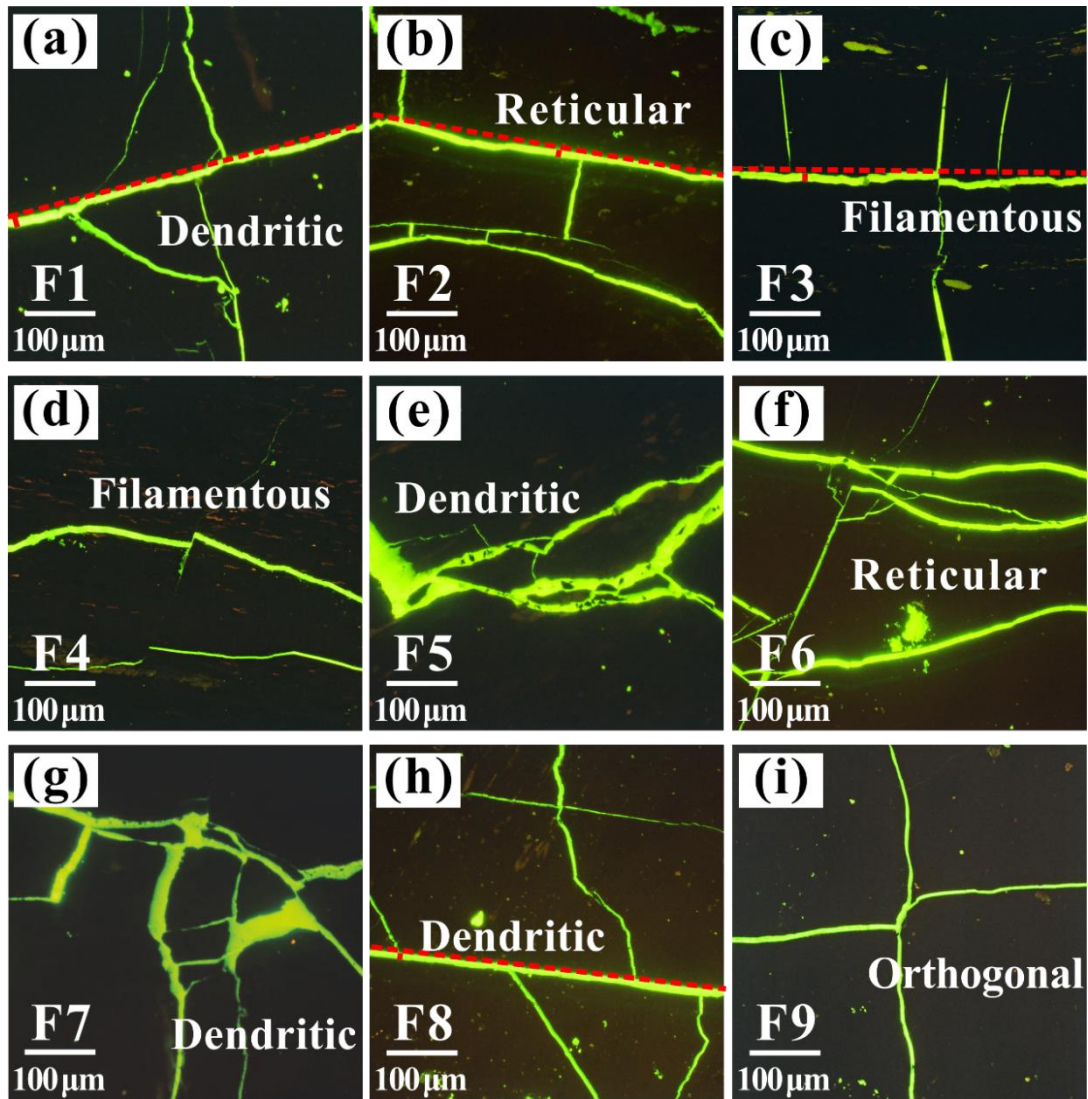


Fuel

Effects of natural micro-fracture morphology, temperature and pressure on fluid flow in coals through fractal theory combined with lattice Boltzmann method --Manuscript Draft--

