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Original article

Supercritical CO_2 source for underground seismic exploration

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A B S T R A C T

Underground seismic exploration is a technical assurance for the geological transparency of the mining face. However, seismic exploration with explosive seismic source has shortcomings such as acquisition difficulties and serious safety hazards. Besides, dynamic detection of the mining face with explosive source is challenging. To this end, the study proposes a supercritical CO_2 source based on the underground seismic geological condition of the roadway. The phase change blasting mechanism of the supercritical source was revealed, and the equivalent energy of the source was calculated. Additionally, a field test was also carried out. The results show that the seismic signals of the CO_2 source have clear P-waves, S-waves, and channel waves; the signal excited by the source has strong energy and rich frequency bands; the signal-to-noise ratio of single CO_2 source is high; and the attenuation images of transmitted channel wave excited by the source shows high resolution and the result is consistent with field validation data. CO_2 source can be used as a new source of underground in-seam seismic exploration and it also helps in reducing the dependence of explosive seismic source. Besides, the study can achieve early warnings of dynamic geological disasters in the working face and has the advantages of high efficiency, safe, low cost, and environmentally friendly.

1. Introduction

With the promotion of safe, efficient, and intensive mining technologies, hidden geological hazards in mining faces require to be identified in advance (Wu et al., 2013). Besides, with the advent of the era of autonomous and intelligent mining, the hyalinization detection for the mining face has become increasingly urgent (Cheng et al., 2019). Ground 3D seismic exploration for assessing geological conditions of the mining face is a relatively mature technology. However, due to the influence of deep mining conditions and complex terrain, the resolution of ground 3D seismic exploration is not able to meet production requirements. Hence, underground seismic exploration must be carried out in the roadway.

In-seam seismic survey has been widely used in detecting small faults and collapse columns and in predicting the thickness of the coal seam (Evison, 1955; Hu et al., 2018; Li et al., 1995; Liu et al., 1992; Zhang et al., 2019). Compared with other underground geophysical exploration methods, in-seam seismic survey owns the advantages of large detection distance, strong anti-interference capability, clear waveform characteristics, highly visual results, and high precision. The survey technology has its unique leverage in the fine exploration of geological structures (Luo et al., 2011; Tang, 2011; Wang, 1997). The seismic sources, which generate seismic signals, are an important part of seismic exploration technology. The excitation effect and signal quality of the sources directly affect the result of the seismic exploration. Seismic sources can be divided into two main categories: explosive source and non-explosive sources (Park et al., 1996). Commonly used non-explosive sources (Haines, 2006) are air gun sources (Fisher et al., 2003; Fuis et al., 2003), spark sources (Xun et al., 2012), mechanical sources (Cosma and Enescu, 2001), and tunneling machine sources (Ciese et al., 2005). At present, the main seismic sources used in the in-seam seismic survey are explosive source and hammer source (Wang et al., 2019). The hammer source has the disadvantages of low energy and poor signal resolution. Whereas, the energy generated by explosive source is large and effective seismic waves can be easily generated. Hence, explosive source shows good results in underground seismic exploration.

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However, the approval and construction procedures of this source are tedious, and the risk of using this source in high gas mining areas is high (Cheng et al., 2019). Therefore, there is an urgent need for innovative researches on seismic sources for underground seismic exploration.

Based on the underground seismic geological condition of the roadway, a CO_2 seismic source is proposed in this paper. The mechanism of this seismic source is revealed, and the TNT equivalence of the CO_2 source is also calculated. The resulted seismic signals from the CO_2 source and explosive seismic source are compared. The applications of the CO_2 seismic source for static and dynamic monitoring of working face are discussed. This technology provides a new research direction of active sources for underground seismic exploration.

2. Supercritical CO_2 source

2.1. Blasting mechanism

Carbon dioxide is a gas under standard conditions, and when the pressure is too high, or the temperature is too low, it will be converted to a liquid or solid. If the temperature and pressure are raised, the temperature is higher than 304.25 K, and the pressure is higher than 7.39 MPa, as show in Fig. 1. It will be in the supercritical state, and its properties will be between liquid and gas. The density of supercritical CO_2 is close to that of liquid. However, the viscosity of supercritical CO_2 is close to that of gas. Besides, the diffusion coefficient of supercritical CO_2 is 100 times higher than that of liquid.

