Evolution characteristics of spontaneous combustion in three zones of the goaf when using the cutting roof and release pressure technique

Xiangjun Chen¹,² | Liyang Li² | Zhibiao Guo¹ | Tinghao Chang³

¹State Key Laboratory of GeoMechanics and Deep Underground Engineering (Beijing), Beijing, China
²Henan Polytechnic University, Jiaozuo, China
³Shenhua Shendong coal Group Co., LTD., Yulin, China

Correspondence
Xiangjun Chen, State Key Laboratory of GeoMechanics and Deep Underground Engineering (Beijing), Beijing, China.
Email: chenxj0517@126.com

Funding information
National Key Research and Development Programme of China, Grant/Award Number: 2016YFC0801402 and 2016YFC0600901; National Natural Science Foundation of China, Grant/Award Number: 51874122 and 51704100; Key Research Projects of Henan Higher Education Institutions, Grant/Award Number: 18A440004; Program for Innovative Research Team of Henan Polytechnic University

Abstract
The changes associated with the cutting roof and release pressure mining method in the three zones that are susceptible to spontaneous combustion in the goaf with “Y” type ventilation system were studied. For the investigated underground coal mine working face, its three zones of spontaneous combustion have a “U” type ventilation system for the traditional mining method and a “Y” type ventilation system for the cutting roof and release pressure mining method. These systems were monitored using a beam tube method, and the evolution characteristics of spontaneous combustion of the three zones was analysed. The monitoring data showed that when using a traditional mining method with a “U” type ventilation system, the scattered tropical zone converts into the oxidation heating zone after 68.5 m in the goaf, and the suffocative zone presents after 85.5 m. For the cutting roof and release pressure mining method together with a “Y” type ventilation system, the scattered tropical zone converts into the oxidation heating zone after 84 m in the goaf, and the suffocative zone appears after 198.8 m. Compared to traditional mining, the width of the oxidation heating zone increases when using the cutting roof and release pressure method. To prevent spontaneous combustion of the goaf, the comprehensive techniques of the pressure balance for fire control, ground fissure sealing, working face sealing, retained roadways guniting and inert gas fire extinguishing have been used in the studied coal mine. The CO concentration of the goaf is less than 300 ppm during the mining process. Safe mining of the tested working face shows that the cutting roof and release pressure technique can be applied to control the coal seam spontaneous combustion.

KEYWORDS
air leakage, control technology, cutting roof and release pressure, goaf, spontaneous combustion three zones, “Y” type ventilation system

1 | INTRODUCTION

China's coal production was 3.747 billion tons in 2015, approximately 1.5 times the total output of five other major coal-producing countries (the US, India, Indonesia, Australia and Russia). China is definitely the world's largest coal-producing country.¹ However, the waste of coal resources in China is also serious. In 2007, the average...
recovery rate of coal mines in China was only 30%, whereas the recovery rates in other developed countries, such as the US, Australia, Germany and Canada, were approximately 80%. China’s coal recovery rate was less than half of the international advanced level.\(^2\) To improve the recovery rate of resources, on January 9, 2013, the National Development and Reform Commission promulgated the “recovery rate of coal mine production management interim provisions,” which requires that for a coal seam with thickness <1.3 m, the recovery rate cannot be less than 85%; for a thickness of 1.3-3.5 m, the recovery rate cannot be less than 80%; and for a thickness greater than 3.5 m, the recovery rate cannot be <75%. According to these requirements, when one ton of coal is excavated, 0.2-0.3 tons of coal is wasted. Coal is a non-renewable resource, and as such, further improvements in the recovery rate of coal resources are desperately needed.\(^3\)

Cutting roof and release pressure and automatically formed roadways are the key technologies of cutting roof and release pressure that have recently emerged.\(^4,5\) This mining method was proposed by researcher Manchao He in 2008 and is based on the “Roof Cut Short-Arm Beam Theory.” Its working principle is as follows: After the formation of the working face system, the roadway to be retained is supported by constant resistance and large deformation anchor cable. Blasting holes are constructed and charged along the roadway side roof at a certain distance ahead of the working face. The pre-splitting roof is formed by directional shaped charge blasting technology, which makes the roadway goaf side roof form a pre-splitting slit surface. After the coal seam recovery support of the working face is advanced, the dense monomer pillars are arranged close to the blasting pre-splitting slit surface to support the gangue in time. Under the action of self-weight and mine pressure, the roof of goaf automatically collapses along the cutting face to form a roadway wall. After the roof fully collapses and compacts, the single pillar is gradually withdrawn, and the roadway wall formed by the collapse is grouted to isolate the goaf, thus retaining a roadway along the working face and serving the mining of the next working face as a roadway adjacent to the working face.\(^6-9\) The technology of cutting roof and release pressure and automatically formed roadways has changed the traditional one working face and double-roadway mining mode of the long wall mining, and formed a new mining mode in which only one advanced gateway excavation needed. Its comparison with traditional long wall mining is shown in Figure 1. As can be seen from Figure 1, in order to mine one coal panel using the traditional long wall mining method, two roadways were excavated, and one coal pillar was retained. While only one roadway was excavated using the cutting roof and release pressure mining method, the other roadway automatically formed, none of coal pillar was retained. It can be seen that although the cutting roof and release pressure technique is used for non-pillar mining technology, it is notably different from the traditional coal pillar mining. Traditional non-pillar coal mining is mostly filled with a support wall on the side of the goaf behind the working face,\(^10-12\) meaning that the hardened wall supports the roof pressure of the coal seam, the mining stress and the pressure of the roof. The gob side of the cutting roof and release pressure method is automatically formed by the caving of roof rock. This method achieves no pillar mining between working faces, which makes the recovery rate of the mining area reach up to 100% in theory. Because the reduction of a roadway excavation, improvement of labor productivity, alleviation of the tense situation of mining excavation, and the advantages of cost reduction and