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Keywords:	Coal; Micro-fractures morphology; Permeability; Fractal theory; Lattice Boltzmann method
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Abstract:	<p>The fluid flow behaviors during the production of coalbed methane (CBM) are generally restricted by the pre-existing natural fractures in coal seams. To better understand the effect of natural micro-fracture morphology on the flow capacity, nine coals collected from Ordos Basin were subjected to optical microscope observations to obtain micro-fractures morphology. And then, an improved box-counting method (BCM) was used to quantify the complexity of the micro-fracture network planar distribution. Besides, the lattice Boltzmann method (LBM) was adopted to simulate the flow in the complex micro-fracture network under different pressures and temperatures. Finally, factors affecting the flow capacity in micro-fracture were elaborated. The results show that the micro-fractures generally present dendritic, reticular, filamentous and orthogonal structures. The natural micro-fracture morphology has a remarkable impact on flow behavior, in which the presence of dominant channels with a length of $\sim 498.26 \mu\text{m}$ and a width of $\sim 10.96 \mu\text{m}$ has a significant contribution to permeability, while the orthogonal micro-fracture network normally is not conducive to fluid flow. The fractal dimension extracted from the nine coals varies from 1.321-1.584, and the permeability calculated from LBM method varies from 0.147 to 0.345 D; in contrast to other studies, a non-monotonic change, an inverted U-shaped, of permeability on fractal dimension was observed. Moreover, permeability decreases as pressure increases and increases with increasing temperature due to the physical properties of methane and coal matrix. Therefore this work may contribute to understand the process of hydrofracturing and hydrothermal methods for improving CBM reservoirs during enhancing CBM recovery.</p>



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to a decrease in permeability.

15. Language should be polished.

Response: Thank you very much for your comment. We have polished the language, sorted out the logic and supplement details.

Reference:

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Highlights

- Dominant channels in the natural micro-fractures greatly improve the permeability.
- Flow features in micro-fractures with various morphologies are quite different.
- Pressure and temperature have opposite influence on coal permeability.

1 Effects of natural micro-fracture morphology, ~~temperature and pressure in~~
2 ~~coals~~ on fluid flow in coals through fractal theory combined with lattice
3 Boltzmann method

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10 **Abstract**

11 The fluid flow behaviors during the production of coalbed methane (CBM) are generally
12 restricted by the pre-existing natural fractures in coal seams. To better understand the effect of
13 natural micro-fracture morphology on the flow ~~capacity~~capability, nine coals collected from
14 Ordos Basin were subjected to optical microscope observations to obtain micro-fractures
15 morphology. And then, an improved box-counting method (BCM) was used to quantify the
16 complexity of the micro-fracture network planar distribution. Besides, the lattice Boltzmann
17 method (LBM) was adopted to simulate the flow in the complex micro-fracture network under
18 different pressures and temperatures. Finally, factors affecting the flow ~~capacity~~capability in
19 micro-fracture were elaborated. The results show that the micro-fractures generally present
20 dendritic, reticular, filamentous and orthogonal structures. The natural micro-fracture
21 morphology has a remarkable impact on flow behavior, in which the presence of dominant

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22 channels with a length of $\sim 498.26 \mu\text{m}$ and a width of $\sim 10.96 \mu\text{m}$ has a significant contribution
23 to permeability, while the orthogonal micro-fracture network normally is not conducive to fluid
24 flow. The fractal dimension extracted from the nine coals varies from 1.321-1.584, and the
25 permeability calculated from LBM method varies from 0.147 to 0.345 D; in contrast to other
26 studies, a non-monotonic change, an inverted U-shaped, of permeability on fractal dimension
27 was observed. Moreover, permeability decreases as pressure increases and increases with
28 increasing temperature due to the physical properties of methane and coal matrix.
29 ~~Therefore~~Therefore, this work may contribute to understanding the process of hydrofracturing
30 and hydrothermal methods for improving CBM reservoirs during enhancing CBM recovery.

