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# A Case Study on the Fracturing Radius and Time Effects of $CO_2$ Phase Transition Fracturing in Coal Seams

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**Abstract:** $CO_2$ phase transition fracturing (CPTF) is considered to be a promising way to improve the recovery efficiency of coalbed methane in deep, tight coal seams. In addition, it is significant to the $CO_2$-ECBM and $CO_2$ storage in coal. To better understand the fracturing radius and time effects of CPTF, a field experimentation was conducted on the Ji-15 coal seam of Pingmei 8th Coal Mine. The results indicate that the fracturing radius and time effects are significantly related; with the increase in fracturing radius, the time for extraction rate to reach the peak value is shorter. The calculated value of effective fracturing radius is 7.56 m via the fitting relationship. According to the $CO_2$ content in different extraction boreholes after fracturing, it can be concluded that the crack zone is 5 m. In addition, the extraction rate of methane firstly increases slowly for a while, and then reaches the peak. This work could provide theoretical directions for the arrangement of fracturing and extraction boreholes in $CO_2$ fracturing works related to $CO_2$-ECBM and gas pre-extraction in coal mining.

**Keywords:** carbon dioxide; phase transition fracturing; fracturing radius; time effects



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## 1. Introduction

Deep geological formations (e.g., coal seam, shale) have been proposed as potential reservoirs for $CO_2$ geo-sequestration to mitigate $CO_2$ emissions. Due to the advantages of maintaining the reservoir pressure and the capacity for $CO_2$ storage, $CO_2$ injection to enhance coalbed methane recovery ($CO_2$-ECBM) seems to be a promising option [1,2]. Coalbed methane is an important mineral resource obtained from the coal seam [3]. It does not only link to the safety conditions of mining, but also contributes to the application of green mining [4,5]. On the other hand, coal is one of the main energy resources of China. After many years of high-intensity mining, shallow coal resources have gradually decreased, which has resulted in a continuous increase in mining depth. With the continuous increase in coal mining depth, the high in situ stress, high gas pressure, and low permeability of deep coal seam severely restrict the production of coal mines. Meanwhile, coalbed methane is a kind of greenhouse gases, but is also a kind of clean energy, which can improve the energy structure of China if it can be used efficiently [6]. At present, protective layer mining [7] and gas extraction [8] have been widely applied in gas disaster prevention. However, the majority of coal mines do not have the conditions for mining protective layers, so the approach of gas pre-extraction is widely used. As a result, there are some problems caused by the low permeability of deep coal seam, such as low efficiency of gas extraction, long extraction time, and unsatisfactory extraction effects, etc. Except for increasing the quantity and length of bore, it is necessary to increase the effective range of fractures to improve the efficiency of gas pre-extraction in deep coal seams [9].

Hitherto, the penetrating techniques, including hydraulic fracturing [10], deep hole pre-splitting blasting [11], water injection [12], and hydraulic flushing in the hole [13,14] have been widely applied in deep coal mines. In recent years, liquid $CO_2$ blasting technology has gradually attracted the people's attention by its advantages of high safety and efficiency. LCB was firstly applied in the U.S., and due to its safe and reliable characteristics, some domestic coal mines tried to use the LCB technique to mine coals in high-gas coal mines in 1990s. Nie et al. [15] conducted the $CO_2$ blasting experiments to study the replaceability of conventional dynamite blasting. The results shown that the blasting process of LCB is safe and reliable, and can be used as a substitute for coal mine blasting products. In the past decade, with the domestication of $CO_2$ fracturing equipment, $CO_2$ phase transition fracturing (CPTF) has been widely used in coal mines. Dong et al. [16–18] studied the mechanism of CPTF, and calculated the equivalent weight of TNT. In addition, Wang et al. [19,20] conducted the field tests and achieved an ideal penetration effect. Song et al. [21] showed that the fractured radius of liquid $CO_2$ in coal seam is 12 m via field tests. Moreover, based on the numerical simulation and field tests, Sun et al. [22] found that the secondary fracturing is more helpful for improving the effect of gas extraction. Wang et al. [23] carried out the field tests with different layout schemes of extraction boreholes, which showed that the staggered arrangement of plum hole is more reasonable. Furthermore, Wang et al. [24] showed that the gas desorption index of drill cuttings after CPTF decreased by 50 percent, and the gas extraction volume increased twofold.

