INTRODUCTION

Surface wells are used for the large-scale recovery and utilization of coalbed methane (CBM).1,2 As the buried depth of coal seams increases, the CBM recovery ratio of surface vertical wells decreases.3 Multibranch wells in coal seams have high CBM production and large controlled areas.4 Their construction cost is 1.5-2 times that of surface vertical wells, but their CBM production is 4-8 times higher.5 Therefore, multibranch wells in coal seams have been widely promoted and applied.6-8 Presently, the morphological structure of multibranch wells mainly depends on the engineering experience in the oil and shale gas fields for design.9-11

The long-term evolution of plants in nature has caused the morphology and function of its leaf veins to evolve into an optimum according to its own resource allocation needs.12 Moisture, inorganic salts, and organic matter in the leaves are all transported in an efficient manner.13,14 Kizilova et al15

Experimental research on leaf vein geometric characteristics of multibranch horizontal well for coalbed methane recovery

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Abstract

The similarity in the structure and function between leaf veins and multibranch wells provided the inspiration for a novel design of multibranch coalbed methane (CBM) well. The leaf vein structure of leaves was analyzed by leaf specimen scanning and microstructure measurements. Fluorescence labeling experiments were used to study the influence of leaf vein structure on moisture transport, and the geometric characteristics were obtained. A CBM extraction physical simulation experiment was carried out in a custom-made experimental system. The temporal and spatial evolution of seepage-temperature fields in reservoir during CBM recovery were studied, and the influence of leaf vein geometric characteristics and how they affected was analyzed. The results indicated that in experimental gas extraction, asymmetrically distributed branch wells improved the CBM recovery 4.02% higher than symmetric structure after 1000 seconds. The reduction in branch well angle leads to the decrease in gas pressure relief. If the branch well angle is reduced by 20°, it reduced by 11.34% after 4000 seconds. When the branch well length increased by 50%, it increased by 28.37%. Coalbed methane recovery effect can be improved by 6.81%, when the distance between branch wells increased by 50%. In the early extraction stage, the reduction in methane pressure and reservoir temperature was positively correlated with the initial methane pressure, but they were less affected in the later stage.

KEYWORDS
bionic, CBM recovery, leaf veins, multibranch coalbed methane wells, reservoirs
discovered that branches are the most basic plant structure, reaching 5-9 levels in plant transport systems and connecting to each other to form a network. Huve et al.16 used microscopy to observe the flow velocity of leaf veins at all levels, and the results showed that thinner veins had slower internal water flows. Salleo et al.17 studied the axial and radial permeability of the main leaf veins of Prunus laurocerasus and Juglans regia by fluorescent labeling experiments. They found that the radial permeability of the main leaf veins of P laurocerasus was higher than the axial permeability, while the water in the main leaf veins of J regia mainly flowed in the axial direction. Lawren Sack et al.18 analyzed the flow resistance at various locations in the vein network using a cross-flow resistance test on maple and robur leaves, as well as a circuit cycle model to reflect the flow resistance around the veins. Peng et al.19 studied the water flow characteristics of symmetric and asymmetric vein fractal network structures. The authors found that the pressure and pressure drop varied significantly between the two fractal network structures and that the distribution of leaf veins greatly influenced the flow performance.

Leaf vein structures have important bionic significance for engineering construction.20 Due to their similarities in both structure and function, leaf veins can be used as the basis for designing multibranch CBM wells. The application of leaf vein bionic technology can reduce the well length and engineering costs and increase the CBM recovery ratio. However, for mature application of this technology, the influence of the geometric characteristics of leaf veins in bionic multibranch CBM wells on the temporal and spatial evolution of seepage-temperature fields in reservoirs should be studied first. Therefore, it is necessary to carry out large-scale, multiphysics-coupled CBM extraction physical simulations which consider the adsorption and permeability of coal-like materials.