31 **Keywords:** Coal; Micro-fractures morphology; Permeability; Fractal theory; Lattice
32 Boltzmann method

33

34 1. Introduction

35 Coalbed methane (CBM) is an essential component ~~in~~of the unconventional energy system due
36 to its huge reserves, the reservoir of which is deemed as a dual-porous medium with pores in
37 matrix and fractures/cleats [1-3]. Pores are generally associated with the processes of gas
38 storage, desorption and diffusion [4]. For fractures, composed by micro-fractures and macro-
39 fractures, they are the most important physical attribute governing gas flow in a CBM reservoir
40 [5, 6]. Generally speaking, natural fractures primarily contributed to the permeability of coal,
41 while the pores in coal matrix have very limited influence on coal permeability [7]. ~~Numerous~~
42 Extensive works including experiments and numerical simulations have been conducted to
43 understand the performance of micro-fracture with the width at ~~the~~-micron scale due to its

44 importance on CBM production [68-2524]. ~~The above works on coal fractures/cleats can be~~
45 ~~classified into two groups: characterization of micro fracture networks and the exploration of~~
46 ~~gas flow behavior.~~

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47 Multiple experimental methods can be used to characterize micro-fractures
48 ~~performance properties (e.g., including Low~~low-field nuclear magnetic resonance (NMR) [8, 9],
49 X-ray computed ~~micro~~tomography (X-ray μ CT) [10-12], ~~focused ion beam coupled with~~
50 ~~scanning electron microscopy (FIB SEM)~~ and the classic optical microscopy [13]. NMR is a
51 non-destructive measurement and it has been adopted successfully to detect and quantify the
52 pore-fracture structure of coals [8], where the T_2 spectrum ~~is~~ larger than 100 ms represents
53 micro-fracture [9]. However, the detailed morphological features of micro-fracture are not
54 accessible through NMR. ~~For~~X-ray μ CT, ~~it~~ can provide realistic three-dimensional digital
55 images and different components reconstruction [10-12]. ~~For instances, Roslin et al. proposed~~
56 ~~an effective method to overcome the partial volume effect of low resolution images based on~~
57 ~~micro CT technique. And~~Jenkins et al. [12] utilized X-ray μ CT to dynamically measure the
58 deformation behavior of tested rock under various loading conditions. ~~Zhou et al. [15] used~~
59 ~~FIB SEM to visualize the geometric structure of pore fracture space, and evaluated the seepage~~
60 ~~capacity of coal samples based on the established three dimensional pore network model.~~
61 However, X-ray μ CT ~~and FIB SEM are~~is expensive and not economically suitable, and are
62 time-consuming. Compared with the above techniques, the micro-fracture morphology
63 observation by optical microscopy is not only ~~economically suitable~~inexpensive but also easy
64 to obtain clear ~~morphologies~~ ~~micro fractures morphologies~~[13]. ~~Besides, the fractal dimension~~
65 ~~can extend the qualitative description of the micro-fracture network to a quantitative description.~~

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66 ~~which quantifies its complexity of distribution [14, 15]~~For assessment of fracture complexity,
67 ~~fractal dimension is generally used to characterize the complexity of pore fracture structure in~~
68 ~~natural geological materials, e.g., shales and coals.~~ The box-counting method (BCM) is one of
69 the most popular algorithms [16, 17] to acquire the complexity, namely fractal dimension,
70 through the images of pore-fracture structure. Herein, the BCM will be utilized to quantify the
71 complexity of micro-fractures.
72 ~~Besides fractal theory,~~ ~~On the other hand,~~ direct numerical methods including finite difference
73 method (FDM) [18], finite element method (FEM) [19] and finite volume method (FVM) [20]
74 can be effectively adopted to simulate the flow behavior in micro-fracture networks. ~~For~~
75 ~~instance,~~ Liu et al. [20] adopted a simulator derived from FDM to solve the multi-mechanistic
76 ~~gas flow model and successfully tested against two sets of in situ field data. And Sun et al. [21]~~
77 ~~used FEM to establish the semi-solid permeability of microstructure constructed from a Voronoi~~
78 ~~tessellation algorithm. Based on FVM and considering the transient incompressible Newtonian~~
79 ~~fluid,~~ Almasoodi and Reza [22] simulated the permeability on the FIB-SEM images of shale.
80 ~~The above methods (FDM, FEM, and FVM),~~ But these traditional simulation methods on the
81 basis of Navier-Stokes equations—_require complicated meshing process to define the
82 simulation domain and are challenging to solve complex geometric boundaries and have low
83 parallel efficiency [18-20]. The lattice Boltzmann method (LBM), as a typical mesoscopic
84 method, has a strong advantage in simulating the flow behavior of porous media with irregular
85 boundaries [21, 22]. For example, Wang et al. [23] decomposed the three-dimensional fracture
86 geometry into primary and secondary roughness through wavelet analysis, and investigated the
87 role of the latter in the flow of rock fractures using LBM. And Zhao et al. [24] adopted LBM