Although there are some experimental studies about CPTF, most of them contribute to the overall extraction. Due to the difficulty of coal mine site monitoring, it is hard to monitor each hole in detail. As a result, to some extent, it is difficult to investigate the time effects of different fracturing radii. On the other hand, the fracturing radius of CPTF and time effects characteristics of penetration are significant to the arrangement of extraction boreholes. Understanding the fracturing radius and time effects of CPTF in coal seam is feasible to make the most of the relationship between fracturing radius and penetration time effects for designing drilling arrangements under different extraction periods. Therefore, it is necessary to further study the valid penetration radius and time effects of CPTF. The results could provide theoretical support for the storage of $CO_2$-ECBM and $CO_2$ in deep coal seams.

## 2. Materials and Methods

### *2.1. Overview of Field Experimentation*

Taking a bottom extraction lane of the Ji-15 return airflow roadway of Pingmei 8th Coal Mine as the field test site of CPTF. The excavated bottom extraction lane is used to cover the return airflow roadway of Ji-15 coal seam for gas pre-extraction, which is 5 m away from the bottom of the Ji-15 return airflow roadway and arranged in the rock layer 12 m below the Ji-16 coal seam (as shown in Figure 1). According to the related geological data, the buried depth and the elevation of the Ji-15 coal seam are 803–930 m and −728–840 m, respectively. They mainly contain vitrain and clarain with an average thickness of 3.5 m. In addition, as for Ji-15 coal seam, the spontaneous combustion period is 4–6 months, the measured gas pressure and content are 2.65 MPa and 14.1 $m^3/t$, respectively, which belongs to the work face with risk of gas outburst.

### *2.2. Experimental Approach*

In order to investigate the fracturing radius and time effects characteristics of CPTF, the CPTF test was conducted at the elevation of −780 m of bottom Ji-15 air way to improve gas extraction. We prepared 33 boreholes, including 2 fracturing boreholes and 31 extraction/monitoring boreholes, which were divided into 3 areas, i.e., the fracturing areas that centered on 15# borehole (FA-I) and 20# borehole (FA-II), and the repeated fracturing area

(RFA), as displayed in Figure 2. To minimize the errors that may occur in a single test, the fracturing work was executed twice, and the consumption of $CO_2$ was limited to about 1.2 kg. Firstly, the 15# borehole was fractured, also called as primary fracturing; then 20# borehole was fractured, recalled as secondary fracturing. The RFA was especially set to determine the repeated fracturing effects occurred in two fracturing tests by observing whether the fracturing radius from 13# and 17# boreholes exceed 9 m or not. If there is a difference between above two boreholes, the fracturing radius of both boreholes will exceed 9 m.

