explosion experiments by Ma *et al*. [15] and Wang *et al*. [21], regardless of differences induced by different experimental conditions and calculation assumptions. Overall, these comparisons demonstrate that the critical CO_2 volume fraction can provide a reliable reference for CO_2 injection to prevent gas explosion in coal mines.

To ensure the critical CO_2 volume fraction in the coalbed, the critical CO_2 volume V_c should be guaranteed. The gas mixture in the coal mine is assumed to consist of CO_2, CH_4 and air. Therefore, the critical CO_2 volume is related to the volume of CH_4 after CBM production, the critical CO_2 volume fraction and the air volume fraction. We assume that the original CH_4 volume in coalbed before CBM production is V_o and the ultimate CH_4 cumulative production is V_p. The volume of CH_4 after CBM production V_{res} is given by:

$$V_{\mathrm{res}} = V_{\mathrm{o}} - V_{\mathrm{p}} \tag{10}$$

V_o, V_p and V_{res} are all under the condition of 298.15K and 101325Pa. V_o can be easily obtained through geological data. But V_p needs to be determined by the reservoir simulation method which depends on various factors such as production years, production rate, production expenses, etc. Then based on the concept of CO_2 volume fraction, the critical CO_2 volume V_c can be derived:

$$V_{\mathrm{c}} = \varphi_{\mathrm{c}}\left(\mathrm{CO_2}\right) V_{\mathrm{res}} / LEL \tag{11}$$

(Eq.(11)) is the equation for the critical CO_2 volume. Therefore, the volume of CO_2 V_{inj} should be higher than the critical CO_2 volume V_c to control CH_4 volume fraction below *LEL* (Eq.(12)):

$$V_{\mathrm{inj}} > V_{\mathrm{c}} \tag{12}$$

3. Case study

The Qinshui Basin is a large complex synclinal tectonic basin with an overall north-south direction. In the Qinshui Basin, the coal seam 3# is the main producing layer for natural gas and coal. In this section, we use the model of the critical CO_2 volume fraction at the South Shizhuang Block in the 3# coal seam and built a simulation model to study the application of CO_2 injection to enhance coalbed methane recovery and improve coal mining safety.

3.1. Parameters for simulation

The reservoir simulation software Eclipse was applied to study the optimum CO_2 injection rate. A compositional simulation model was built to describe the multi-component gas mixture. The model size was 500m×500m×10m, using a five-point pattern. The basic data for the South Shizhuang Block was shown in Table **1**. The 3D image of the coalbed model was shown in Fig. **1**. And well spacing was set as follows: one injection well was located at the center of the coalbed to inject CO_2, while four production wells were located around the injection well to produce

CBM. The well spacing between the injection well and the production well was 424.26m, and the well spacing between production wells was 300m.

Table 1: Parameters for modeling

Parameter	value	Parameter	value
Temperature(K)	298.15	CH_4 viscosity(cp)	7.5×10^{-5}
Coalbed thickness(m)	10	Pressure(MPa)	3.5
Coal density(kg/m^3)	1447.5	CH_4 specific density	0.678
Permeability(mD)	5	Diffusion coefficient(m^2/d)	0.022
Gas content (m^3/t)	17	CH_4 Langmuir pressure(MPa)	4.689
Water density(kg/m^3)	990	CO_2 Langmuir pressure(MPa)	1.903
Water compressibility(MPa^{-1})	5.8×10^{-4}	CH_4 Langmuir volume(m^3/t)	11.8
Water viscosity(cp)	0.607	CO_2 Langmuir volume(m^3/t)	24.08