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88 to ~~investigate~~discuss the effect of structure, surface roughness and aperture on flow in
89 constructed fracture networks with rough surfaces. ~~Generally speaking, natural fractures~~
90 ~~primary contributed to the permeability of coal, while the coal matrix has very limited influence~~
91 ~~on coal permeability [7].~~

92 ~~The previous works on coal fractures/cleats can be classified into two parts: characterization of~~
93 ~~micro-fracture networks [68-1314] and the exploration of gas flow behavior in the micro-~~
94 ~~fracture networks [185-234]. Hence, it is of significant for understanding the effect of natural~~
95 ~~fracture network on permeability -value to~~~~through~~ ~~investigatinge~~ the characteristics and
96 distribution of natural fractures in coal ~~to understand its permeability.~~ ~~Besides, owing to the~~
97 ~~complexity of the natural fracture network in coal, much related work has performed flow~~
98 ~~simulation in the fracture network constructed by algorithms such as Voronoi tessellations~~
99 ~~method [24, 25] and Fracture Pipe Network Model (FPNM) [26], whereas rare researches have~~
100 ~~been conducted on the real complex natural fracture networks with specific morphologies.~~

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101 Many studies adopted an idealistic tube model with a circular cross-section to simplify the flow
102 simulation [27, 28]. ~~But However,~~ in most cases, the shape of micro-fractures ~~is non-circular~~
103 ~~and irregular~~ in coal, ~~which~~ is much complicated, ~~non-circular and irregular~~. Therefore, Yuan
104 et al. [29] compared the ~~original-realistic~~ shape with the permeability characteristics of circle,
105 square and equilateral triangular cross-sections. ~~And it was, which~~ found that the permeability
106 of the network with circle cross-section is the highest, followed by the ~~original-realistic~~ shape,
107 and the final are square and equilateral triangular, ~~which.~~ ~~This finding~~ corroborates the
108 importance of accurately acquiring ~~morphological features in~~ micro-fracture networks.
109 ~~(morphological features).~~ ~~Besides, owing to the complexity of the natural fracture network in~~

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110 ~~coal, much related work so far have performed flow simulation in the fracture network~~
111 ~~constructed by algorithms such as Voronoi tessellations method [26, 27] and Fracture Pipe~~
112 ~~Network Model (FPNM) [28], whereas but rare researches have been conducted on the real~~
113 ~~complex natural fracture networks with specific morphologies. Thus, we focus on the flow~~
114 ~~characteristic with real morphologies of micro-fractures.~~

115 In this study, we aim to investigate the flow behavior in natural micro-fractures with various
116 morphologies under different pressures and temperatures. To detailed address the flow behavior
117 in micro-fractures, the specific morphologies of natural micro-fractures were firstly obtained
118 by optical microscopy. And then, the BCM was used to quantify the complexity of the natural
119 micro-fracture network. Finally, the LBM was applied to simulate the flow behavior in the
120 natural micro-fracture network with specific morphologies in coals, and the ~~dominating~~
121 ~~controlling~~ factors were ~~discussed~~revealed. This study may provide insights into the flow
122 mechanisms of natural micro-fracture networks with complex morphologies~~iesy~~ in
123 unconventional reservoirs.