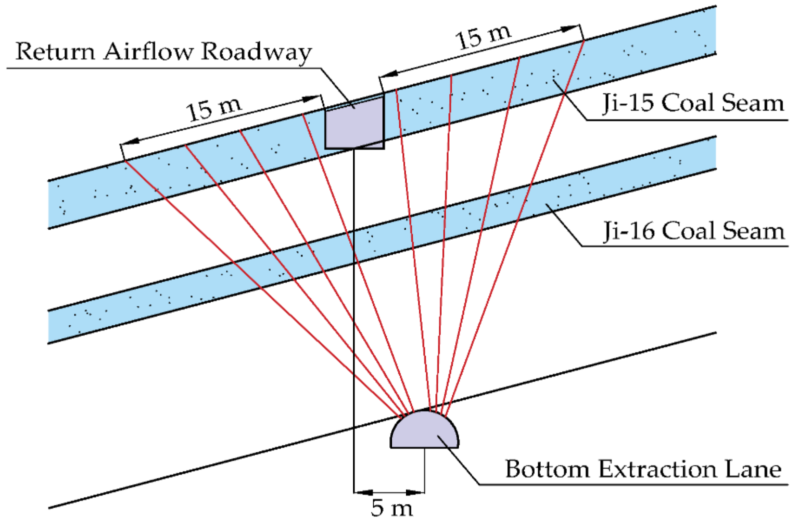



**Figure 1.** Schematic diagram of field experimentation.

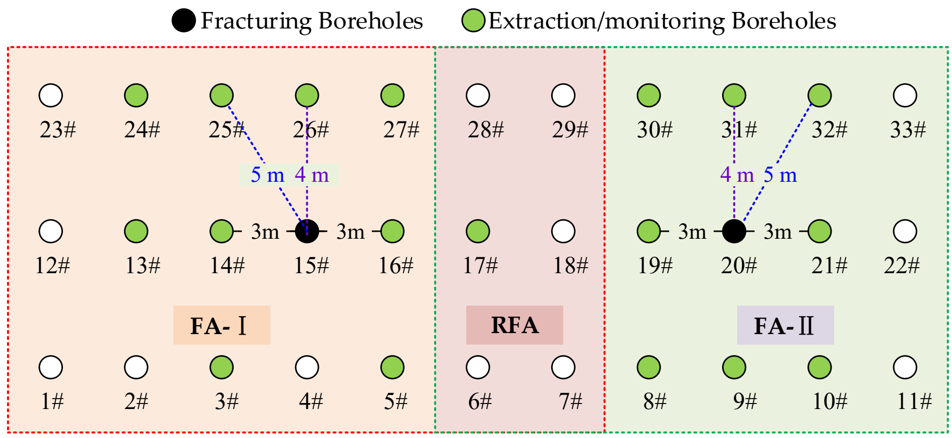



**Figure 2.** Schematic diagram of boreholes layout.

Based on the distance between the fracturing and the extraction boreholes, the fracturing boreholes were divided into three groups: Group-A (3 m), Group-B (4 m) and Group-C (5 m). As shown in Figure 2, the 14# and 16# boreholes of FA-I belonged to Group-A, the 4# and 26# boreholes belonged to Group-B, and the 3#, 5#, 25#, and 27# boreholes belonged to Group-C. Similarly, in FA-II, the 19# and 21# boreholes were divided into Group-A, the 9# and 31# boreholes were divided into Group-B, and the 8#, 10#, 30#, and 32# boreholes were divided into Group-C. All the extraction boreholes in each group were monitored and recorded to analyze the changes in $CO_2$ content before and after fracturing. Additionally, the redundant monitoring method was adopted to summarize each row of boreholes using a gas meter to monitor the total volume and flow rate to ensure the accuracy of the monitoring data. The specific fracturing and monitoring equipment used in our work are shown in Figure 3 below.

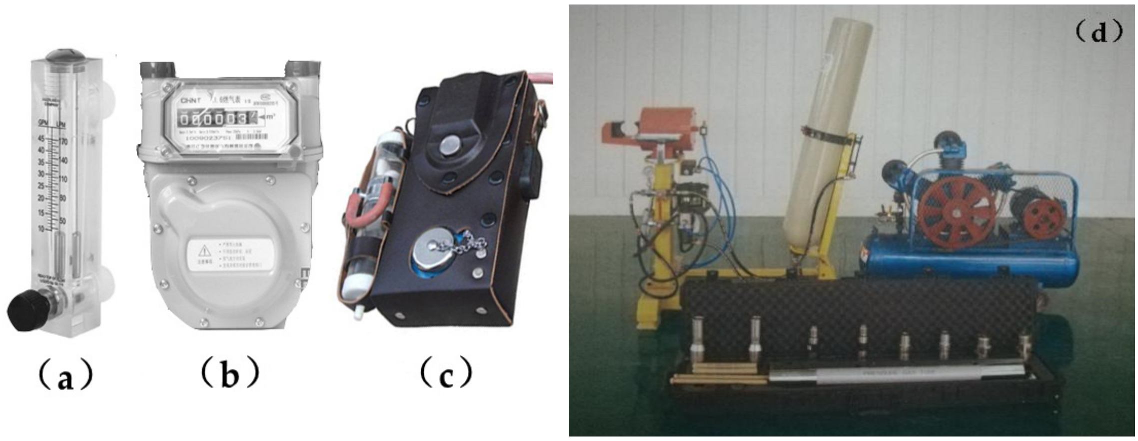


**Figure 3.** Underground monitoring and fracturing equipment. (**a**) rotameter; (**b**) gas meter; (**c**) optical interference methane concentration monitor; (**d**) $CO_2$ phase transition fracturing apparatus.