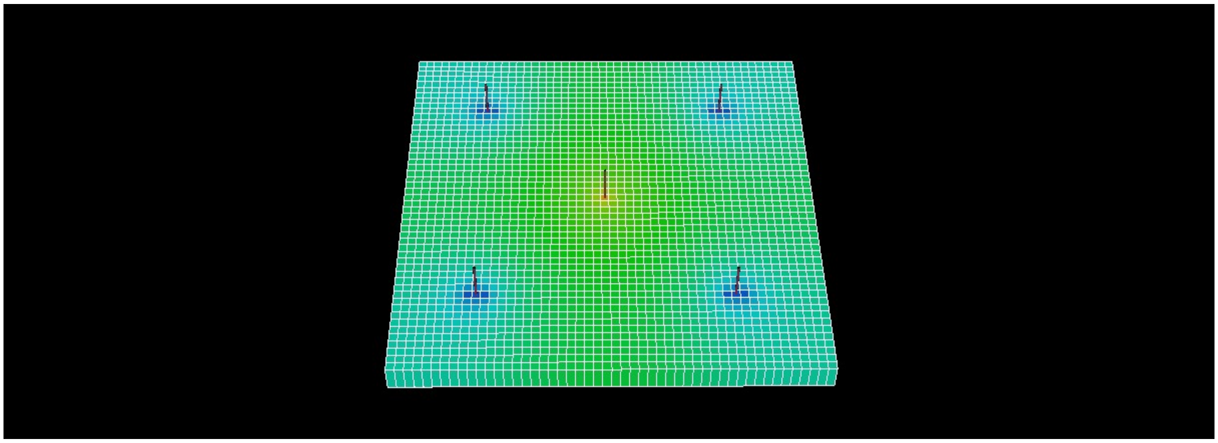

Figure 1: A 3D image of a model for a coalbed with four production wells and one injection well.

3.2. CO_2 injection rate

CO_2 injection rate is defined as the injected CO_2 volume per unit time. The best recovery can be predicted by studying the injection rate of CO_2, which can affect CH_4 desorption and diffusion velocity, further influence CH_4 production and volume fraction in coalbeds. A high CO_2 injection rate leads to the increase of formation pressure which can suppress CH_4 desorption. Moreover, excessive injection rate causes early CO_2 breakthrough at the bottom hole of the production well, which means that the injected CO_2 will be produced directly through the production well and flow much faster in a highly permeable zone. This results in poor development efficiency of CBM. On the contrary, the lower CO_2 injection rate induces insufficient replacement and reduces CBM ultimate recovery. Consequently, an optimum CO_2 injection rate needs to be determined based on CBM recovery.

In order to accurately study the effect of CO_2 injection rate on recovery efficiency, we design six schemes of CO_2 injection rates ranging from 0m^3/d to 10000m^3/d (Table **2**) in the model:

CBM production rate and cumulative production of the following 8 years are predicted through contrasting different CO_2 injection rates, and the results are shown in Figs. **2** and **3**. CBM recovery of different injection rates is presented in Table **3**.

Table 2: Schemes of CO_2 injection rates

Scheme number	CO_2 injection rate(m^3/d)
1	0
2	2000
3	4000
4	6000
5	8000
6	10000

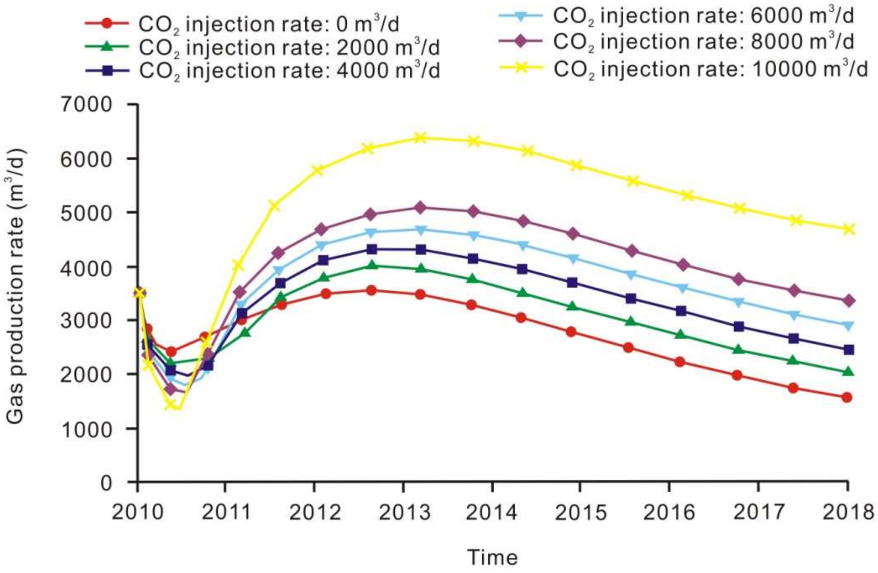

Figure 2: CBM production rate against time at different CO_2 injection rates.