**FIGURE 1** Comparison plane graphs of cutting roof and release pressure mining method and traditional long wall mining
efficiency, the cutting roof and release pressure technology has been applied in the Shenhuai, Zhong, Chuan and Jizhong Energy coal enterprises in China.

Under the traditional mining mode, the working face is ventilated by a slot, and the air flow is discharged from another roadway to the return air roadway after passing through the working face. The shape of the air flow transport route is similar to the letter “U”, which is called “U” ventilation system. After adopting the mining mode of cutting roof and release pressure and automatically roadways formed, the existing two working face roadways are all used as air inlet roadways, and the remaining roadways are used as air return roadways. The shape of the air flow transport route is similar to the letter “Y”, which is called “Y” ventilation system. After adoption of the cutting roof and release pressure mining method, the working faces that have traditionally used a “U” type ventilation system have been adjusted to apply a “Y” type ventilation system, changing the face ventilation circuit and the goaf gas migration rule. Most scholars believe that the “Y” type ventilation system will increase the risk of spontaneous combustion in the goaf, while a number of other researchers believe that the “Y” ventilation system can reduce the difficulty in the management of the coal spontaneous combustion.

In addition, the fundamental reason for spontaneous combustion of coal left over in the goaf is that the inner surface of the broken coal reacts with the oxygen in the air and releases a large amount of heat. If the generated heat cannot be timely taken away, the reaction rate of coal oxidation will be further accelerated, and more heat will be accumulated until the ignition temperature is reached thus the coal spontaneous combustion happened. Coal spontaneous combustion not only burns a large amount of coal resources, jeopardizes the mine safety production, but also seriously destroys territorial resources, causes a series of ecological environment problems, and brings great harm to the social and economic development and people’s health. The goaf can be divided into tropical zone, oxidized to temperate zone and asphyxiation zone. The caving coal and rock in the tropical zone are in the state of free accumulation. Oxygen supply is sufficient but air leakage is large, resulting in the generated heat by the oxidation of residual coal is not easy to accumulate, thus the spontaneous combustion of coal seam is difficult to occur. The caving coal and rock in the oxidized to temperate zone are partially compacted, with small pore, a certain amount of air leakage, sufficient oxygen supply and certain heat storage conditions, which are prone to spontaneous combustion. The caving coal and rock in the asphyxiation zone are completely compacted, with very small pore, almost no air leakage and insufficient oxygen supply, so it is difficult to spontaneous combustion. The classification of “three zones” of spontaneous combustion is the theoretical basis for prevention and control measures of spontaneous combustion in the goaf. In view of the zoning of three zones, the method of beam tube monitoring is mostly used now. This method mainly detects the change of gas composition in goaf with the advance of working face by burying beam tube sampler in goaf, so as to determine the “three zones” range of spontaneous combustion in goaf. To study the problem of fire prevention and extinguishing under the condition of non-pillar coal mining technology, especially the coal spontaneous combustion mechanism, scholars have conducted considerable studies. For a long time, most scholars have studied the “three zones of spontaneous combustion” in association with a “U” ventilation system. Generally, the gas pressure in goaf of “U” ventilation system is fan-shaped distribution with the center of the intersection of working face and air inlet and air return way. For the “Y” type ventilation system, the characteristics of spontaneous combustion in the goaf and prevention and control technology have all been obtained from research on the filling technology. As part of the filling process, the roadway wall is composed of, for instance, a flexible film and high water material. The gas pressure in the goaf is mainly an elliptical distribution centered on the intersection point between the working face and the upper air entry. When applying the cutting roof and release pressure technique, the goaf wall is composed of rock or coal broken roof. The formation processes for the two materials are different, therefore there is a significant difference between the two materials. Thus, the impact on the face of the airflow is bound to be different. Whether the spontaneous combustion characteristics and the prevention and control technology of the goaf using “Y” type ventilation conditions are suitable for the cutting roof and release pressure technique need be further studied and verified.

