INTRODUCTION

According to the second nationwide coal resources prediction result, the total coal resources of China amount to $5.572 \times 10^{12}$t.\(^1\) In spite of the abundant amounts, majority of the coal reservoirs in China are characterized by low permeability, soft quality, thick seam, and poor lateral continuation.\(^2,3\) Meanwhile, China also has vast coal bed methane (CBM) resources, and its recoverable reserves of 1.023 x 10\(^{11}\) m\(^3\), accounting for 13% of the total CBM resources of 12 CBM richest countries,\(^4\) making it rank the third in the world. The byproduct of such rich reserves is the high coal-seam methane (CMM), and the content of methane ranges from 8 m\(^3\)/t to 20 m\(^3\)/t in most of mine areas,\(^5-8\) meaning that the coal mines are threatened by potential hazard of gas outburst and gas explosion.\(^9\) As the CBM accumulation is positively correlated with coal reservoirs, it has distinct characteristic of regional enrichment. China has 3284 gassy and outburst-prone coal mines distributing in 26 coal rich provinces in 2012.\(^4\)

In Qinshui Basin, which is the biggest CBM block of Shanxi Province, the CBM reserves buried below less than 2000 m account for one-third of the national total.\(^10\) The most lethal reason restricting the coal exploitation in this region is high gas content, which will endanger the safety of the mining working face.\(^11\) Buried about 600 m at the base of the Lower Permian system, the coal seam in Qinshui Basin is thick and gassy. Most coal seams in Qinshui Basin exceed 6 m in thickness and the CBM geological reserves amount reaches 6.85 x 10\(^{12}\) m\(^3\), with an extremely high content of gas outburst and gas explosion.\(^9\)
greater than 20 m³/t in some areas. Moreover, just like other coal producing regions, Qinshui Basin also has a low permeability, generally ranging from 0.1 md to 0.2 md. The strong gas adsorption of coal seam deteriorates this condition. These complicated CMM occurrence conditions (high methane content, low permeability, strong adsorption) give Qinshui Basin great gas pressures, and great difficulties in pre-drainage in the virgin coal seam, thus leading to highly potential hazard of gas accident.

To address the high gas content of coal seam, the most useful methods are mining the protective seam and gas pre-extraction in coal mines. However, mining protective seam demands highly strict conditions, and especially works poorly in single coal seam. Therefore, it is necessary to drill boreholes for gas drainage in single coal seam or multiple coal seams of which the intervals between seams are large.

With the development of equipment and technology, various novel gas drainage methods are applied to solve methane problems. Chinese CMM extraction practice first started in 1938 and was systematically commenced in early 1950s. In the past 80 years, gas drainage technologies underwent lots of innovations, from initial extraction pump (1938) to subsequent underground boreholes (early 1950s) and cross-measure boreholes (mid-1950s); from high-level suction gateway (mid and late 1950s) to active stimulation technologies including hydraulic fracturing and hydraulic cutting and loose blasting (1960s); from surface boreholes in 1970s to the combination of surface and underground extraction (1990s); from mining-induced gas flow increasing in early twenties to some new CMM extraction technologies in recent decade. All the above mentioned gas drainage measures are applied according to three factors, including coal bed geology, CMM occurrence and mining conditions, and they can be classified as underground, surface and the combination of underground and surface. Contemporarily, underground CMM extraction technologies are relatively developed in China, and become the main method for gas control. However, gas extraction is not limited to a single extraction method, and the combination of multiple extraction methods is the current development direction.

Along with the technical innovations, multiple gas drainage methods have been proposed for addressing gas challenge, such as in-seam borehole extraction, high-level suction gateway, and gob buried pipe extraction. Their synergy is the trend of multi-purpose underground gas drainage. However, the drainage effect of this current combination was based on the experience of technicians, and gas drainage schemes coordination are not up to expectation. A new arrangement of underground boreholes with typical pattern and special layout enabling long-lasting drainage and multi-dimensions is in urgent need. Therefore, inverted ‘π’ shape km borehole group was put forward to deal with this dilemma.