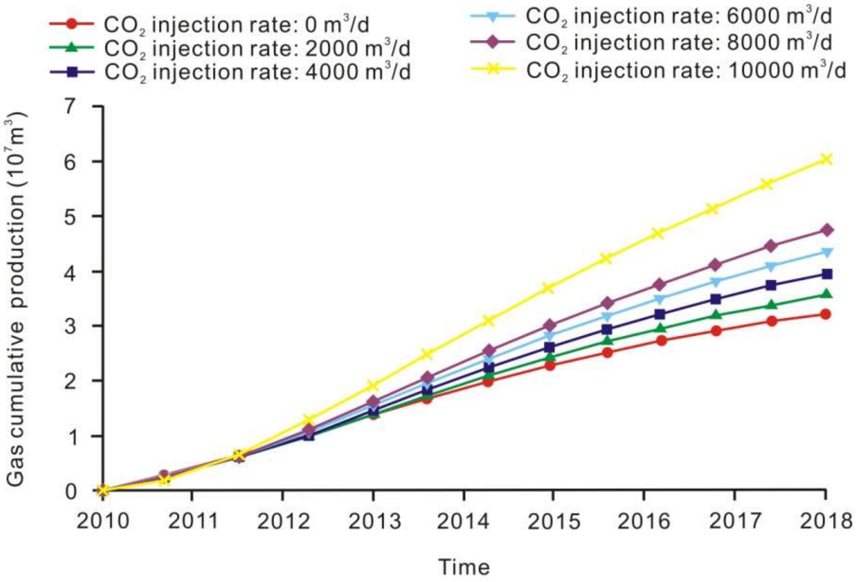

Figure 3: CBM cumulative production against time at different CO_2 injection rates.

Table 3: CBM recovery at different CO_2 injection rates

Scheme number	Recovery (%)
1	58.41
2	64.82
3	71.10
4	78.86
5	86.24
6	109.51

3.3. Discussion

Figs. **2** and **3** indicate that more CH_4 is produced with CO_2 injection than without CO_2 injection, which demonstrates that CO_2 can replace CH_4 on the coal matrix, thus enhancing CBM recovery. Fig. **2** also shows that the gas production rate decreases with the increase of CO_2 injection rate in the early production stage (the first six months). This is because only the free gas is produced, and the injection effect is not obvious due to the short injection time. However in the later production stage (after the first six months), the gas production rate rises with the increase of CO_2 injection rate. At this moment, the injected CO_2 starts to work. The CH_4 adsorbed at coal matrix is gradually desorbed and becomes the free gas with the decrease of the pressure. As the free gas is easy to be produced, the gas production rate rises obviously.

The comparison of recovery between six CO_2 injection rates is shown in Table **3**. It is noticeable that when CO_2 injection rate reaches 10000m^3/d, the gas production rate increases sharply compared with other injection rates, and the CBM recovery rises to 109.51% (higher than 100%). Because at the injection rate of 10000m^3/d, the injected CO_2 is produced along with CBM, causing the calculated value of CBM recovery to exceed 100%. Consequently, the CO_2 injection rate of 8000m^3/d is the optimum injection rate in this case, which can achieve the best CBM recovery 86.24%.

However, injected CO_2 brings an environmental problem. It can diffuse to the atmosphere directly due to coal structure damages during coal mining. In order to reduce CO_2 emission, several suggestions are proposed:

(1) Inject CO_2 according to the critical CO_2 volume

In order to prevent gas explosion, CH_4 volume fraction should be controlled lower than *LEL*. However, injected CO_2 can diffuse into the atmosphere which contributes to the greenhouse effect. Consequently, we hope to inject CO_2 into coalbeds as little as possible to reduce CO_2 emissions. Because the air volume fraction in coal mines is definitely larger than the required air volume fraction for CH_4 combustion, we can easily ensure CO_2 volume fraction below *LEL* by injecting the critical volume of CO_2. Therefore we suggest injecting CO_2 according to the critical CO_2 volume. In this way, we can meet the requirements of explosion prevention. Simultaneously, the cost is cut, because less CO_2 is needed.

(2) Turn valueless coalbeds into CO_2 storage places rather than coal mining resources

For the deep coalbeds with an active aquifer, they are easy to collapse. Therefore, we suggest not to mine at these coal seams. Instead, use them for carbon dioxide storage. This method can cut down the production cost, avoid the mining risk, and reduce CO_2 emissions.

4. Conclusions

(1) The model of the critical CO_2 volume fraction can be used to ensure CH_4 volume fraction out of the explosion limits and prevent gas explosion during coal mining. It is proved to be reasonable through comparisons with experimental results from other researches.

(2) The reservoir simulation method can be used to optimize the CO_2 injection rate. The case study demonstrates that the optimum CO_2 injection rate is 8000m^3/d, which achieves the peak recovery of 86.24% after 8 years of production.

(3) In order to reduce CO_2 emission in the process of coal mining and acquire high economic benefits, CO_2 injection based on critical injected CO_2 volume is recommended. For the valueless coalbeds, we suggest abandoning mining and use them for CO_2 storage.

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