In this paper, a bionic design for a CBM well based on the structure and function of leaf veins is proposed. The leaf vein structures of leaves were obtained and analyzed by leaf specimen scanning and microstructure measurement, and further analysis was performed in Matlab. Fluorescent labeling experiments were used to measure the moisture transport in leaf veins and to study the influence of leaf vein geometric characteristics on recovery effect. The results provide a scientific design basis for multibranch CBM wells inspired by leaf veins.

## 2 | EXPERIMENTAL METHODS

### 2.1 | Fluorescent labeling experiment

Fluorescence labeling was used to track the moisture transport in leaf veins using fluorescein (C20H12O5) as the solute of the fluorescent solution at a concentration of 0.5 g/L. Mature and fresh leaves were placed in clean water and held in a low light environment by a glass splint. Blue LED lights were used to irradiate the surface of the leaves and ensure that the light was parallel. An orange filter, two yellow filters, and a CPL polarizer were installed in front of the lens of an HD camera. At the beginning of the experiment, the blue LED light group was turned on first, and then, the CPL polarizer was rotated to reduce the surface reflection of the leaves. The entire flow process of the fluorescein solution in the leaves was recorded by an HD camera. Finally, the captured images were imported into Matlab for binarization, and the flow velocity of the fluorescein solution in the veins was obtained for analysis.

### 2.2 | CBM extraction physical simulation experiment

#### 2.2.1 | Materials

The experimental coal sample was obtained from gas coal of the Honglin Coal Mine in Fuxin. The results of industrial analysis and elemental analysis of the coal samples are shown in Table 1.

Filling structure has a huge impact on the briquette, which mainly depends on coal particle shape and size.21-23 In order to ensure briquette and raw coal have high similarity, coal particle size ratio was determined according to Horsfield filling theory.24,25 Fuller filling curve,26 and densest filling experience.27,28 After crushing, sieving, and drying, the pulverized coal and sodium humate solution were uniformly stirred into the coal-like material. The proportion of coal-like material is shown in Table 2.

| Industrial analysis | Elemental analysis |
|---------------------|--------------------|
| $M_{daf}$ [%]       | $C_{daf}$ [%]      |
| $A_d$ [%]           | $H_{daf}$ [%]      |
| $V_{daf}$ [%]       | $O_{daf}$ [%]      |
| $F_{Ca}$ [%]        | $N_{daf}$ [%]      |
|                     | $S_{daf}$ [%]      |
| 6.22                | 77.89              |
| 28.99               | 5.54               |
| 24.43               | 13.62              |
| 40.36               | 1.26               |
|                     | 0.69               |
2.2.2 | System

The experimental platform consists of a briquetting system, test box, methane supply system, methane extraction system, and data acquisition system, as shown in Figure 1A. The briquetting system consists of a machine press (YL32G-500) and indenter, as shown in Figure 1B, and the test box in Figure 1C is the main part of the experimental system with an internal size of 1000 mm × 1000 mm × 320 mm. A methane inlet is located at the center of the sealing cap, and a methane outlet is located on both the front and rear sides of the test box. There are 72 data acquisition ports on the left and right sides of the test box, which ensures that the monitoring tubes enter the briquette and collect various data in real time. The methane extraction system consists of extraction pipe designed with double copper pipes. The outer pipe is a protection pipe (Φ16 mm), and the inner pipe is the methane pipe (Φ10 mm). Four extraction holes with diameters of 2 mm and a spacing of 14 mm are arranged along the annulus of the extraction pipes. The data acquisition system is mainly composed of a pressure sensor (SLDYB-2088), temperature sensor (TP100), paperless recorder (MIK-R6000F), computer, and wiring terminal, as shown in Figure 1D. All sensors are connected to a paperless recorder for data conversion, and data are transmitted to a computer via a communication interface (RS-485) for processing and analysis.