2 | MODEL DESCRIPTION AND METHODOLOGY

2.1 Double stress relief circle model of gateway and borehole

Double stress relief circle model of gateway & borehole is based on the stress relief circle theory. The model considers the gateway and borehole as similar holes, and the stress of surrounding rock is redistributed, which results in the increase of fractures and permeability. Therefore, the gas flow becomes easier. The model is shown in Figure 1. These dotted lines in the Figure 1 means the boundary of different zone, and divide the gateway and borehole surrounding rock into four parts, where A-D means fracture zone, plastic zone, elastic zone, and original stress zone, respectively.

Stress relief circle theory is an important model that studies fracture development around gateways and boreholes, and it is the theoretical foundation of the proposed inverted π-shape km boreholes layout. The theory considers that the coal mass around the gateway under the mining stress present deformation and fracture development, thereby forms...
an approximate annulus fracture area around the gateway.\textsuperscript{25} The existence of stress relief circle, on one hand, increases the permeability of coal seam, consequently provides gas flow channels; on the other hand, with the relief of mining-induced stress, more methane is desorbed from coal seam and gas drainage becomes easier accordingly.\textsuperscript{26}

On the basis of stress relief circle theory, Liu et al\textsuperscript{27} analyzed the plastic zone radius and fracture developing condition around the gateway; Hu et al\textsuperscript{28,29} numerically studied the surrounding rock of gateway. According to the deformation, the surrounding rock from the gateway to the further area was radially divided into fissure zone, plastic zone, elastic deformation zone, and the original state of rock area; and according to the gas seepage status inside the coal mass, the area was divided into complete percolation area, transition area, seepage barrier area, and the original rock seepage area. Based on Liu's and Hu's works, Figure 2 shows the change in stress and permeability from surrounding rock to gateway, and the law of gas flow distribution. As the distance of surrounding rock and roadway increases, stress first increases and then decreases, and permeability first decreases and then increases, and gas flow capacity also decreases and then increases.

As the gateway and boreholes proceed, the stress of their surrounding rock changes, and a stress relief circle around them is formed, respectively, which damages rock and generates fractures. Rock fractures are expanding and generating new fractures. The fractures between the borehole and gateway are interconnected, which greatly improves the porosity of coal.\textsuperscript{30} Permeability is the important factor to predicate the ability of gas flow in coal mass. Palmer and Mansoori\textsuperscript{31} simplified the regularity of permeability changing with the porosity as follows:

\[
\frac{k}{k_0} = \left(\frac{\phi}{\phi_0}\right)^3
\]

Where the subscript 0 refers to the reference state, \(k\) is the permeability, and \(\phi\) is the porosity. From the Equation 1, as the fractures are evolving, coal porosity increases, the permeability also increases, and the gas in coal mass flows more easily.

The interaction between boreholes is considered. The gateway can be regarded as a big borehole, and the gateways and boreholes will influence each other. The gas pressure at one point between the boreholes is given as\textsuperscript{27}:

\[
T_{ia}(x,y,z) = p_{ia}(x,y,z) - p_0(x,y,z)(1 + \sum_{j=1}^{N} \frac{p_j(x,y,z)}{p_0(x,y,z)})(i=1,2,3 \ldots)
\]  

where the value of \(p_j(x,y,z)\) denotes the contribution of the reduced gas pressure due to the borehole \(i\).

In the coal seam, both free and adsorbed methane are controlled by a mass conservation equation:

\[
\frac{\partial c}{\partial t} + \frac{\partial (\rho \phi)}{\partial t} = -\nabla m - \nabla (\rho V)
\]

where \(c\) is the quantity of adsorbed gas per volume of coal matrix, \(kg/m^3\); \(\rho\) is the gas density, \(kg/m^3\); \(\phi\) is the fracture porosity, \%; \(m\) is the mass diffusion flux of the adsorbed gas, \(kg/(m^3\cdot s)\), and \(V\) is the gas velocity of the free gas, \(m/s\).