124 **2. Methodology and validation**

125 **2.1 Coal sampling and basic analysesanalysis**

126 Nine coal blocks ($30 \times 30 \times 30 \text{ cm}^3$) with different coal ranks were selected from the ~~E~~eastern
127 Ordos Basin, north China. The maximum vitrinite reflectance ($R_{o, \max}$) and maceral composition
128 were carried out with a Leitz MPV-III microscope photometer following the Chinese National
129 Standard of GB/T 6948–1998. The $R_{o, \max}$ varies from 0.62% to 1.78% as shown in Table 1,
130 which may indicate the variable inner micro-fractures existed [30]. Coal macerals were tested
131 by the point counting technique according to the scheme of the International Committee ~~of~~for

132 Coal and Organic Petrology [31]. The coal composition differs, with vitrinite of 65.4-90.2%,
133 inertinite of 4.5-25.6%, exinite of 0-5.9% and mineral being 0.2-8.3%. Natural mMicro-
134 fractures of coals ~~are~~ selectively developed in macerals/submacerals, for example, micro-
135 fractures ~~is are most~~ developed well in the ~~submacerals of~~ telocollinites while others including
136 the desmocollinite, vitrodetrinite, inertodetrinite and semifusinite are not conducive to micro-
137 fractures develop~~ment~~ed [30].

138 2.2 Micro-fractures characterization by optical microscopy

139 The morphological characteristics of the natural micro-fractures can be clearly observed by
140 optical microscopy. The specific preparation process of used sample coals preparation is as
141 follows: first melted a certain proportion of resin and paraffin was melted, and then was poured
142 it into the micro-fractures of coal. After that, the coal blocks were cut and polished into the
143 sample blocks with the area of $\sim 3 \times 3$ cm². To the end, LABORLUX 12 POL optical microscopy
144 (Leitz Company of Germany) was utilized to observe the natural micro-fractures performance
145 of the polished sample to obtain including the morphological characteristics. The coal samples
146 were polished into slices with an area of 3 cm \times 3 cm first. Then observation of the micro-
147 fractures was performed using LABORLUX 12 POL optical microscopy (Leitz Company of
148 Germany) at China University of Geosciences at Beijing (CUGB). Natural Mmicro-fractures
149 morphologies ~~images~~ with the image resolution of 0.4937 μm were ~~obtained~~ achieved, which
150 contain as shown in Fig. 1 and varied various shapes involving dendritic, reticular, filamentous
151 and orthogonal structure as shown in Fig. 1-ete. It can be found that ~~the natural dendritic~~
152 micro-fracture network is mostly composed of a backbone and several branches extending out
153 (see Fig. 1a, e, g, and h). The natural reticular micro-fracture network can be divided into

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154 ~~regular type (Fig. 1b) and irregular, complicated, disorganized type (Fig. 1f)-, which have the~~
155 ~~common feature is that there are of~~ more than two main channels and the part of branches
156 ~~connecting the main channels, and their difference is whether the channel is curved and~~
157 ~~disorganized. The natural filamentous micro-fracture network primarily has a channel similar~~
158 ~~to a with ribbon with weak weak connectivity is more likely to deteriorate because of its~~
159 ~~narrowness. Comparatively, What is easier to distinguish is the orthogonal micro-fracture~~
160 ~~network is easy to distinguish, which has a pair of orthogonal channels.---~~

161 After collecting the images, these images need to be preprocessed including noise reduction
162 and image segmentation. First to reduce noise, which normally due to the limitations of the
163 experimental equipment, herein the median filter is chosen to reduce the noise for studied
164 images (Fig. 2). And then the images need to be segmented ~~by Otsu algorithm, which has been~~
165 ~~proved to be an. Previous researchers have proved that global thresholding method is~~ effective
166 ~~and conciseness threshold segmentation method to determine the threshold [16, 32]-for image~~
167 ~~segmentation.~~ After thresholding, the micro-fractures were distinguished from the background
168 in the selected coals. As shown in Fig. 2c, black is the micro-fracture and white is the coal
169 matrix in the binary images. Detailed observation shows that the noise in the red rectangular
170 frame of Fig. 2c is significantly less than that in Fig. 2b; what's more the edge of the micro-
171 fracture in Fig. 2c is smoother after noise reduction.