The briquette was divided into four layers for compaction. Sensors were placed between two layers. Extraction pipes were placed between the first layer and the second layer, and were connected to the methane outlet of test box through linker. The briquetting pressure was set to 5 MPa, and the dwell time was 40 minutes. Before the start of the experiment, methane was injected into the test box to displace the residual air in the briquette. At the beginning of the experiment, methane was injected into test box until the internal methane pressure reached the target value. After the methane pressure inside the test box stabilized for 24 hours, the methane outlet was opened and all monitoring equipments began to monitor the data. The experimental process is shown in Figure 2.

2.2.3 | Schemes

Two arrangements of extraction pipes and sensors were used in this experiment, as shown in Figure 3. Scheme I includes both symmetric and asymmetric branch well arrangements, and scheme II sets the different lengths, angles, and distances of the branch wells. The selection of the parameters in schemes refers to the statistical data of vein

### Table 2: Proportion of coal-like material

| Ingredient               | Pulverized coal |
|--------------------------|-----------------|
|                         | 100 [mesh]  | 80 [mesh] | 60 [mesh] | 40 [mesh] | Sodium humate | Water | Total |
| Proportion [%]           | 44.37        | 6.96      | 11.31     | 24.36     | 3.6           | 9.4   | 100   |
| Mass [kg]                | 198.78       | 31.18     | 50.66     | 109.13    | 16.13         | 42.11 | 448   |

**FIGURE 1** CBM extraction physical simulation experiment: (A) experimental platform; (B) briquetting system; (C) test box; and (D) data acquisition system.
geometric parameters. The initial methane pressure was set to 0.55 MPa, 0.75 MPa, and 0.95 MPa, which referred to the average value of the 5# coal seam in Shaqu Coal Mine (Shanxi, China). To monitor methane pressure and reservoir temperature changes in real-time during the experiment, sensors were arranged in three briquette layers. Briquettes were formed with a briquetting pressure of 5 MPa and dwell time of 40 minutes.

3 | RESULTS AND DISCUSSION

3.1 | Geometric characteristics of leaf veins

In this paper, zelkova, clove, aspen, and tilia leaves were used as the research subjects and are shown in Figure 4. Fifty mature leaves were taken from each type. The difference in leaf vein structure is mainly determined by its living environment, and they are not obvious in the same environment. The selected leaves are from ten different cities in China (Shenyang, Harbin, Beijing, Tianjin, Xian, Shanghai, Taiyuan, Guangzhou, Shenzhen, and Yinchuan). These cities are distributed in different climatic zones which contain all the living environments which ensure enough biodiversity of selected leaves. The main geometric characteristic of leaf vein structures include the length of primary leaf veins $L_1$, the length of secondary leaf veins $L_2$, the angle between primary and secondary leaf veins $\phi$, the distance between secondary leaf veins $H$, the diameter of primary leaf veins $D_1$, the diameter of secondary leaf veins $D_2$, and the leaf area $S$. 
Distribution of primary and secondary leaf veins

The symmetry refers to whether the secondary veins intersect the primary vein at the same point on either side of the primary vein, as shown in Figure 5A, which contains both symmetric and asymmetric secondary veins. In Figure 5B, different species of plants have different proportions of asymmetric secondary leaf veins, with asymmetric secondary leaf veins accounting for 73% in clove, 71% in aspen, 68% in zelkova, and 55% in tilia leaves. Therefore, the asymmetric secondary veins are present in the highest percentage in the leaves with netted venation.

The distribution histograms in Figure 6 show that the angle distribution between primary and secondary leaf veins varies between plant types. Most of the angles between primary
and secondary leaf veins are 40°-50° in zelkova, 35°-45° in clove, 30°-50° in aspen, and 35°-55° in tilia. However, their means do vary and were 48.30°, 43.81°, 37.26°, and 52.01°, respectively.

Secondary veins are the main transport channels for moisture, inorganic salts, and organic matter in leaves.\(^{12-14}\) The relationship between the total length \(T\) of secondary leaf veins and the leaf area \(S\) is shown in Figure 7. The data show a positive correlation between the total length of secondary leaf veins and the leaf area, but there are large differences between different plant species.