According to the Langmuir equation, Fick's law and Darcy's law, the Equation 3 can be written as:

\[
\frac{\rho_c V_m P c}{V_m (P + P_f)^2} \frac{\partial P}{\partial t} + \frac{M_c}{RT} \left[\frac{\phi}{\partial t} + P \frac{\partial \phi}{\partial t}\right] - \nabla (D V c + \frac{\rho c}{\mu} \nabla p) = 0
\]  

where \(P\) is the gas pressure of coal, \(Pa\); \(V_m\) is the molar volume of methane under standard conditions, \(m^3/mol\); \(\rho_c\) is the coal density, \(kg/m^3\); \(M_c\) is the molar mass of methane, \(kg/mol\); \(R\) is the universal gas constant, \(J/(mol\cdot k)\); \(T\) is the temperature of coal, \(K\); \(k\) is the fracture permeability, \(m^2\); \(\mu\) is the methane viscosity, \(Pa\cdot s\).

With the gateway being excavated, coal mass around the gateway produces large number of fractures, leading to imbalance of gas adsorption pressure. Gas pressure in the fractures drops, resulting in methane desorption and flowing into the fractures.\textsuperscript{32} Affected by the negative pressure inside the boreholes, the free gas inside the coal seam of gateway relief pressure area will flow through the fractures into the boreholes and then be pumped to the gas pipelines to the ground. This process further breaks the adsorption equilibrium, causing the coal seam methane desorption into free methane continuously, and then to be taken away from the coal seam. The diagram of methane flow progress is shown in Figure 1.

**FIGURE 2** The elastic–plastic secondary stress and rock permeability distribution around a gateway
2.2 | Technological support

Kilometer drilling rig (km drilling rig), also known as Horizontal directional drilling (HDD), is a special drilling rig which can drill horizontal boreholes with great length, generally reaching 600 m into coal seam for methane pre-drainage.33–35 As a new technology developed in recent years, it has many positive features over traditional techniques. These advantages, including the drainage of a large area from a single drill site, the ability of effectively increasing permeability by deep drilling and by orientation of laterals, dramatically improving the gas drainage efficiency.

Apart from these, another predominant characteristic of the km drill is that it can precisely ascertain the conditions of geology and the tending of coal seams via exploring the roof strata and the floor strata, which provides detailed coal recovery data. Although widely applied in gassy mines, the utility of km drill is mainly limited within the coal seam and the fissure zone with hard primary rock, thus has not achieved its full use.

Based on the analysis of CMM conditions, the current situation of CMM extraction as well as the advantages of 1000 m borehole (km borehole), a new layout of borehole arrangement can be suggested. Named as inverted ‘π’ shape km borehole group pattern, this layout has two peculiarities and aims at two goals. First, the borehole group all consists of km boreholes. Second, the boreholes are laid out in the shape of an inverted ‘π’ throughout three strata (caving zone, fissure zone, and coal seam), and the borehole layout in the bottom of caving zone had not been used before. Therefore, by this unique arrangement, all the contemporary techniques of underground gas drainage during preparation and production period can be combined in just one set of boreholes, and the feasibility of km boreholes can be greatly broadened. Every km borehole and its branch will work the same as multi-branched horizontal wells. With this inverted ‘π’ borehole group, both the construction cost and the time-consumption can be cut down, while the drainage efficiency is improved simultaneously.

2.3 | Inverted π shape km boreholes group model

Inverted π shape km boreholes group is a new underground gas drainage boreholes pattern, which works in a wide area and lasts a long period in extracting coal mine methane. Before the gateway excavation, drill field should be constructed in the coal seam besides the gateway. After this, the km drilling rig is used to drill a group of km boreholes from this drill field. Part of the boreholes are horizontally situated in the coal seam and on the bottom of caving zone, extracting the gas within the gateway area; the other part of the boreholes can be arranged in the fissure zone and gradually deviated from the roadway in both horizontal and vertical directions, which can play a role of degassing the methane during the period of recovery. The layout is very similar to the symbol ‘π’ in lateral view, thus the name of the layout is given. The arrangement of boreholes is shown in Figure 3.