With these special properties, supercritical CO_2 can be employed in in-seam seismic survey. The blasting process is described as follows. This process begins with inducing a heater with a current to generate a lot of heat. As temperature of the heater is rapidly increased over 200 , the liquid CO_2 in the vessel changes to a high-density gaseous CO_2 in a supercritical state and the gas volume expands more than 600 times. When the pressure in the vessel is higher than the strength of the rupture disc, the rupture disc will be ruptured, releasing high-pressure CO_2 gas. Finally, the resulted impact force will blast the surrounding coal mass.

CO_2 blasting is a low-temperature, non-explosive blasting technology. Because it does not generate high temperature and spark during the excitation process, this process will not cause gas and coal dust explosion and can be safely used in high gas coal mines. The main chemical materials, liquid CO_2 and heaters are low-temperature gas and non-explosive equipment, respectively. Special approval procedures are not required for purchasing and storing. The transporting and storing these materials are safe. The construction operation is simple and special gunners are not required. Besides, the non-destructive oscillation and shock wave generated during the excitation process have no destructive effect on roadway supports. Therefore, the CO_2 seismic source is intrinsically safe.

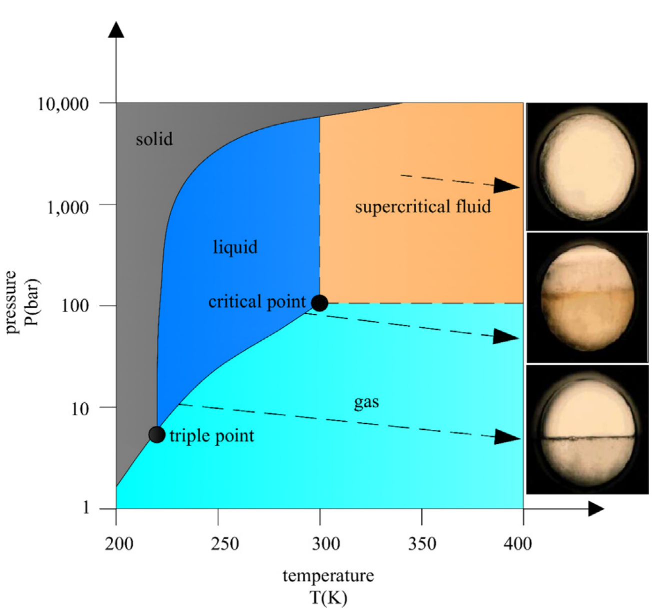


Fig. 1. Temperature and pressure change.

2.2. CO_2 blasting apparatus

The schematic diagram is shown in Fig. 2-a. The CO_2 source is mainly composed of a liquid storage tube, a heater, a rupture disc, and a jet valve. The liquid storage tube is a high-strength hollow steel pipe with length of 1080 mm and an outer diameter of 54 mm. Its internal volume is 1.8 L, which has a capacity of 2 kg of liquid carbon dioxide. The equipment diagram is shown in Fig. 2-b. The heater is the main heat source, is a cylindrical roll, which can be excited by a current. The rupture disc is a special steel disc that placed between the liquid storage tube and the jet valve. It has some shear strength and it is a disposable consumable. The jet valve is a cylindrical steel pipe and it is threadedly connected to the storage pipe. Two sides of the jet valve have symmetrical openings for the diversion of carbon dioxide gas and they can be adjusted according to technical requirements. The liquid storage tube is connected to a drill pipe, and it is delivered to a designated position of the blast hole by using a drilling machine. After that, the hole is sealed by a water injection sealing device.

2.3. Calculation of the equivalent energy of the CO_2 seismic source

The pressure limit of the shearing plate in the CO_2 gun is 120 MPa and the liquid storage pipe has a capacity of 2 kg of liquid CO_2. The energy generated during excitation can be calculated by the equation as follows:

$$W = \frac{P_1 V}{K-1}\left[1-\left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}}\right]$$

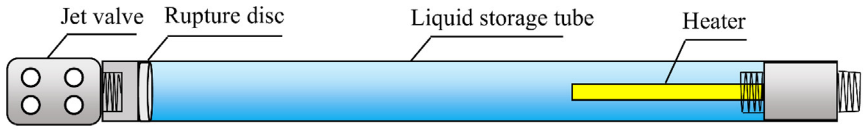
where: W is the excitation energy; P_1 is the pressure limit of the shearing plate; P_2 is atmosphere pressure; V is reservoir volume; K is the adiabatic index of carbon dioxide.