However, to the best of our knowledge, the spontaneous combustion characteristics of the goaf and distribution of the three zones of spontaneous combustion in the goaf using cutting roof and release pressure technique have not been studied to date. This gap in the research will affect the development of goaf spontaneous combustion prevention measures and the promotion of cutting roof and release pressure technique. Inflammable coal seams have been a stumbling block hindering the comprehensive promotion of cutting roof and release pressure technique, which is regarded as the third mining technology revolution. Therefore, the evolution characteristics and control technology of the three zones of spontaneous combustion in the goaf for the cutting roof and release pressure technique were studied to promote the popularization of spontaneous combustion control in coal seams and to lay a theoretical and technical foundation for the full implementation of this revolutionary method.

The following part of this paper is organized as follows: Section 2 selects the indices of the three zones of spontaneous combustion, Section 3 discusses the evolution characteristics of the three zones of spontaneous combustion and
the corresponding prevention and control technologies, and Section 4 summarizes the conclusions.

2 | METHODOLOGY

2.1 | Overview of the studied coal mine

The studied mine named Halagou coal mine is located in Daliuta town, Shenmu county, Shanxi Province, China. The length of the mine is 8.4-11 km, its width is 8.3-10 km, and it covers an area of 85 km². The approved production capacity of the mine is 16 million t/a. There are 8 layers of recoverable and locally recoverable coal seams. The main mining coal seam is 2-2 coal, 3-1 coal and 4-2 coal, which is a nearly horizontal coal seam. So far, the mine has been identified as a gas mine. The spontaneous combustion grade of the 12 coal seam in the Jingtian area is class I, and the spontaneous combustion period is 1-3 months. The seam can readily spontaneously combust. Coal dust has explosion hazard.

The strata in the mine field show a monoclinic structure with SW inclination, and the undulation is not large, with wide and gentle undulation, and the dip angle is generally less than 1 degree. A small-scale normal fault exists in the southern part of the mine. There is no magmatic intrusion and distribution of karst collapse pillars. The geological structure type of the mine field belongs to a simple category. The topographic characteristics of the minefield are high in the Middle-East and low in the west. The surface elevation is 1084.1-1349.6 m, with a relative height difference of 265.5 m. Geomorphology is mainly composed of sand dunes and sand beams deposited by aeolian sand, sand dunes and sand beams eroded by flowing water, in which micro-geomorphic units such as gullies and depressions are developed.

2.2 | Overview of the working face

The 12201 fully mechanized coal face is the first mining face of the 12 coal seam in the two areas. Its thickness ranges from 0.8 to 2.2 m, with an average of 1.92 m, and its depth is 60 to 100 m. The roof of the coal seam is siltstone with the thickness ranging from 3.9 to 0.52 m (average ~1.84 m). The top of the roof of the coal seam is 12 up coal seam; the thickness is 0.0 to 2.75 m with an average of 1.56 m. The upper part of the 12 up coal seam is mudstone with a thickness between 2.14 and 0.55 m (average ~1.35 m). The old roof is composed of fine sandstone (thickness ~3.34 m) and siltstone (thickness ~4.05 m). The floor of the coal seam is siltstone, with an average thickness of 3.67 m. In accordance with the “operation of 12201 fully mechanized face of Halagou coal mine of Shendong Coal Group regulations,” when the coal seam thickness is less than or equal to 1.9 m, it will be mined in accordance with 1.9 m mining high cutting coal; when the coal thickness is more than 1.9 m, it will be mined in accordance with the mining height fully mechanized coal thickness. It can be seen that the gob of 12 coal left a lower amount of coal. However, on the top of the roof of the 12 coal seam, there is a 12 up coal seam with an average thickness of 1.56 m. All of the 12 up coal seam is left in the goaf of the 12201 working face. Because of the instability of the coal seam, it cannot be mined. However, the 12 up coal seam is only 1.84 m from the 12 coal seam, and it is completely in the caving range of the 12 coal mining.

The inclination length and the strike length of the 12201 working face are 320 m and 747 m, respectively. The working face is pushed to the cutting hole 12202, and the roadway is reserved. The technique of cutting roof and release pressure is used. The length of the reserved roadway is 580 m. The ventilation system has been adjusted from a “U” type system to a “Y” type system. The working face ventilation system is shown in Figure 2. The arrow in Figure 2 points in the direction of the airflow under the “Y” type ventilation system.

2.3 | Indexes and test method of the three zones of spontaneous combustion

The spontaneous combustion zone of the goaf is divided according to the basic conditions of the oxidizing environment and coal spontaneous combustion in the goaf. When dividing
the spontaneous combustion zone in the mined area, three indices are usually used: O\textsubscript{2} concentration, air leakage rate in the goaf and the temperature characteristics of the measuring point.