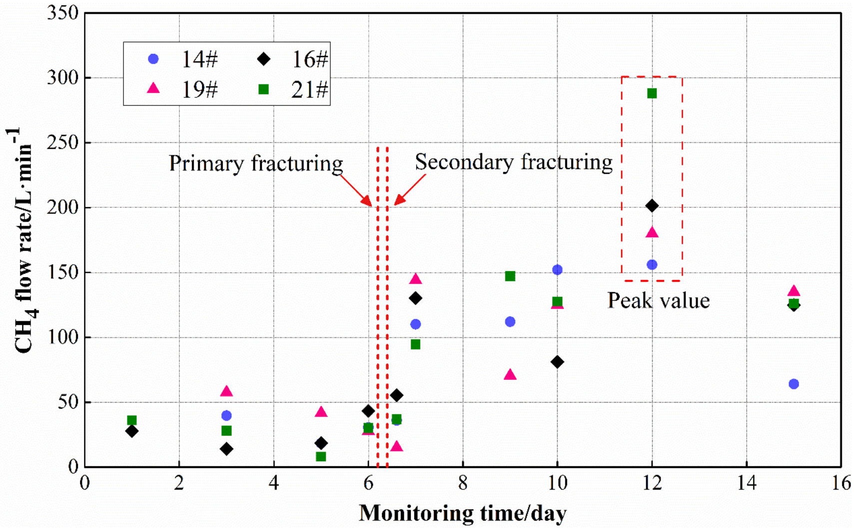
It should be noted that, before and after fracturing, 20 mL gas was extracted from 14# borehole of Group-A, 26# and 31# boreholes of Group-B, and 3# and 10# boreholes of Group-C for gas chromatography to analyze the changes in $CO_2$ content and further determine and verify the fracturing radius.

## 3. Results and Discussion

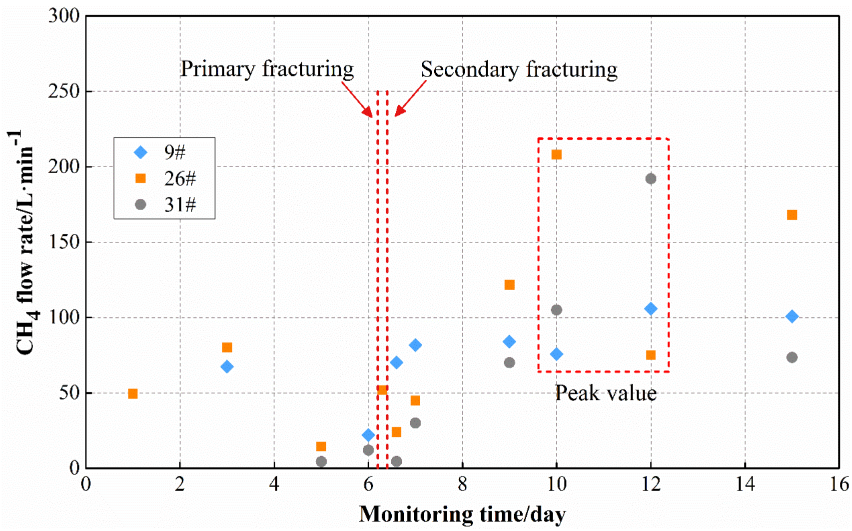
### *3.1. Fracturing Radius and Time Effects Relation*

To determine the fracturing radius and time effects of CPTF, the flow rate and concentration of extraction boreholes from FA-I and FA-II are monitored and recorded. According to Figure 4, the appearance time of penetration peak of different groups are different. With the increase in fracture distance, the peak time of the penetration decreases gradually. Additionally, then, the $CH_4$ extraction velocity of all the boreholes of Group-A in FA-I and FA-II reached the peak value on the 6th day after fracturing. By contrast, the extraction flow rate of 26# borehole in Group-B reached the peak on the 4th day after fracturing, while the 9# and 31# boreholes achieved their peak at the 6th day after fracturing. Averagely, the peak time of borehole in Group-B appeared on the 5th day, while extraction velocity of the boreholes in Group-C were significantly advanced. As a result, the $CH_4$ extraction velocity of most boreholes in Group-C reached the peaks on the 3rd and 4th day after fracturing.