It is calculated that the energy generated by the CO_2 seismic source is about 596 kJ, which is equivalent to 140 g of TNT. The TNT equivalent of explosive source in in-seam seismic survey is generally 80–300 g (Dong et al., 2014; Wang et al., 2017).

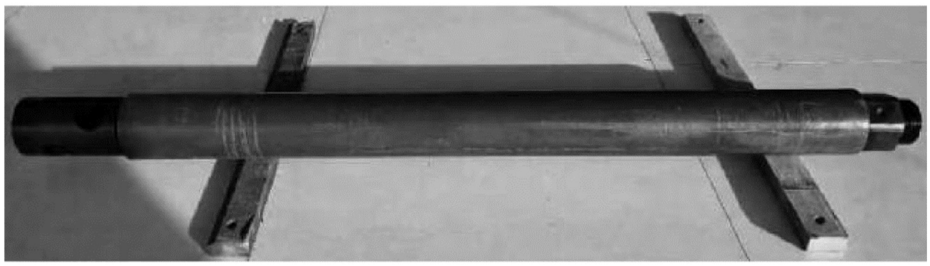
3. Field test

3.1. Geological setting

Xinyuan coal mine is in the northwest of Yangquan coalfield, which is in the middle part of Jinzhong City, China. The basic structure of this coal mine is monoclinic, striking along the east–west direction and tilting to the south with an inclination less than 10°. This coal mine has a high risk of gas outburst, among which the 3# and 15# coal seam are at the highest risk, especially the 3# coal seam. The test site is located at 3417 working face. The geological structure of mining face is a monoclinic structure with the south side lower than the north side. And the coal seam inclines southward with an inclination of 2°–10°. Moreover, 3# coal seam is mined at the 3417 working face. This coal seam has a thickness ranging from 2.10 m to 2.55 m with the average of 2.35 m.



(a) The schematic diagram



(b) The equipment diagram

Fig. 2. Supercritical CO_2 source.

Besides, geological structure of this coal seam is uncomplicated and relatively stable, and this coal seam mainly contains bright coal. Its roof strata, from the bottom to the top, consists of mudstone, sandy mudstone, and siltstone with a total thickness over 4.7 m. Its floor strata consist of sandy mudstone with a thickness of 5.99 m. Fig. 3 shows the location and the stratigraphic compositions of the strata in Xinyuan coal mine.

3.2. Seismic observation system layout

A seismic recording line consisting of 40 single-component receivers, labeled as green boxes in Fig. 4, was arranged along the intake airway of the 3417 working face. These receivers were fixed to the top of exposed anchors in the roadway with tight docking devices. These receivers were arranged at intervals of 10 m in middle of the coal seam. CO_2 sources, labeled as red squares in Fig. 4, were arranged in auxiliary intake airway of 3417 working face. Blast holes were arranged with a 25 m interval in middle part of the coal seam and depth of these blast holes increased from 17 m to 37 m. The measured depth data of each blast hole is listed in Table 1. CO_2 sources were placed at the bottom of blast holes by drilling machines and blast holes were then sealed by injection sealers. CO_2 sources were fired in sequence. The parameters of the observation system are shown in Table 2. Due to poor coupling performance, the geophones coupled with R19, R22, R24, and R39 anchors were invalid.

4. Data analysis and results

4.1. Analysis of seismic signals from CO_2 sources

As is shown in Fig. 5, a YWZ11 intrinsically safe seismic acquisition system, consisting of a host, an acquisition base station, connecting cables, and geophones, is used in this observation. This system has the advantages of distributed acquisition, independent storage, lightweight, and high reliability. The host and acquisition stations are synchronized by a crystal oscillator. The sampling frequency of acquisition stations is 10 kHz, and the intrinsic