1. O\textsubscript{2} concentration: The concentration of O\textsubscript{2} reflects the possibility of coal spontaneous combustion. When the O\textsubscript{2} concentration is greater than 18%, it is a tropical zone. When the concentration of O\textsubscript{2} is between 10% and 18%, it is an oxidized to temperate zone. When the concentration of O\textsubscript{2} is <10%, it is a zone of asphyxia.

2. Air leakage rate in the goaf: The distribution of spontaneous combustion and air leakage of the gob coal are closely linked. When the goaf air leakage wind speed is greater than 0.24 m/min, it is scattered tropical. When the wind speed is between 0.1 m/min and 0.24 m/min, it is an oxidized to temperate zone. When the wind speed is less than 0.1 m/min, it is a zone of asphyxia.

3. Temperature characteristics: The temperature rise rate (K, °C/d) in the goaf area reflects the extent of spontaneous combustion risk. When The temperature rise rate K is ≥1°C/d, it is defined as the range of the oxidation temperature zone, and then the width of the “three zones” is determined by the above conditions.

Among the three indexes, it is difficult to measure the air leakage velocity in goaf, and most of them are analyzed by numerical simulation. When testing three zones of goaf in field engineering practice, the zoning can be carried out according to the oxygen concentration and temperature rising characteristics. However, since the temperature rising rate of the measuring point can only represent the temperature change of the measuring point location, it is difficult to characterize the spontaneous combustion of coal in the goaf, thus has certain limitations in application. Because of the strong gas diffusion, the measured gas concentration can characterize the risk of spontaneous combustion of coal in a certain area, so the oxygen concentration index has been widely used in the three zones of goaf in the field test. This paper divides the three zones of spontaneous combustion in goaf using the oxygen concentration index, and monitors them by the beam tube method. To be specific, the beam tube is implanted in the goaf behind the working face, and the oxygen concentration in the goaf is monitored by the beam tube. The steps of monitoring the O\textsubscript{2} concentration by beam tube method are as follows:

1. Install the beam tube monitoring system. Substations, pumps, and optical terminals are arranged in turn on the working face and connected in series by optical cables.

2. Bury the beam tube. A beam tube is embedded in the transport channel of 12201 working face at intervals of 30-50 m, and the depth of the beam tube is not less than 10 m. DN25 mm galvanized iron pipe is used to protect the beam tube.

3. Layout monitoring points. To obtain the three zones of spontaneous combustion of the goaf along working face 12201, a GC-4085 type mine automatic gas chromatograph and JSG4 mine fire beam tube monitoring system were used to arrange monitoring points along the slot at a 50 m interval to monitor the gas composition in the goaf. The location of each measuring point is shown in Table 1 and Figure 2. Table 1 gives the distance between each measuring point and the cutting eye of 12021 working face, and Figure 2 shows the specific location of each measuring point.

4. Gas sampling analysis in goaf. The goaf gas is pumped to the sub-station for gas analysis, and then the analysis results are uploaded to the ground data processing system through optical terminals and cables.

5. Three zones division. According to the monitored oxygen concentration, when the oxygen concentration drops to 18% or less, the goaf will be transferred from tropical zone to oxidized to temperate zone, and when the oxygen concentration continues to drop to 10% or less, the goaf will be transferred from oxidized to temperate zone to asphyxiation zone.

3 | RESULTS AND DISCUSSION

3.1 | Evolution characteristics of the three zones of spontaneous combustion

The length of working face 12201 is 320 m. The distance between the open-off cut and stop line is 747 m. The length of the gob side entry retaining wall is 580 m. The working face from the open-off cut to the 12202 cut has been worked using the traditional mining method. A switch to the cutting roof and release pressure techniques was made after pushing of the open-off cut of working face 12202. In the traditional mining mode, the working surface uses a “U” type ventilation mode, whereas for the cutting roof and release pressure modes, a “Y” type ventilation system is adopted.
The distance between the open-off cut 12202 and the open-off cut of working face 12201 is approximately 195 m. The distribution of the eight mined-out gas monitoring points is shown in Figure 1. The No. 1 and 2 points are in the area that uses a traditional mining mode, that is, uses a “U” type ventilation system. The No. 3 point is at the junction of where the traditional method and cutting roof and release pressure techniques are used, and therefore, the “U” type and the “Y” type ventilation systems occur at this junction. The remaining measuring points are where the cutting roof and release pressure techniques are used, where there is a “Y” type ventilation system. Oxygen concentrations at different points in the working face and at advancing distance from the working face are shown in Figure 3. The red line in Figure 3 indicates the boundary concentration of the three zones of spontaneous combustion, while the dashed line indicates the distance pushed by the working face at the boundary concentration.