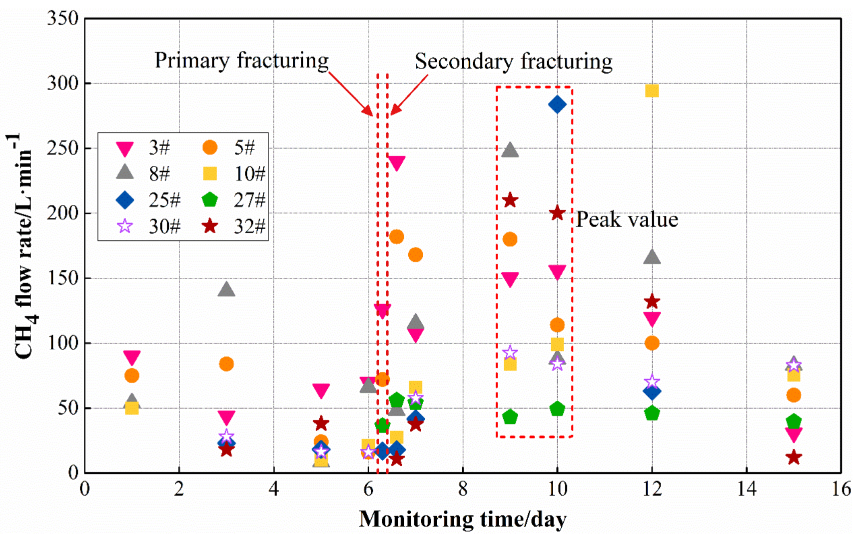
Based on Figure 4, combined with the extraction data of 13# and 17# boreholes in Figure 5 below, the relation between penetration radius and peak time can be concluded (as shown in Figure 6). It can be seen that with the increase in fracturing radius, the extraction rate of boreholes present shorter peak time, which means that the extraction rate of the boreholes begins to decay earlier. According to the crack zone of coal seam after fracturing, the further away from the fracturing center, the sparser the cracks are. Therefore, the further the fracturing area from the center, there will appear smaller gas seepage flow and desorption volume. In this work, the area with the furthest distance was the first to show attenuation, which is caused by the redistribution of stress and the reduction in coal seam permeability. In other words, the essence of penetration time effects is that closure of cracks in coal rock caused by stress redistribution, which leads to the attenuation of CH4 flow rate. To sum up, it can be inferred that the time effect of penetration is not only related to the fracturing radius, but also certainly linked to other factors, e.g., in situ stress, physical and mechanical properties of coal rock, pressure and consumption of $CO_2$. This should be considered in real-world engineering.




(**a**) Group-A (3 m).




(**b**) Group-B (4 m).




(**c**) Group-C (5 m).