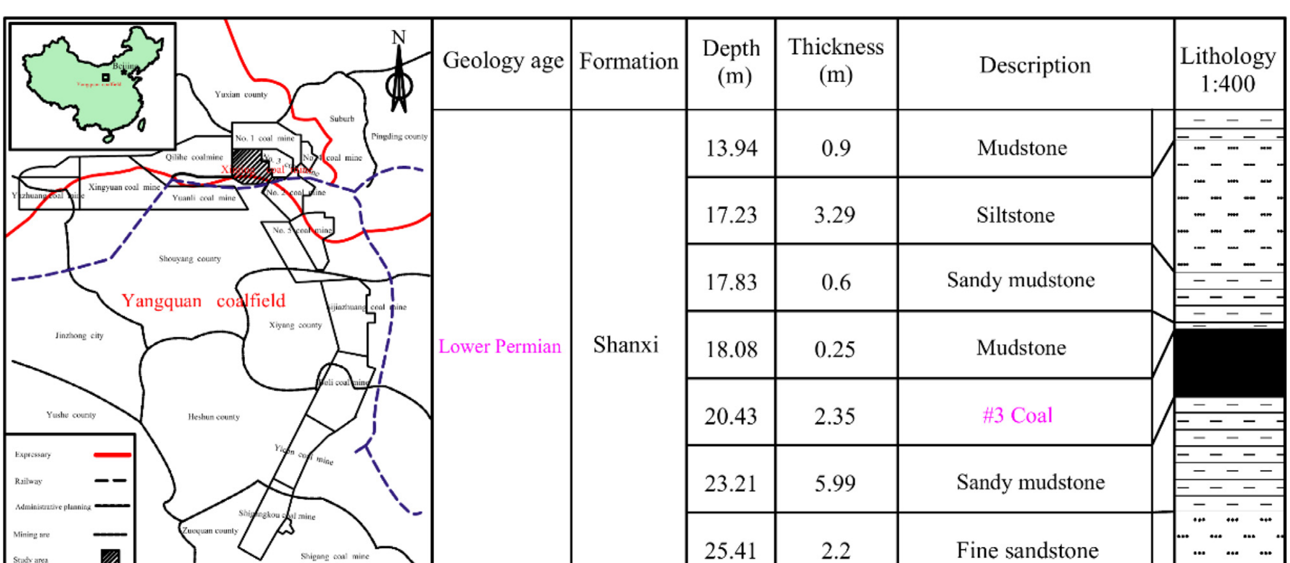


Fig. 3. Study area location and the detailed stratigraphic column of coal-bearing strata in the Yangquan coalfield.

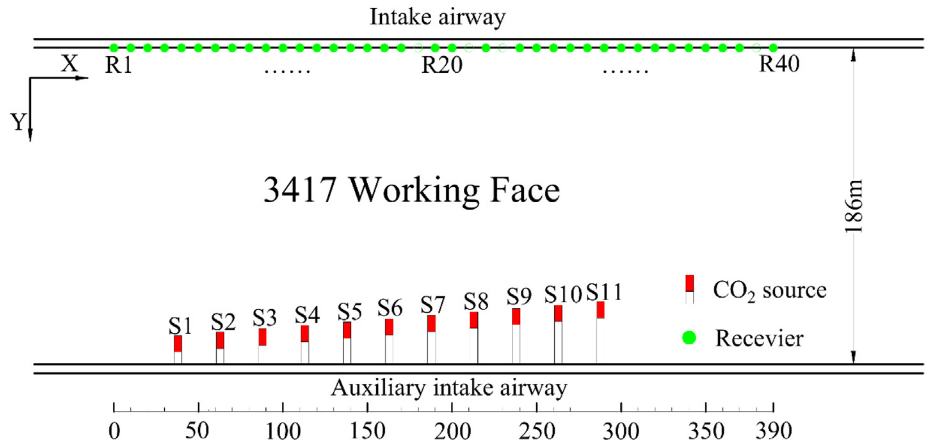


Fig. 4. Layout plan of the observation system.

Table 1
Hole depth.

Hole No.	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
Hole depth (m)	17	19	21	23	25	27	29	31	33	35	37

Table 2
Observation system parameters.