It is apparent in Figure 3 that a “U” type ventilation system was used for ventilation of the working face associated with the traditional mining mode. Monitoring points No. 1 and No. 2 were in the “U” type ventilation system. When the work surface pushed 73 m, monitoring point No. 1 entered the oxidation zone. When the work surface pushed 89 m, it entered the suffocation zone. The oxidation zone depth is 73-89 m at the working face, and the oxidation zone width is approximately 16 m. After the work surface pushed through 64 m, monitoring point No. 2 entered the oxidation zone. After the work surface pushed through 82 m, it entered the suffocation zone. The oxidation zone depth is 64-82 m at the working face, and the oxidation zone width is approximately 18 m. Monitoring point No. 3 is located at the junction where the traditional method and the cutting roof and release pressure techniques are used, that is, at the junction of the “U” type and “Y” type ventilation systems. After the work surface pushed 76 m, monitoring point No. 3 entered the oxidation zone. After the work surface pushed 100 m, it entered the suffocation zone. The oxidation zone width is 76-100 m at the working face, and the oxidation zone width is approximately 24 m. Monitoring points No.4 through No. 8 were located in the “Y” type ventilation system associated with the cutting roof and release pressure techniques. After the work surface pushed 86 m, monitoring point No. 4 entered the oxidation zone. After the work surface pushed 208 m, it entered the suffocation zone. The depth of the oxidation zone near the gob side entry is 86-208 m at the working face, and the oxidation zone width is approximately 122 m. After the work surface pushed 85 m, monitoring point No. 5 entered the oxidation zone. After the work surface pushed through 201 m, it entered the suffocation zone. The depth of the oxidation zone near the gob side entry is 85-201 m at the working face, and the oxidation zone width is approximately 116 m. After the work surface pushed 60 m, monitoring point No. 6 entered the oxidation zone. After the work surface pushed 193 m, it entered the suffocation zone. The width of the oxidation zone near gob side entry is 60-193 m at the working face, and the oxidation zone width is approximately 133 m. After the work surface pushed 73 m, monitoring point No. 7 entered the oxidation zone. After the work surface pushed 176 m, it entered the suffocation zone. The depth of the oxidation zone near the gob side entry is 73-176 m at the working face, and the oxidation zone width is approximately 103 m. After the work surface pushed 116 m, monitoring point 8 entered the oxidation zone. After the work surface pushed 216 m, it entered the suffocation zone. The depth of the oxidation zone near the gob side entry is 116-216 m at the working face, and the oxidation zone width is approximately 100 m.

In summary, it is apparent that when using the traditional mining mode with “U” type ventilation system, the area that lays 0-68.5 m behind the working face is the heat dissipation zone, the area that is 68.5-85.5 m behind the working face is the oxidation temperature zone, and the area that is more than 85.5 m behind the working face is the suffocation zone. In addition, when the cutting roof and release pressure techniques together with the “Y” type ventilation system was applied, the area that is 0-84 m behind the working face is the heat dissipation zone, the area that is 84-198.8 m behind the working face is the oxidation temperature zone, and the area that is more than 198.8 m behind the working face is the suffocation zone.

### 3.2 Prevention and control technology of spontaneous combustion in the goaf

According to the mechanism and process of coal spontaneous combustion, coal spontaneous combustion is a complex process that is affected by many factors. The necessary and sufficient conditions for coal spontaneous combustion are: (a) coal with a spontaneous combustion tendency is in a broken and accumulated state; (b) continuous aeration conditions; (c) accumulation of generated heat from coal oxidation, which is difficult to disperse in a timely manner; and (d) the coexistence time of the aforementioned three conditions. The first factor is related to the internal characteristics of coal and coal conditions, which indicates the ability of coal to interact with oxygen. Factors 2 and 3 are external factors that are dependent on the geological conditions of the mine and the technical conditions.
According to the four conditions that are required for the spontaneous combustion of coal, it is apparent that if air leakage to the spontaneous combustion area can be eliminated or reduced, there will be insufficient oxygen for the oxidation process. To a certain extent, this can delay the spontaneous combustion of coal, thereby preventing the occurrence of spontaneous combustion for a certain amount of time.

Therefore, the prevention and control of spontaneous combustion of coal seams starts with the prevention of air leakage and the reduction of oxygen concentration in the goaf. The “Y” ventilation system increases the risk of spontaneous combustion in goaf to a certain extent. In the process of mining with cutting roof and release pressure, certain technical measures should be taken to prevent air leakage and prevent spontaneous combustion in goaf. In view of the actual situation at the Halagou coal mine, the technical measures for preventing and extinguishing fire are as follows.