**Figure 4.** Relationship between extraction rate and time of different extraction groups.

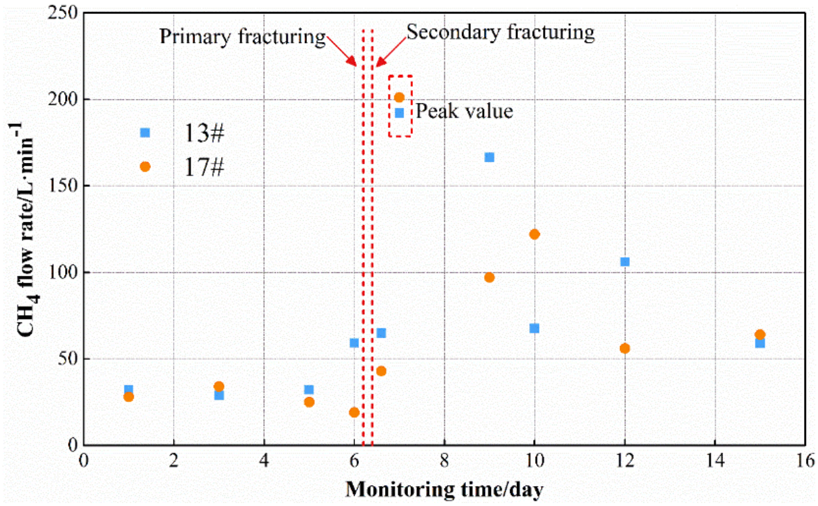



**Figure 5.** $CH_4$ flow rate of 13# and 17# boreholes.

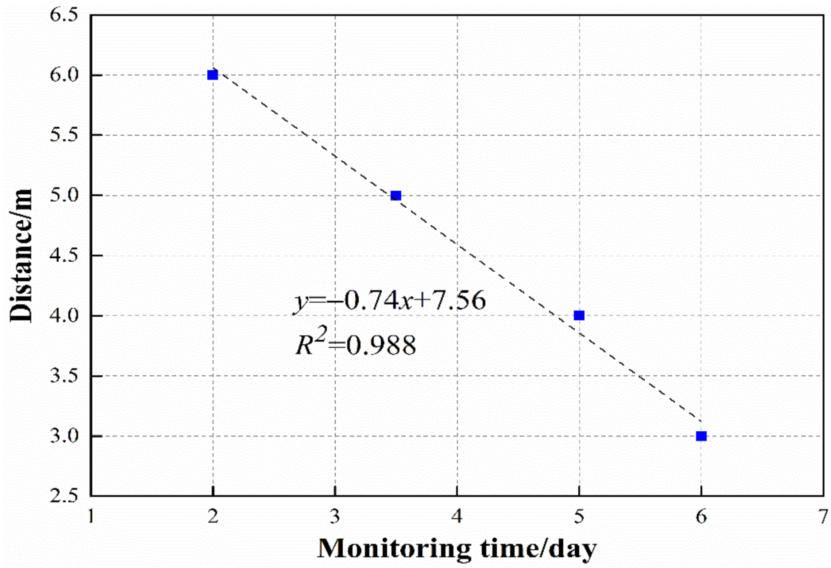



**Figure 6.** Relationship between the fracturing radius and time.

### *3.2. Determination of Fracturing Radius*

#### 3.2.1. Radius of Penetration Area

According to the fitting curve in Figure 6, the relationship between the fracturing radius and time effect present a negative relation: $y = -0.74x + 7.56$. If the time for the peak extraction rate is set to 0, that is, there is no increase in extraction rate in the area after fracturing, then the penetration radius derived from the above formula is 7.56 m. The previous study indicated that the outermost layer of the penetration zone of liquid $CO_2$ phase transition fracturing is vibration zone [17], so it can be judged that the radius of the vibration zone of CPTF in coal seams is 7.56 m. Moreover, through the monitoring of the 24# borehole at a distance about 7.56 m from the extraction borehole, there is no penetration effects at a distance of 7.56 m from the fracturing borehole.

#### 3.2.2. Radius of Crack Zone

It is generally believed that the CPTF zone can be divided into three zones: crushed zone, crack zone, and vibration zone [17,19]. In order to further determine the range of the crack zone caused by phase transition fracturing, in this work, chromatographic analysis was performed on the gas extracted from the 14#, 26#, 31#, 3#, and 10# boreholes before and after fracturing, and the changes in $CO_2$ content from those boreholes before and after fracturing are observed and recorded.

As depicted in Table 1, the $CO_2$ increment decreases with the increase in distance, and then decreases to about 5% at the distance of 5 m. However, the $CO_2$ gas in extraction boreholes is extracted at a short time interval before and after fracturing; therefore, it is accepted that the increases in $CO_2$ content in extraction boreholes come from the fracturing fluid. At the moment of fracturing, a large number of cracks are generated in the surrounding coal rock, and $CO_2$ gas diffuses through those cracks. Nonetheless, it is difficult for $CO_2$ gas to penetrate into the extraction borehole through the vibration zone in a short time, because there are no well-developed cracks in it. Therefore, the increments of $CO_2$ can be used to determine the range of fractured area. Based on the changes in $CO_2$ content of monitoring boreholes, it can be determined that the radius of the crack zone caused by $CO_2$ phase transition in Ji-15 coal seam is about 5 m.

**Table 1.** $CO_2$ content of monitoring boreholes before and after fracturing.

| **Group** | | **A-3 m** | | **B-4 m** | | | | **C-5 m** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Gas samples | Borehole | 14# | | 26# | | 31# | | 10# | | 3# | |
| | Before/after fracturing | B | A | B | A | B | A | B | A | B | A |
| Results | $CO_2$ percentage | 0.857 | 1.186 | 0.969 | 1.034 | 0.775 | 1.123 | 2.120 | 2.247 | 1.378 | 1.446 |
| | After/Before | 1.38 | | 1.07 | | 1.45 | | 1.06 | | 1.05 | |