	Serial number	Interval (m)	Location	Number
CO_2 source	S1-S11	25	3417 Auxiliary intake airway	11
Receiver	R1-R40	10	3417 Intake airway	40

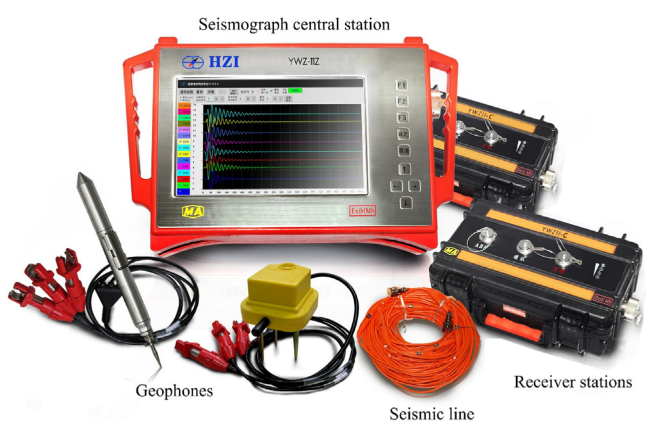


Fig. 5. YWZ11 intrinsically safe seismic acquisition system.

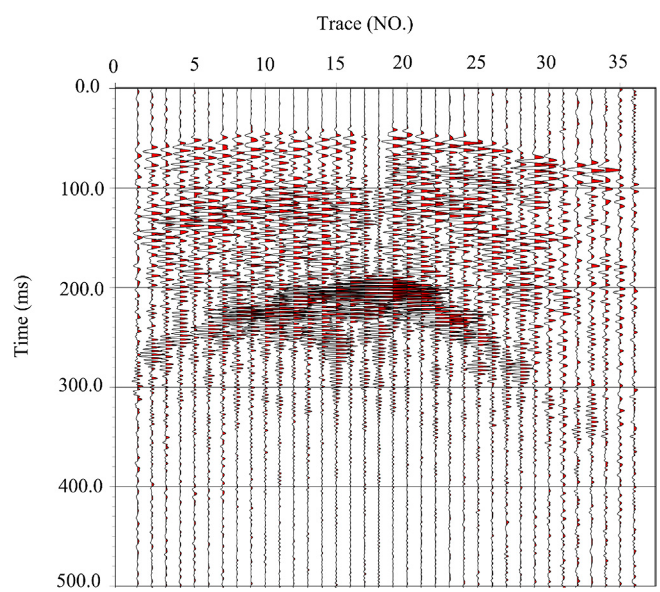


Fig. 6. Original seismic record of the S6 CO_2 source.

frequency of geophones is 60 Hz. Fig. 6 shows the original seismic signal of S6 CO_2 source, which consists of three groups of seismic waves. These waves are characterized by hyperbola in the common-shot gather. The first arrival signal is refraction P-wave from the surrounding rock whose velocity is 3500 m/s. The second arrival signal is refraction S-wave from the surrounding rock whose velocity is 2000 m/s. The third arrival wave, the Ariy phase of the transmitted channel wave, has the strongest energy and its velocity is 1100 m/s. The spectrum of the transmitted channel wave signal is shown in Fig. 7. This signal has a frequency range of 50–350 Hz with a main frequency of 210 Hz. Range of the channel wave spectrum is consistent with the spectrum range of a conventional explosive seismic source (Feng et al., 2018). The seismic spectrum excited by CO_2 source in the underground coal seam meets the requirements of in-seam seismic survey.

4.2. Transmitted channel wave tomography

The attenuation coefficients of transmitted channel waves were employed for detection area imaging. A plane model with an XY coordinate is established. The R1 geophone, which is located at the entrance of the wind tunnel of the 3417 working face, is set at the original point of the observation system and grid size is 2.5 m × 2.5 m. The X-direction is 390 m long, and the Y-direction is 190 m. In other words, the X-direction and the Y-direction have 153 and 76 grid points, respectively. After preprocessing the data, the maximum amplitude of each ray was calculated and substituted into the algorithm. Then, the SIRT iteration was performed to obtain the attenuation coefficients. Finally, the image of the