3.2.1 | Pressure equalizing ventilation

To reduce the working face crossheading air flow in the goaf, the Halagou coal mine adopted a reduced working surface with wind and pressure ventilation measures. That is, applying comprehensive methods of construction of adjustment air volume facilities at the 12202 main retreat, adjustment of the air volume and pressure at the 12201 transport trough and the 12201 air trough, reduction of the gas pressure difference between the goaf and mining space, adjustment of the wind window and control wind pressure in the 12203 transport along the chute and 12204 transport along the trench at the same time. In the 12202 open-off cut, a 2 × 18.5 kW fan has been placed to increase wind pressure. The pressure difference between the gas pressure and the gas pressure in the stay is controlled within 100 Pa. Working face 12201 back to the wind is 585 m³/min and wind speed is 1.0 m/s. Air distribution of the transport trough is 447 m³/min and the wind speed is 0.55 m/s. The air volume of the left lane is 1032 m³/min and the wind speed is 0.92 m/s.

3.2.2 | Ground fissure sealing

The burial depth of coal seam 12 of the Halagou coal mine is shallow. When the coal seam 12 was mined, roof collapse caused the ground to produce a large number of cracks (Figure 4). Figure 4 shows the development of ground fissures after mining of working face 12201. The Halagou coal mine uses an exhaust ventilation system, so the wind pressure in the ventilation system of the mine is often less than the atmospheric pressure. This step creates a pressure difference between the atmosphere and the lane. It has the necessary conditions for the ground air to enter the mined out area through the excavated area. The air pressure difference is shown in Figure 5. Figure 5 shows the variation of surface atmospheric pressure and gas pressure in retained roadway. The statistics associated with external air leakage are shown in Figure 6. It is apparent in Figure 6 that there is external air leakage at the mine. The external air leakage is 27-112 m³/min with an average of 64 m³/min. During an unstable period, the maximum external air leakage is as high as 218 m³/min. The Halagou coal mine arranges timely backfilling and plugging of ground cracks every day (Figure 7). Figure 7 shows the situation of surface cracks in working face 12201 after sealing.

3.2.3 | The working surface leakage plugging

The working face associated with the cutting roof and release pressure techniques uses a “Y” type ventilation system. That is, the airflow along working face 12201 that returns through the roadway and the inlet airflow of the transportation are mixed in the upper corner into the left lane slot. In the process of flowing along the working surface, a part of the wind flow enters the goaf along the interface between the working face and the goaf. After an area is mined out, air passes through the lane and the goaf area of the interface into the lane, mixes with the wind in the lane, and exits through the open-off cut of working face 12202. Turbulent winds will run through the corners in the process of flowing from the working face to be transported through or flowing from the return air trough into the working face. Air flow is affected by centrifugal forces, and the outer part of the air flow is formed by the deceleration and pressurization of the area. After the turn, because the flow rate is large and the radius of the curvature is small, a vortex area will appear on the inside due to inertia. The size and intensity of the vortex are larger than the outer vortex area, which causes flow of the wind to the goaf. In addition, if the wind from the return airway attempts to enter the work surface, it will almost flow into the mined area perpendicular...
The closer to the air trough, the easier the air leakage in the gob side entry is to the bottom of the goaf. It eventually blows into the alley. To this end, the working area of the air leakage area must be blocked to prevent fresh air from blowing into the mined area, which results in the oxidation of coal.

The working surface mainly leaks from the return airway and from the working surface to the mined-out area. The Halagou coal mine internal air leakage prevention measures are as follows.

Build a wall in the return airway
Build a wall approximately every 50 m in the return airway behind the working face in the process of advancing working face 12201 to reduce the air trough of goaf air leakage.

Hang a wind account in the front of the working face
Hang a wind account from the return airway 12201 to the brackets in the front of the working face. This can reduce the air leakage flow into the goaf.

Reduce the air distribution
The mining intensity and working air leakage volume are proportional to the square; therefore, a reduction in the air quantity of the working face can reduce air leakage into the goaf, thereby reducing the goaf float coal oxidation generated by CO emission. Adjusting the working face of the Halagou coal mine air entering the working surface will decrease the supply from 700 m$^3$/min to 400 m$^3$/min.

3.2.4 | Gunit on the side of the lane

The necessary and sufficient conditions that facilitate roadway air leakage are the existence of air leakage channel and pressure difference between the ends of the channel. Whether it is external or internal leakage, the wind is drawn into the retaining lane through the interface between the lane and the gob from the goaf. Because of the pressure difference between the retaining road and the goaf, the gas in the goaf area is drawn into the roadway through the fissure of the roadway. To further reduce the risk of spontaneous combustion of residual coal in the goaf, on the basis of reducing the air leakage to the mined-out area, the Halagou coal mine also uses a spraying method to block the roadway fissure of the retaining road. The mine adopts the two spraying methods with a spray thickness of 80 mm. The effect of shotcrete is shown in Figure 8. Figure 8 shows the situation of retaining roadway wall after blocking cracks by grouting.