The distribution histograms in Figure 8 show that different plants have notably different distributions of the distance between their secondary leaf veins. Zelkova has the smallest distance between their secondary leaf veins, followed by clove and aspen, and tilia has the largest. The distance between the secondary leaf veins adopts a normal distribution, indicating that it is independent of other veins in different plants. The expectations of the distance between secondary leaf veins in zelkova, clove, aspen, and tilia have large gaps, which are 0.062 mm, 0.11 mm, 0.16 mm, and 0.18 mm, respectively.

**FIGURE 7** Total length \(T\) of secondary leaf veins vs the leaf area \(S\)

**FIGURE 8** Distribution of the distance \(H\) between secondary leaf veins
Analysis of the distribution of the primary and secondary leaf veins in the four plants shows obvious differences. Secondary leaf veins are dominated by asymmetric structures, while the density of primary and secondary leaf veins varied greatly in different plants. The angle between primary and secondary leaf veins and the distance between the secondary leaf veins in different plants follow a normal distribution. The angles between primary and secondary leaf veins are mainly distributed between 30°-55°, and the distance between the secondary leaf veins varies widely in different plants.

3.1.2 Fractal feature of tertiary leaf veins

Tertiary veins in leaves form a network with self-similarity. Traditional geometry cannot describe its characteristics accurately. Fractal dimension is an effective indicator of the irregular characteristics of tertiary leaf veins. A cube box of length r needs 1/r small cubes to cover the line segment of per unit length. To cover a square per unit area, 1/r² cubes of the same size are needed. Covering a cube box of per unit length, 1/r³ cubes of length r are required. Therefore, the exponent of r is the same as the dimension of the geometry it covers. A is any nonempty bounded subset in the Euclidean space R^n, and N_r(A) is the minimum number of cube boxes that can cover A with a side length r. If there is a positive number d, when the side length r → 0, then the following relationship exists:

\[ N_r(A) \propto \frac{1}{r^d} \]  

(1)

\[ d \] is the fractal dimension of A, which satisfies the following equation:

\[ \lim_{r \to 0} \frac{N_r(A)}{1/r^d} = k \]  

(2)

where k is a positive number. Taking the logarithm of the two sides of the formula (2) gives the following formula:

\[ \lim_{r \to 0} (\log N_r(A) + d \log r) = \log k \]  

(3)

So the fractal dimension is:

\[ d = \lim_{r \to 0} \frac{\log k - \log N_r(A)}{\log r} = - \lim_{r \to 0} \frac{\log N_r(A)}{\log r} \]  

(4)

As shown in Figure 9A, the tertiary vein distribution within the same plant is generally the same, while the tertiary vein distribution between different plants is noticeably different. The average fractal dimension of tertiary leaf veins of zelkova, clove, aspen, and tilia are 1.43, 1.48, 1.55, and 1.65, respectively. The tertiary leaf veins of tilia are the densest, followed by aspen, while the tertiary leaf veins of zelkova and clove are the least dense.

Figure 9B,C shows that the fractal dimension of tertiary leaf veins of the four plant types was negatively correlated with the secondary leaf vein density and positively correlated with the distance of secondary leaf vein. To ensure adequate moisture transport capacity, the density of tertiary leaf veins should be increased at lower secondary leaf vein densities.

3.1.3 Microstructure of leaf veins

Paraffin sections of fresh leaves were observed under an optical microscope (OLYMPUS BX51-P), and the obtained transverse microstructures of 100 leaf veins in four plants are shown in Figure 10. As it can be seen, the thickness, vein shape, and vascular bundle distribution varies between leaves from different plant types. The transverse shape of tertiary leaf veins...
leaf veins is round in all leaves, but the shape of primary and secondary leaf veins varies between plant types. For example, the transverse shape of primary and secondary leaf veins in zelkova and aspen is round, but it is half-moon in clove. The transverse shape of primary leaf veins in tilia is nearly round, and the transverse shape of secondary leaf veins is half-moon.