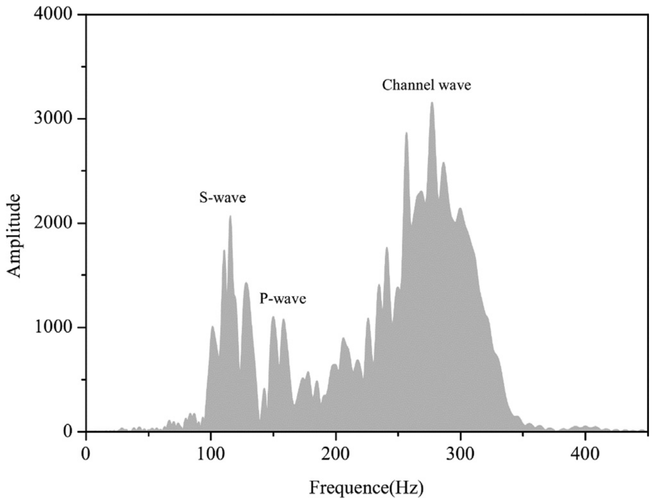


Fig. 7. Spectral characteristics of the S6 CO_2 source.

attenuation coefficients of transmitted channel waves was obtained, which is shown in Fig. 8.

By comparing the abnormal area in Fig. 8 and the data of revealed collapse columns in this roadway, it is inferred that this abnormal area is a collapse column, which is located at 337 m–339 m from entrance of the intake airway of 3417 working face. This abnormal area extends approximately 16 m into the coal seam. As shown in the transmitted tunnel signal in Fig. 5, the energy of the 29th-35th channel waves is low, indicating the straight lines between the locations of seismic sources and the detection points pass through the above-mentioned collapse column area, and the distribution of straight lines is shown in Fig. 9.

To verify the accuracy of the detected location of the subsided column, drilling exploration was carried out from the wind tunnel to the working face to determine the actual boundary of the subsided column. As shown in Fig. 8, the maximum error between the estimated boundary and the actual boundary is 8 m. As the collapse column is located at the edge of the detection zone, the number of ray coverage is low, resulting in the reduction in the detection accuracy.

5. Discussion

The mining processes employed by some large coal enterprises are highly mechanized without using explosives, which makes it impossible to adopt the explosive seismic source for the seismic exploration at the working face. Hence, the radio wave penetrating method is commonly used. However, this approach is limited by the power of radio waves (Lu et al., 2017; Wang et al., 2016). With

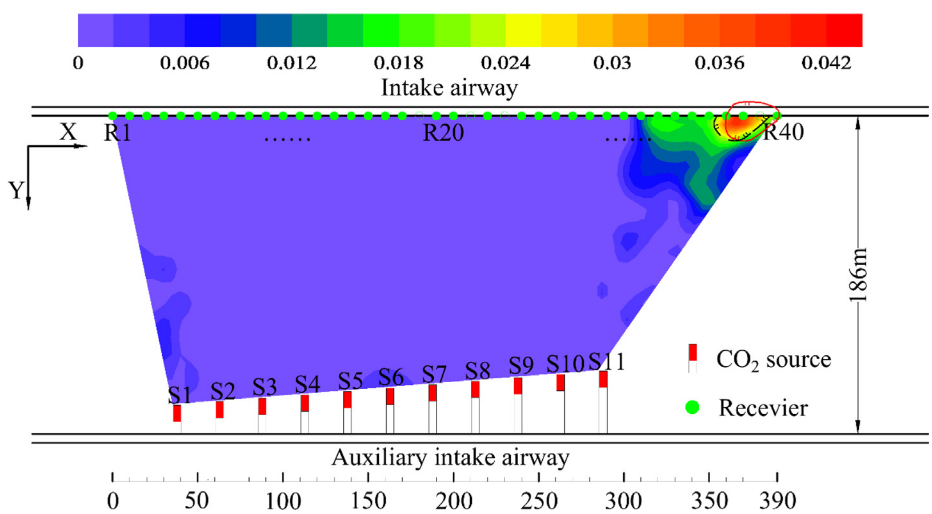


Fig. 8. The result of channel wave attenuation tomography based on CO_2 sources.