3.2.5 | Anti-fire technology of inert gas

The Halagou coal mine uses an interval nitrogen injection method to accelerate the inerting of the mined area. A certain
length of thick-walled steel pipe is buried as a nitrogen injection pipe along the goaf in the face of the air trough. The hydraulic support or work surface transportation head and tail of the working face are used as traction transport. The nitrogen injection pipeline moves along with the advance of the working face to maintain it at a certain depth in the goaf.

3.3 | Effect analysis of prevention and control technology

Working face 12201 of the Halagou Coal Mine which initiated with the traditional mining method on July 11, 2015, was converted to the cutting roof and release pressure techniques after attaining 195 m and was finished on November 27, 2015. This face was closed permanently on December 25, 2015. At 346 m, the CO concentration in the mined-out area reached 326 ppm, following which, comprehensive control technology was adopted. The CO concentration in the mined-out area was maintained below 300 ppm, allowing for the safe mining of the 12201 working face.

4 | DISCUSSION

As can be seen from the Section 3.1, compared with traditional methods, the width of oxidized to temperate zone increases and the risk of spontaneous combustion increases. However, after taking preventive measures, the safe mining of working face is effectively guaranteed without spontaneous combustion. Compared with other regions, the area with more air leakage passages has more serious spontaneous combustion problems. Besides the air leakage inside the working face, there is also external air leakage, which increases the risk of spontaneous combustion and the difficulty of control. Even so, it can still be safely mined. It can be seen that the cutting roof and release pressure technology has strong applicability in the area of spontaneous combustion coal seam.

5 | CONCLUSION

To prevent goaf spontaneous combustion with the cutting roof and release pressure technique, O₂ concentrations were monitored with the beam tube method in the goaf, and the evolution of the three zones of spontaneous combustion inside the goaf were analysed when the traditional and cutting roof and release pressure mining methods were applied. Comprehensive fire prevention measures were developed for the cutting roof and release pressure technique. According to the analysis of the monitoring data, the following conclusions are made.

Under the traditional mining method with the “U” type ventilation system, when the working face is pushed 68.5 m, the goaf is transformed from a cooling zone to an oxidation and rising temperate zone. At 85.5 m, it is converted into the suffocation zone. Under the cutting roof and release pressure technique with the “Y” type ventilation system, when the working face is pushed 84 m, the mined-out area transfers from the cooling zone to the oxidation zone. When it is pushed 198.8 m, it enters into the suffocation zone.

After implementation of comprehensive measures such as pressure ventilation, fire prevention, ground fracture plugging, plugging the air leakage in the working face, left side tunnel spraying plugging and inert gas fire extinguishing, the CO concentration of the gob is reduced to below 300 ppm in the process of mining, and safe mining of the working face 12201 was achieved. This safe mining practice suggests that the cutting roof and release pressure technique is suitable for the easy spontaneous combustion of coal seams.

Through the monitoring of O₂ concentration, the three zones of evolution characteristics of goaf spontaneous combustion were obtained when the cutting roof and release pressure technique was applied. The evolution characteristics accurately reflect the oxidation temperature in the goaf, and it provides a basis to prevent goaf spontaneous combustion. Because many factors would influence the three zones of spontaneous combustion, the evolution characteristics of goaf spontaneous combustion when using the cutting roof and release pressure technique needs further study under other different geological conditions.

ACKNOWLEDGMENTS

The author(s) disclose receipt of the following financial support for the research, authorship, and/or publication of this article: The project was financially supported by the National Key Research and Development Programme of China (2016YFC0801402, 2016YFC0600901), the National Natural Science Foundation of China (No. 51874122, No.51704100), the Key Research Projects of
REFERENCES