The process of the layout and its function is as follows. (a) Before the gateway excavation, the gas drainage in the working face is completed by the boreholes drilled in coal seam. To enhance the extraction efficiency, multi-laterals can be branched to achieve flow-increasing effect. (b) Once the gas content of the working face drops below 8 m³/t, it is proper for the gateway tunneling. By then, the boreholes in gateway section are abandoned. Meanwhile, other boreholes should remain normal operating to ensure the tunneling face safety. By means of draining the CMM which comes from the mining-induced stress relieved area, the methane emitting into the working face is prevented. To reduce the number of km boreholes in the coal seam, ZDY-4000 drilling rig drills normal boreholes in the coal seam. The boreholes have a length of 120 m during the groove excavation, and they will pre-drain the coal seam methane. (c) During the coal mining proceeding, the in-seam km boreholes, the bottom of caving zone boreholes and the bottom of fissure zone boreholes are near the corner of the working face. They drain the methane from the working face corner, gob and fissure zone. A short time later, the boreholes laid out in the middle and top of fissure zone are working. The working situation of km boreholes is shown in the Figure 4.

In the entire working period, the km boreholes take the role of gas pre-drainage boreholes of gateway tunneling, gas drainage boreholes of gateway tunneling, in-seam gas pre-drainage boreholes, buried pipes in upper corner, gas drainage boreholes of gob and gas drainage boreholes of fissure zone, respectively, in different stages. The working time lasts from gateway tunneling to coal mining. It not only streamlines construction process, but also takes the place of the high-level suction roadway, improving economic performance while reducing engineering workload.

2.4 | Strata division and layout parameters of the layout

The advantage of inverted π-shape km borehole group is the three-dimensional layout of boreholes. Therefore, to promote the gas drainage, it is necessary to put up a fine division of the strata above the gob. The most famous existing dividing theory is the ‘Three Zone’ theory, which defines the seam from coal to ground surface as caving zone, fissure zone and bending zone. According to the mining overburden movement, the deformation of coal-rock mass induces the pressure relief and permeability increase.36–38
Section 2.3 refers to the theoretically determined approximate scope of km borehole layout. Engineering practice is needed to further determine the accurate parameters of inverted π-shape km boreholes layout. The work should mainly determine the number of boreholes and the relative distance of boreholes to gateway. The boreholes are gathered in the coal seam, the bottom of caving zone, and the fissure zone, respectively. The top of caving zone does not lay out boreholes.

**Figure 3** The arrangement of inverted π-shape km boreholes group (the branch boreholes are not shown in the figure); Section A-A: Lateral view of the arrangement of the group; Section B-B: Front view of the arrangement of the group

**Figure 4** Kilometer boreholes come into direct contact with the gob while backstopping
2.4.1  Arrangement of in-seam boreholes

In-seam boreholes should be arranged to drain the methane in the coal mass of the gateway and the two coal walls. Through the field data measurement of the km borehole and the coal mine, and by taking the safety factor into account, the valid gas drainage radius can be set to 2.5 m. In the horizontal direction, the boreholes can be laid within 20 m alongside the coal walls, and their interval is set to 5 m. In the vertical direction, if it is thin coal seam, boreholes are laid in the center of coal seam; if it is thick coal seam, two or more rows of boreholes are laid.

2.4.2  Arrangement of borehole at the bottom of caving zone

To promote gas pre-drainage rate before the gateway excavation, some km boreholes are laid at the bottom of caving zone, and the stress relief circle of the boreholes must reach the coal seam. Rock permeability is far below than coal seam permeability, so the effective radius of borehole gas drainage in the rock is less either. According to the theory of stress relief circle, stress released zone around borehole is the annulus 3-5 times the borehole diameter. Therefore, the scope that coal bed roof above 5 times of borehole diameter area is rock valid borehole drainage area for coal seam gas pre-drainage, and it is called bottom of caving zone. Within the scope of the effective radius of boreholes, the rock boreholes could pre-drainage coal seam methane. The height of bottom of caving zone is calculated by the following formula:

\[ a = \frac{h}{(K_p - 1) \cos \alpha} \]  

where \( a \) is the height of bottom of caving zone, m; \( h \) is the mining height of coal seam, m; \( K_p \) is the bulking coefficient of the caved rock; \( \alpha \) is the dip angle of coal seam, (°).

Fissure zone height means the distance from the coal seam roof to the upper of fissure zone. The maximum height of the fissure zone is obtained by the following formula:

\[ b = \frac{100h}{1.6h + 3.6} \pm 5.6 \]  

where \( b \) is the height of fissure zone, m.