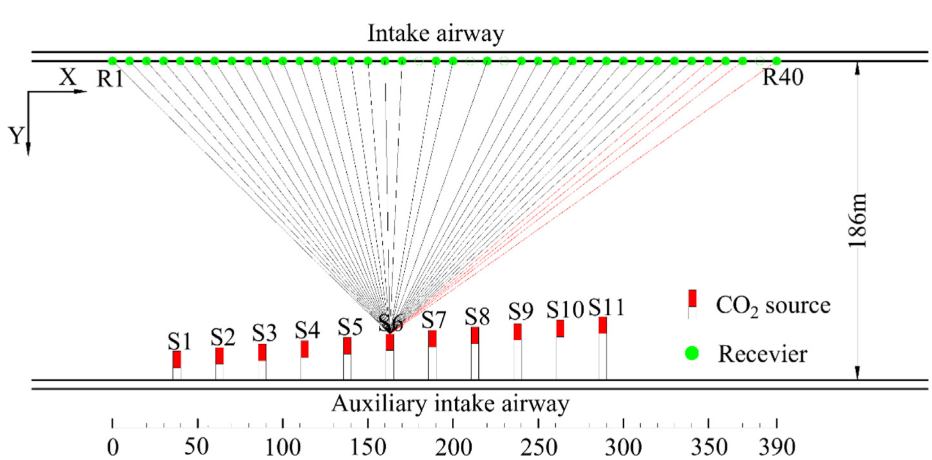


Fig. 9. Ray distribution of the S6 CO_2 source.

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a low penetration depth, the radio wave penetrating method is not able to penetrate the width of the working face, resulting in a lack of geological data of the working face (Wang et al., 2016). Cheng et al. (2019) proposed that shearers can be used as seismic sources. However, because signal-to-noise ratio is low, this technology is currently in the experimental stage.

According to the coal mine safety regulations, it is emphasized that long-distance blasting must be employed when blasting is carried out in a coal seam; Operators must be evacuated to a safe place to detonate explosives; the time to enter the working surface after blasting must be longer than 30 min (Hu, 2014). Taking a typical working face with a length of 1000 m as an example, a transmitted channel wave survey with a 10 m interval requires 100 shots, which requires a waiting time of 3000 min. Additionally, the time for connecting gun lines is expected to be at least 1500 min. Hence, the total operation time will be over 4500 min. In summary, the conventional explosive seismic source not only poses a challenge to the battery lifetime of portable instruments, but also can not meet the needs for high production and high efficiency of coal mines.

To resolve the gas drainage problem in coal seams of low-permeability, the CO_2 gas phase fracturing is used for improving gas permeability and effectiveness of gas drainage, and it has been adopted in the mining areas like Pingdingshan, Luan, and Yangquan (Wang et al., 2015; Cao et al., 2017). To shorten the extraction time of the gas drainage after the formation of the mining face, the CO_2 gas fracturing is applied to the mining face during the tunneling of coal roadway, and gas is extracted from the working face in advance. The CO_2 gas fracturing technology provides favorable conditions for the CO_2 seismic source. Without constructing additional blast holes and preparing liquid CO_2, the transmitted channel waves can be simultaneously obtained during the CO_2 gas fracturing process. Along with excavation of the roadway in the coal seam, continuous underground seismic exploration can be carried out with constant CO_2 gas fracturing in the working face, dynamic detection of geologic anomalies can be realized in the mining working face, such as abnormal gas enrichment and abnormal stress variation.

Therefore, the CO_2 source proposed in this study is a new way for underground seismic exploration. The advantages of this method are listed as follows: eliminating the dependence of explosives in in-seam seismic survey; enabling the monitoring and warning of geological disasters in working face; showing the advantages of high efficiency, safe, low cost, and environmentally friendly.

6. Conclusions

A large amount of heat generated by the electrical heater causes a rapid rise in the temperature of 2 kg of liquid CO_2, resulting in reaching a high-density supercritical state. At the same time, the pressure of liquid storage tube raises rapidly. When gas pressure breaks through the pressure limit of the rupture disc, the rupture disc breaks down, releasing high-pressure gas to generate seismic waves with TNT equivalence of 140 g.

The excitation energy of a 2 kg CO_2 source is strong. The resulted transmitted P-waves, S-waves, and channel waves have the characteristic of high signal-to-noise ratios. Besides, main frequency of transmitted channel wave has the same spectral characteristics as that of the conventional explosive source. The seismic wave generated by the CO_2 source meets the requirements of in-seam seismic survey.

The transmitted channel wave signals from 11 shots of CO_2 sources at the working face were collected. The attenuation coefficients were employed for constructing the inversion image and a collapse column area was identified. The drilling results were used to verify the effectiveness of this channel wave attenuation imaging method based on CO_2 sources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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