Microscope images were imported into Image-Pro-Plus 6.0 and AUTOCAD to measure the microstructural parameters of leaf veins, and their average values are shown in Table 3. The average leaf thickness of the four plants ranged from 155.19 to 206.4 μm and is proportional to the leaf area. Although the average width of primary leaf veins in the four plants is approximately the same, the vessel and sieve tube diameters of primary and secondary leaf veins in zelkova and aspen are nearly twice that of clove and tilia. The vessel and sieve tube average diameter of tertiary leaf veins in four plants is small.

### 3.2 Moisture transport performance of leaf veins

Figure 11 shows the flow velocity changes in the fluorescent solution in the leaf veins of the four plant types. From the figure, the maximum moisture transport velocity in the leaves of zelkova, clove, aspen, and tilia are 3.15 m/h, 4.31 m/h, 8.75 m/h, and 6.5 m/h, respectively. The maximum moisture transport velocity in primary leaf veins of aspen is 1.67 times that of secondary leaf veins, which is 2.02 in tilia.

Based on the data from the fluorescent labeling experiment, a numerical simulation of the moisture transport in leaf veins was carried out using COMSOL Multiphysics software. The average transport velocity in primary and secondary leaf veins of the four plants were 5.68 m/h and 3.71 m/h, respectively. By inversion, the liquid diffusion coefficients of primary and secondary leaf veins were $6.50 \times 10^{-4}$ m$^2$/s and $4.26 \times 10^{-4}$ m$^2$/s, their standard deviation was $0.27 \times 10^{-4}$ m$^2$/s and $0.12 \times 10^{-4}$ m$^2$/s, respectively, while the diffusion rate of the fluorescent solution in the mesophyll was set to $1 \times 10^{-9}$ m$^2$/s.

Figure 12A shows that the system pressure drop decreases as the angle between primary and secondary leaf veins increases. In the asymmetric structure, when the angle is increased from 30° to 90°, the system pressure drop is reduced by $4.85 \times 10^{-3}$ Pa, compared with $3.37 \times 10^{-3}$ Pa in the symmetrical structure. Thus, the asymmetric structure of secondary leaf veins has less pressure loss than the symmetric structure. This shows that increasing the angle between the first and second veins helps reduce the energy consumption of water transport in the system.

As shown in Figure 12B, as the angle between the primary and secondary leaf veins increases, the fluorescein accumulation in the leaves continuously increases, but the increase become smaller and smaller. When the flow time is 48 500 seconds and the angle is 30°, the fluorescein accumulation in the leaves is $5.49 \times 10^{-10}$ mol, and when the angle increases to 90°, the fluorescein accumulation reaches $8.50 \times 10^{-10}$ mol. There is a mutual influence between leaf veins at vein intersections, and the smaller angles between the veins will disturb the moisture transport more.

Figure 12C shows that the length of secondary leaf veins has a great influence on the moisture transport in the leaves. When the flow time is 48 500 seconds and the branch length is 24 mm, the fluorescein accumulation in the leaves is $7.06 \times 10^{-10}$ mol. When the length of secondary leaf veins increases to 29 mm and 34 mm, the fluorescein accumulation in the leaves increases to $8.27 \times 10^{-10}$ mol and
9.42 \times 10^{-10} \text{ mol}, with increases of 17.14\% and 33.43\%, respectively. Therefore, increasing the length of secondary leaf veins improves moisture transport.

Figure 12D shows the influence of the number of secondary leaf vein branches on fluorescein accumulation. As the branch number increases, the fluorescein accumulation increases, but the increase gradually diminishes. When the flow time is 48 500 seconds and the branch number is 10, the fluorescein accumulation in the leaves is 7.50 \times 10^{-10} \text{ mol}. However, when the branch number is 16, 14, 12, or 10, the fluorescein accumulation at the same time is 7.76 \times 10^{-10} \text{ mol}, 7.89 \times 10^{-10} \text{ mol}, 7.97 \times 10^{-10} \text{ mol}, and 8.02 \times 10^{-10} \text{ mol}, and the relative increase from 10 branches is 3.47\%, 5.24\%, 6.25\%, and 6.92\%, respectively. Therefore, secondary leaf veins with more branches interfere more strongly with the moisture transport in leaves.