### 3.3. Verification of Penetration Radius

The redundancy check method was adopted to our field test to minimize the external disturbance, and a RFA was set in our work. The fracturing radius can be further determined by the comparison between the 17# borehole of RFA and 13# boreholes of FA-I. It can be seen from Figure 5 that the gas extraction rate of 13# and 17# boreholes all reach their peak values on the next day after fracturing, which indicates that the region of 6 m away the fracturing borehole still exist penetration effects. However, the penetration effects of both 13# and 17# boreholes began to decay rapidly on the day after the fracturing, which show that the 17# borehole was not affected by secondary fracturing. In other words, the fracturing radius of CPTF is between 6 and 9 m. It is consistent with the calculated value of 7.56 m above.

### 3.4. Penetration Effects of CPTF

According to Figures 4 and 5, it is clear that the $CH_4$ extraction rate do not reach the peak immediately after fracturing, but reach the peak after rising slowly, which is similar to other studies [20,22,25,26]. It may be due to the gas desorption and drainage, and the decrease in adsorption stress. On the gas pressure of 2 MPa, the adsorption-induced swelling of the coal was about 0.6‰ [27–29]. That is to say that the swelling of a coal seam with the thickness of 4 m is about 24 mm. Therefore, in the area with developed fissure network, the gas desorbs faster, and the adsorption stress of coal releases faster. On the other hand, due to the influence of surrounding rock formations, the in situ stress did not recover in time, resulting in a slow increase in $CH_4$ extraction rate. However, as the total volume of gas in coal seam decreased continuously, the desorption volume of unit interval also decreased, and the ground stress recovered gradually; therefore, the fracturing-induced fissures in the coal rock began to close, which caused a decrease in the $CH_4$ extraction rate. As for the area far away from the fracturing center, the gas desorbs slowly, and the adsorption stress cannot be released in time, resulting in a faster recovery of the ground stress, which leads to the closure of fracturing-induced fissures in the coal rock, and terminates the increase in the gas extraction rate early.

The extraction boreholes, located 3–4 m away from the fracturing center, have similar time effects, because there is little difference in the internal fissure network in coal rock within the range of 3–4 m from the fracturing borehole after fracturing. Time effects of the extraction boreholes 5 m away from the fracturing center are significantly lower than that of the extraction boreholes within the range of 3–4 m, which indicates that the fissure density at a distance of 5 m from the fracturing center decrease. It is consistent with the judgment made by the $CO_2$ volume of boreholes.

Furthermore, the 13# and 17# boreholes, 6 m away from the fracturing center, are on the edge of vibration zone, which have relatively few fissures. These fissures quickly close under the action of stress, the effects of penetration weaken rapidly, and the gas extraction rate reaches the peak on the second day after fracturing, and then decreases rapidly.

## 4. Conclusions

To understand the fracturing radius and time effects characteristics of CPTF, a field experiment was conducted at the bottom of Ji-15 air way of Pingmei 8th Coal Mine. According to the dynamic data of $CO_2$ and $CH_4$ contents in fracturing and extraction/monitoring boreholes after fracturing, the following conclusions can be drawn:

1. The fracturing radius and time present a linear negative correlation: $y = -0.74x + 7.56$. With the increase in fracturing radius, the extraction rate of boreholes presented a shorter peak time.
2. The effective penetration radius of CPTF in Ji-15 coal seam is about 7.56 m, the crack zone is about 5 m, and the fracturing scope is 6–9 m. The further away from the fracturing center, the sparser the cracks are. The time effects of penetration are not only related to the fracturing radius, but also certainly linked to the in situ stress, physical and mechanical properties of coal rock, and the pressure and consumption of $CO_2$.
3. After fracturing, the outflow rate of each extraction borehole reached their peaks after a period of increase, which is mainly related to the release of adsorption stress and recovery of ground stress.

Evidently, the fracturing radius of CPTF and the time effects characteristics of penetration are greatly significant for the arrangement of extraction boreholes in real-world engineering. Therefore, understanding the fracturing radius and time effects of CPTF in coal seam is feasible to make the most of the relationship between fracturing radius and penetration time effects for designing drilling arrangements reasonably. This work could provide significant theoretical support for the arrangement of fracturing and extraction boreholes of $CO_2$ fracturing related to the $CO_2$-ECBM and $CO_2$ storage in deep coal seams.

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