In the vertical direction, fissure zone boreholes are laid between the upper of caving zone and the upper of fissure zone (namely from \( a \) to \( b \)), the vertical interval of boreholes is 5-20 m. In the horizontal direction, the distance between gateway centerline and boreholes in the plane projection increases step by step, and the horizontal interval of boreholes is 5-25 m.

3  FIELD TEST

3.1  Test site

The Yuwu Coal Mine was located at the Lu’an coalfield of Shanxi Province, China. The primarily mined coal seam, No.3 coal seam, is a single coal seam. The parameters of No.3 coal seam are as follows: the coal thickness is 5.9 m, the original gas content is 8.40-18.10 m³/t, the residual gas content is 3.51 m³/t, the absolute value of original gas pressure is 0.52–0.55 MPa, the porosity is 4.93%-6.71%. The parameters show that the coal seam is low permeability, strong adsorption, difficult drainage, and high gas content. Worse, the production data of nearby coal mine with similar geological conditions reveals that No.3 coal seam has the risk of coal and gas outburst.

3.2  Gas drainage scheme

3.2.1  Gateway tunneling period

No.A working face is a tunneling face, where km boreholes are used for gas pre-drainage in coal seam. To avoid
3.2.2 | Mining face pre-drainage period

In the process of gateway excavating, short in-seam boreholes were drilled by regular rig for gas pre-drainage in the excavated gateway. Gas drainage in coal seam lasted a long time, generally about 3 months. The borehole number and coverage area of regular in-seam borehole was far more than that of km borehole in coal seam. Therefore, the methane concentration and methane flow in regular boreholes were the main statistics in this period.

The incline length of No.B mining face was 300 m. For the sake of controlling the total mining face, in-seam boreholes at haulage gateway and return airway were laid, respectively. Two rows of boreholes were laid in the coal seam at the thickness of 6.3 m. The bottom row of boreholes was parallel with coal seam, and the upper row of boreholes had 3° inclination to the bottom ones. The lengths of the boreholes of bottom and upper row were 155 m and 160 m, and the distance between tapping position and floor were 1.5 m and 2.5 m, respectively. The interval of the boreholes was 2.5 m. The incline angle of boreholes ranged 2°-3° to avoid water accumulation in the boreholes. The in-seam boreholes were shown in Figure 8.

Six boreholes were combined as a group, and an orifice plate flow meter was installed to record the methane flow, and then the gas was merged into drainage pipeline. After the in-seam boreholes were completed, the total average gas flow in return airway and haulage gateway was 12.69 m³/min and 14.02 m³/min, respectively. After the gas was drained for 6 months, coal mining began. The methane in gob migrated into fissure zone, and then the km boreholes in fissure zone came into operation. Meanwhile, in-seam boreholes were still working until they were destroyed.
3.2.3 | Mining period

In mining period, km borehole in fissure zone and regular in-seam borehole both play a role in gas drainage. Nine roof high-level boreholes were constructed at No. C working face to extract the methane that migrated into fissure zone, and the boreholes were located at the No. 1 km drill field in the return airway. The plane and profile compared diagram of boreholes were shown in Figure 9.

The gas concentration and gas flow in km borehole in mining period were shown in Figure 10, indicating that they firstly increased and then decreased in the borehole in fissure zone. The data of in-seam boreholes in mining period were not shown in Figure 10.

The fluctuation of gas extraction data is due to the mining influence on fracture development in fissure zone. After mining in the working face, the boreholes in the lower part of the fissure zone close to the gob area, and the gas released by mining in the coal seam is extracted. After a period of times, gas volume began to decrease. With the increase of the working face mining distance, the fracture in the fissure zone develop further, the boreholes above the fracture zone also begin to play a role, and the amount of gas extraction begins to increase. When the working face mining is close to the end, the gas volume begins to decline.

4 | RESULTS AND DISCUSSION

The data of section 3.2 were recorded from three different working faces of the same coal seam in Yuwu Coal Mine, as shown in Table 1. However, the incline width of working face and the length of boreholes of every working face were different. To accurately evaluate the inverted π-shape km borehole gas drainage layout, standardization of the gas drainage data of three different working faces is necessary.