172 2.3 Fractal theory applied for micro-fractures network

173 The fractal theory proposed by Mandelbrot [33] can be used to evaluate the natural porous
174 properties such as coals and shales. The fractal dimension, the characteristic parameter of fractal
175 theory, can effectively quantify the complexity of pore-fracture structure. For a two-

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176 dimensional (2D) system, the fractal dimension changes from 1 to 2; a larger the fractal
177 dimension represents a more complicated fracture system. Previous research has been
178 demonstrated that [fractal dimensions of pore-fracture structure](#) ~~fractal dimensions~~ can be
179 acquired from images by the box-counting method [16, 17, 34, 35]. In this study, the fractal
180 dimensions of obtained 2D micro-fracture images were determined by the BCM to quantify the
181 complexity of the micro-fracture distribution. [The details of BCM have been listed in our latest](#)
182 [work \[35\], and the following is a brief description:](#)

183 By covering a binary image with boxes of length r , the fractal dimension D can be estimated
184 as:

$$185 \quad D = -\lim_{r \rightarrow 0} \frac{\log(N(r))}{\log(r)} \quad (1)$$

186 where $N(r)$ is the number of boxes required to cover the ~~complete~~ image ~~completely~~. [The](#)
187 [side length \$r\$ of the box needs to be assigned a series of values, and the number of boxes \$N\(r\)\$](#)
188 [required to cover the image is counted. Then a set of \$\[\log\(r\), \log\(N\(r\)\)\]\$ values of each sample](#)
189 [are plotted in the coordinate system with the abscissa of \$\log\(r\)\$ and the ordinate of \$\log\(N\(r\)\)\$.](#)
190 [The slope is determined by the least square fitting method, which is the fractal dimension \$D\$.](#)

191 Within the calculation process, we adopted the method proposed by Wu et al. [36] to avoid
192 boundary effects, using the common divisors of the length and width of the image as a series
193 of box sizes.

194 In addition, the fracture porosity (FP) of each sample was calculated following Eq. (2), as listed
195 in Table 1.

$$196 \quad FP = \frac{\text{fracture pixel}}{\text{total pixel}} \times 100\% \quad (2)$$

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197 **2.4 Flow simulation using lattice Boltzmann method**

198 ~~In the present study,~~ The flow simulation was carried out based on the Bhatnagar Gross Krook
 199 (BGK) model [37], which is the most widely used model. The distribution functions f_i can be
 200 expressed as:

$$201 \quad f_i(x + \mathbf{e}_i \delta_t, t + \delta_t) - f_i(x, t) = -\frac{1}{\tau} [f_i(x, t) - f_i^{(eq)}(x, t)] \quad (3)$$

202 where x is the position of the particles; t is time; δ_t is the time step; τ is the relaxation time;
 203 \mathbf{e}_i is the discrete propagation velocity vector in i direction, $f_i^{(eq)}$ is the equilibrium
 204 distribution function of \mathbf{e}_i for density ρ and fluid velocity \mathbf{u} .

205 The relaxation time τ is adopted:

$$206 \quad \tau = \frac{\nu}{c_s^2 \delta_t} + \frac{1}{2} \quad (4)$$

207 where ν is the kinematic viscosity; $c_s = \sqrt{RT} = c / \sqrt{3}$ is the sound speed, in which R is
 208 the gas constant and T is the temperature.

209 The DnQb model (n is the spatial dimension and b is the number of discrete velocity vectors)

210 proposed by Qian et al. [38] is the most representative. We utilize the D2Q9 model (see Fig.
 211 2d), and its equilibrium distribution function $f_i^{(eq)}$ can be expressed as:

$$212 \quad f_i^{(eq)} = \omega_i \rho \left[1 + \frac{\mathbf{e}_i \cdot \mathbf{u}}{c_s^2} + \frac{(\mathbf{e}_i \cdot \mathbf{u})^2}{2c_s^4} - \frac{\mathbf{u} \cdot \mathbf{u}}{2c_s^2} \right] \quad (5)$$

213 where $c = \delta_x / \delta_t$ is the lattice velocity, and both the lattice size δ_x and time step δ_t are
 214 set to 1. The \mathbf{e}_i and weight coefficient ω_i are defined as:

$$215 \quad \mathbf{e}_i = c \begin{bmatrix} 0 & 1 & 0 & -1 & 0 & 1 & -1 & -1 & 1 \\ 0 & 0 & 1 & 0 & -1 & 1 & 1 & -1 & -1 \end{bmatrix}$$