### 3.3 Influence of geometric characteristics on multiphysics in reservoir

To study the influence of leaf vein geometric characteristics on multiphysics in reservoirs, a CBM extraction physical simulation experiment of multibranch CBM well was carried out via custom-made experimental system. Figure
FIGURE 12  Influence of leaf vein structure on its moisture transport. A. Pressure drop changes. B. Angle ($\phi$) between primary and secondary leaf veins. C. Length ($L_2$) of secondary leaf veins. D. Branch number ($n_2$) of secondary leaf veins.

FIGURE 13  Methane pressure contours in two schemes

13 shows the methane pressure contours in two schemes. When the asymmetric multibranch CBM well is used for CBM recovery, there is only a small interaction between the primary and branch wells, and the influence range in the reservoir is larger. The pressure relief effect is significantly improved when the distance between the branch wells is reduced. When the angle between the primary and the branch wells and the length of the branch wells is reduced, the control area of the wells is decreased, and the pressure relief effect is weakened.
3.3.1 Symmetric and asymmetric structure

Figure 14A shows the influence of symmetric and asymmetric structures on methane pressure. P18 and P19 are within the extraction range of the asymmetric multibranch well, while P26 and P27 are within the extraction range of the symmetrical multibranch well. The methane pressure at P26 is greater than at P19, and the methane pressure at P27 is greater than at P18. When the time is 1000 seconds, the methane pressure at P26 is 0.155 MPa, which increased by 4.02% compared with P19. The methane pressure at P27 is 0.351 MPa, which is 2.93% higher than that at P18. Therefore, the asymmetric multibranch CBM well have superior extraction.

3.3.2 Angle of the branch well

Figure 14B shows the influence of the angle of the branch well on methane pressure. The angles of the branch wells at P23, P24, and P26 are all 75°, while the angles of the branch wells at P10, P11, and P12 are all 55°. At a extraction time of 4000 seconds, the methane pressure at P23 is 0.141 MPa, while the methane pressure at P17 is 0.181 MPa, which represents an increase of 28.37%. Therefore, the branch well length has the greatest influence on the recovery of multibranch CBM wells compared with the symmetry and the angle of the branch well.

3.3.3 Length of the branch well

Figure 14C shows the influence of the length of the branch well on methane pressure. The lengths of the branch wells at P17, P18, and P19 are all 0.22 m, while the lengths of the branch wells at P23, P24, and P26 are all 0.33 m. When the extraction time is 4000 seconds, the methane pressure at P23 is 0.141 MPa, while the methane pressure at P17 is 0.181 MPa, which represents an increase of 28.37%. Therefore, the branch well length has the greatest influence on the recovery of multibranch CBM wells compared with symmetry and the angle of the branch well.

3.3.4 Distance between the branch wells

Figure 14D shows the influence of the distance between the branch wells on methane pressure. The distances between the branch wells at P4, P5, and P6 are all 0.11 m, and the distances between the branch wells at P23, P24, and P26 are all 0.33 m. When the extraction time is 4000 seconds, the methane pressure at P23 is 0.141 MPa, while the methane pressure at P12 is 0.157 MPa, which represents an increase of 28.37%. Therefore, the branch well length has the greatest influence on the recovery of multibranch CBM wells compared with the symmetry and the angle of the branch well.
P26 are all 0.165 m. When the extraction time is 4000 seconds, the methane pressure at P6 is 0.132 MPa, while the methane pressure at P23 is 0.141 MPa, which is an increase of 6.81%. Therefore, as the distance between the branch wells decreases, the recovery of multibranch CBM well increases.

3.3.5 | Reservoir temperature

Figure 15 shows that methane pressure and reservoir temperature at the same position follow the same trend, but the methane pressure enters stabilizes before the reservoir temperature. Since the adsorbed methane begins to desorb only after the free methane is extracted, this leads to the decrease in the reservoir temperature.