The basic principle of standardization often refers to unified principle, simplified principle, coordination principle and optimization principle. Among them, unified principle is to ensure things’ necessary efficiency and order, form, function or other features, and to determine suitability for a period of times and a certain condition consistent with specification, and make the same specification replaced original object to achieve equivalence function.

According to the unified principle of the standardization, the assumption parameters of working face are as follows: (a) the strike length and incline width of working face are 500 m and 230 m, respectively; (b) the number of km boreholes is 18, nine boreholes in coal seam and the bottom of caving zone, and nine borehole in fissure zone is nine; (c) the number of regular boreholes is 400. The original data of boreholes and gas drainage are shown in Table 1, and the standardized data are shown in Table 2.

The total amount of coal seam methane within a working face is sum of the drained gas amount and residual coal methane amount. When the residual coal methane in a certain coal seam is given, considering whether the gas drainage meets the standard can reflect the rationalization of the gas drainage layout. According to the layout proposed in section 2 where gas drainage amount is equal to the sum of gas pre-drainage by km borehole in gateway, pre-drainage of coal in-seam gas by regular borehole, gas drainage amount by km borehole in fissure zone, and the rest of gas drainage by coal in-seam borehole in mining period. Based on the unified principle, the drained gas amount was converted into the assumptive amount of working face, the calculated gas drainage amount accounted for the percentage of total amount of coal seam, then whether the gas drainage standard was met was determined. No.3 coal seam parameters were shown in Section 4.1. Based on Provisions on the Prevention of Coal and Gas Outburst, coal seam gas content must decrease to below 8 m³/t before mining. Based on Basic Indicators for Mine Gas Drainage, absolute gas emission amount of No.3 coal seam is 14 m³/min, within the range of 10-20 m³/min. Therefore, working face extraction rate should be greater than or equal to 30%. By calculation, after gas drainage, the coal seam gas content before mining decreased to 7.71 m³/t, and the gas drainage rate was 34.2%, both in line with the requirements of relevant laws and regulations.
It demonstrated that the arrangement of inverted π-shape km boreholes was reasonable and effective. What's more, in this testing case the gas drainage amount at the joint of each stage was not calculated. It is foreseeable that if we can implement the arrangement of inverted π-shape km boreholes and supplement by the regular coal in-seam borehole, gas
drainage amount will increase, and gas drainage rate in working face will be improved, too.

Throughout the km borehole working period, it plays a part of gas pre-drainage borehole before excavating gateway, gas drainage borehole of excavated gateway, gas pre-drainage of coal in-seam borehole, buried pipe in upper corner, gas drainage borehole of gob and gas drainage borehole of fissure zone, respectively. And the working time of km borehole group runs through the whole period of working face from gateway excavating to mining period. The arrangement of inverted π-shape km boreholes group model is not only an inheritance but also a breakthrough of the traditional combination layout of gas drainage, and it will be a good choice to extract coal seam methane in single coal seam.

5 | CONCLUSIONS

By analyzing the mechanism of rock mechanics and gas flow of gateway and borehole, a double stress relief circle model of gateway and borehole was proposed. Surrounding rock of gateway and boreholes divided into fracture zone, plastic zone, elastic zone, and original stress zone, respectively. Additionally, under the influence of mining stress, they affected each other, which resulted in initiation, occurrence and propagation of cracks between gateway and borehole, and permeability increased, and gas migration easily.

Combined traditional gas drainage technology method and horizontal directional drilling and multi-branched horizontal well, a new gas drainage layout—inverted π shape km boreholes group model—was presented. This model arranged km boreholes in coal seam, bottom of caving zone and fissure zone, and drained methane at difference periods.

Inverted π shape km boreholes group model was adapted in Yuwu Coal Mine. The gas content of coal dropped to 7.71 m³/t and the gas drainage rate reached 34.2%, meeting the requirements of relevant laws and regulations. It demonstrates that the gas drainage layout of inverted π-shape km boreholes arrangement is feasible.

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CONFLICTS OF INTEREST
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