1. British Petroleum (BP). Statistical Review of World Energy 2016. London: British Petroleum; 2016.
2. Ren CP, Ding RJ, Li S. Reasons and countermeasures of Chinese low coal extration rate. J Liaoning Tech Univ. 2010;29:136-137.
3. Balat M. Usage of energy sources and environmental problems. Energ Explor Exploit. 2005;23:141-167.
4. He MC, Zhu GL, Guo ZB. Longwall mining “cutting cantilever beam theory” and 110 mining method in China-The third mining science innovation. J Rock Mech Geotech Eng. 2015;7:483-492.
5. He MC, Zhu GL. Research on development strategy of mining engineering in the Thirteenth Five-Year Plan. Coal Eng. 2016;48:1-6.
6. Zhang GF. Study on the Mechanism and key Technology of Roof Cutting and Pressing Along Goaf. Beijing: China University of Mining and Technology (Beijing); 2010.
7. Sun XM, Liu X, Liang GF, Wang D, Jiang Y. Key parameters of gob-side entry retaining formed by roof cut and pressure releasing in thin coal seams. Chin J Rock Mech Eng. 2014;33:1449-1456.
8. Zhang GF, Yu XP, Huang ZG, Xia YY. Disaster control technology for hard coal mining in upper protective layer of close distance outburst seams. Coal Eng. 2015;47:88-91.
9. Guo PF, He MC, Wang J, Zhou H. Test study on multi tray bolt in gob-side entry retaining formed by roof cut and pressure releasing. Geotech Geol Eng. 2017;35:1-10.
10. Yang HY, Cao SG, Wang SQ, Fan YC, Wang S, Chen XZ. Adaptation assessment of gob-side entry retaining based on geological factors. Eng Geol. 2016;209:143-151.
11. Tan YL, Yu FH, Ning JG, Zhao TB. Design and construction of entry retaining wall along a gob side under hard roof stratum. Int J Rock Mech Min. 2015;77:115-121.
12. Zhang ZZ, Bai JB, Chen Y, Yan S. An innovative approach for gob-side entry retaining in highly gassy fully-mechanized ongwall top-coal caving. Int J Rock Mech Min. 2015;80:1-11.
13. Yang HH, Xue EL, Luo W, Song LB. Application of non pillar mining technology of top cut and pressure relief automatic roadway in Shenhua Group. Coal Science & Technology Magazine. 2015:1-3.
14. Qi HG. Study and application of thin seam mining technology and complete equipment. Coal Sci Technol. 2014;42:12-16.
15. Zhang GF, He MC, Yu XP, Huang ZG. Research on the technique of no-pillar mining with gob-side entry formed by advanced roof caving in the protective seam in Bajiao coal mine. J Min Saf Eng. 2011;28:511-516.
16. Liu SL, Li HM. Application of pre-splitting blasting technology on roof of gob-side entry retaining. Coal Sci Technol. 2012;40:4-8.
17. Wang JS. Research on Mining Coal Bed Spontaneous Combustion and Prevention Basic of Shendong Mining Area. Liaoning Technical University. 2006.
18. Cai ZW. Study on the Law of coal spontaneous combustion in goaf of fully-mechanized face with Y-type ventilation. Anhui University of Science and Technology. 2009.
19. Liu W, Qin YP, Hao YJ, Gui T. Numerical simulation on spontaneous combustion of goaf under “Y” type ventilation. J Liaoning Tech Univ. 2013;32:874-879.
20. Wu JM, Li MZ, Zhou CS. The test and analysis of gob air leakage in gob-side entry retaining with Y-type ventilation condition. Saf Coal Min. 2012;43:132-134.
21. Lu GB, Geng M. Spontaneous combustion of coal mined-out area and its mechanism of control research. J Liaoning Tech Univ. 2009:28-28-30.
22. Yang XH, Ma BC, Fan SW. Analysis on gas control effect based on gateway retained along goaf Y type ventilation. Coal Sci Technol. 2011;39:46-48.
23. Wang DM, Dou GL, Zhong XX, Xin HH, Qin BT. An experimental approach to selecting chemical inhibitors to retard the spontaneous combustion of coal. Fuel. 2014;117:218-223.
24. Parsa MR, Tsukasaki Y, Perkins EL, Chaffee AL. The effect of densification on brown coal physical properties and its spontaneous combustion propensity. Fuel. 2017;193:54-64.
25. Zhang YL, Wu JM, Chang LP, Wang J, Xue S, Li Z. Kinetic and thermodynamic studies on the mechanism of low-temperature oxidation of coal: a case study of Shendong coal (China). Int J Coal Geol. 2013;120:41-49.
26. Choi H, Jo W, Kim S, et al. Comparison of spontaneous combustion susceptibility of coal dried by different processes from low-rank coal. Korean J Chem Eng. 2014;31:2151-2156.
27. Jo W, Choi H, Kim S, et al. Changes in spontaneous combustion characteristics of low-rank coal through pre-oxidation at low temperatures. Korean J Chem Eng. 2015;32:255-260.
28. Kim J, Lee Y, Ryu C, Lim H. Low-temperature reactivity of coals for evaluation of spontaneous combustion propensity. Korean J Chem Eng. 2015;32:1297-1304.
29. Qin B, Li L, Ma D, Liu Y, Zhong X, Jia Y. Control technology for the avoidance of the simultaneous occurrence of a methane explosion and spontaneous coal combustion in a coal mine: a case study. Proc Saf Environ. 2016;103:203-211.
30. Cui TJ, Ma YD, Wang LG. Simulation on spontaneous combustion of goaf under “U” type ventilation and improvement. J Syst Simul. 2015;27:3096-3101.

How to cite this article: Chen X, Li L, Guo Z, Chang T. Evolution characteristics of spontaneous combustion in three zones of the goaf when using the cutting roof and release pressure technique. Energy Sci Eng. 2019;7:710-720. https://doi.org/10.1002/ese3.287