Figure 16A shows that during extraction, as the methane pressure decreases, a large amount of adsorbed methane begins to desorb, accompanied by a continuous endothermic process. The reservoir temperature at T33 is reduced from 6.97°C to 2.56°C, which is the lowest temperature, followed by T35, with T32 having the highest temperature. Figure 16B shows that the reservoir temperature changes at different positions in the horizontal direction and is affected by an uneven change in the methane pressure. In addition, the reservoir temperature is lower close to the wells.

3.3.6 | Initial methane pressure

Figure 17 shows that the early stage of the extraction process has a greater initial methane pressure. Thus, the methane
pressure decreases more rapidly, resulting in a larger reduction rate. During the later stage of the extraction process, the initial methane pressure has little effect on the drop rate of methane pressure. Although the methane pressure gradient is obvious at the early stage, the methane pressure is basically the same in the later stage.

Figure 18 shows that the reservoir temperature at the same position follows the same trend as the as different initial methane pressures. The reservoir temperature rapidly decreases in the early stage and slows down in the later stage, and higher initial methane pressures lead to a larger reservoir temperature reduction. At an initial methane pressure of 0.95 MPa, the reservoir temperature at T33 is 4.4°C, and when the initial methane pressure drops to 0.75 MPa and 0.55 MPa, the reservoir temperature at T33 decreases to 4.00°C and 3.20°C, respectively.

4 | CONCLUSION

In this paper, a bionic multibranch well inspired by leaf veins was proposed for CBM recovery. The geometric characteristics of leaf veins were obtained by studying leaf vein structures and their influence on moisture transport. Furthermore, the influence of geometric characteristics on coupled seepage-temperature fields in coal seam was studied via a CBM extraction physical simulation experiment. This research provides a novel design for multibranch CBM wells.

1. In leaves with reticulate venations, secondary leaf veins with asymmetric structures showed less pressure loss than symmetric structures. The fractal dimensions of tertiary leaf veins were negatively correlated with the density of secondary leaf veins and positively correlated with the distance of secondary leaf veins. At the intersection, the leaf veins mutually influenced one another, and smaller angles led to an increased disturbance to the moisture transport. Longer secondary leaf veins improved the moisture transport. Secondary leaf veins containing more branches and smaller distances between their veins interfered more strongly with moisture transport.

2. By examining the influence of leaf vein structure on moisture transport, the geometric characteristics of multibranch CBM wells on the basis of leaf vein bionics were determined to be:
   - An asymmetric branch wells arrangement helps increase the CBM production.
   - The angle between the primary and the branch wells was positively correlated with the CBM production.
   - The main and branch wells should extend to the edge of the target coal seam.
   - The length of the branch well was positively correlated with the CBM production.

6. Asymmetric branch structure was more conducive to increasing CBM recovery effect. After 1000 seconds in the experimental extraction, the gas pressure relief of asymmetric structure was 4.02% higher than that of symmetric structure between branch wells. The reduction in branch well angle or length leads to the decrease in its control area and gas pressure relief. However, the branch well length had the greatest influence compared with the symmetry, angle, and distance. When the branch well length increased by 50%, the gas pressure relief increased by 28.37% after 4000 seconds. If the branch well angle is reduced by 20°, the gas pressure relief will be reduced by 11.34% in coal reservoir. Coalbed methane recovery effect can be significantly improved by decreasing the distance between branch wells. Increasing the distance by 50% will improve the gas relief pressure by 6.81%. Since it is affected by uneven changes in methane pressure, the reservoir temperature was lower close to the wells. The methane pressure stabilized before the reservoir temperature at the same position. In the early stage of the recovery, higher initial methane pressures lead to a more rapid decrease in the methane pressure and a larger difference in the reduction rate. But in the later stage, it had little effect on the drop rate of methane pressure. Additionally, the larger the initial methane pressure, the larger the reservoir temperature reduction.

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