$i = 0, 1, \dots, 8$

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216
$$\omega_i = \begin{cases} 4/9 & i=0 \\ 1/9 & i=1-4 \\ 1/36 & i=5-8 \end{cases} \quad (6)$$

217 For isothermal gas flow, the macroscopic parameters, such as density and momentum, can be
 218 determined as:

219
$$\rho = \sum_i f_i, \quad \rho \mathbf{u} = \sum_i \mathbf{e}_i f_i \quad (7)$$

220 The pressure boundary conditions are applied to the inlet and outlet. The stationary non-slip
 221 boundary is drawn on the solid wall. We default the simulation to reach a steady state when the
 222 velocity change of each grid between two time steps is less than 0.0001%. Note that the fact
 223 that the isothermal boundary condition has been adopted in the above deduction.

224 The lattice units are used in [the above-mentioned](#) parameters. Therefore, it is
 225 necessary to convert the studied physical quantity (e.g. permeability) from the lattice unit to the
 226 physical unit. The permeability can be determined by Eq. (8) following the theoretical model
 227 of capillary model.

228
$$\frac{K}{K_{LBM}} = \left(\frac{L}{L_{LBM}} \right)^2 \quad (8)$$

229 where K and K_{LBM} are the intrinsic permeability with physical unit and the permeability
 230 simulated by LBM, respectively. L is the real scale of coal sample and L_{LBM} is the scale of LBM.
 231 Other physical property parameters such as kinematic viscosity required for methane under
 232 different pressure and temperature conditions can be obtained from the open source software
 233 called Peace software.

234 **[2.5.3. Validation of Box-counting and Lattice-lattice Boltzmann methods](#)**

235 **[3.2.5.1 Box-counting method](#)**

236 Sierpinski Carpet as a classic figure (as shown in Fig. 3a) in fractal theory can be used to verify

237 the accuracy of our calculation program. The definition of fractal dimension determines
238 Sierpinski Carpet's theoretical fractal dimension $D = \frac{\ln 8}{\ln 3} \approx 1.8928$. As presented in Fig. 3b,
239 the actual result we calculated is also 1.8928, which indicates that the actual result is in good
240 agreement with the theoretical value. In other words, this comparison confirms that our program
241 is feasible.

242 **2.5.3.2 Lattice Boltzmann method**

243 The second validation is carried out by simulating the flow of two-dimensional Poiseuille with
244 different lattice sizes including 100×100 , 250×250 and 500×500 . The normalized
245 streamwise velocity profiles $U = u / u_{\max}$ are compared with the analytical solution as shown
246 in Fig. 4, which shows that the simulation results based on a series of lattice sizes are highly
247 consistent with the analytical solutions. This consistency also confirms that the LBM is suitable
248 for understanding the flow [capacity capability](#).

249 **4.3. Results and discussion**

250 Micro-fracture morphology, pressure and temperature are three of the important factors
251 affecting permeability and thus enhancing CBM recovery [39-41]. This section captured the
252 flow characteristics of methane under different micro-fractures morphologies, different
253 pressures and temperatures based on the D2Q9 model. The pressure gradient was set to 0.1
254 MPa/m in the simulation along the flow direction.

255 **4.3.1 Effects of micro-fracture morphology on flow [capacity capability](#)**

256 The pre-existing natural fractures characteristics are of importance on the hydraulic fracturing
257 stimulation effect [7]. Herein, the effect of pre-existing natural fracture morphology on methane
258 flow in coal will be discussed in detail. The velocity distribution results with different micro-

259 fractures morphologies are displayed in Fig. 5 as the simulation reaches steady state (i.e. the
260 velocity change of each grid between two time steps is less than 0.0001%). Fig. 5 demonstrates
261 that the pressure-driven methane migration in various micro-fracture networks is different. It is
262 easy to find out that the existence of dominant channels is conducive to the gas flow ~~of methane~~,
263 that is, there is a wide channel connecting the inlet to the outlet in the micro-fracture network
264 ~~(as shown by the red dotted line in Fig. 1).~~ The length and width of the dominant channel was
265 ~~counted into listed in Table 2, and it is seen that~~ which has the average length and width are of
266 ~~~498.26 μm and 10.96 μm, respectively.~~ The velocity in the dominant channel is much larger
267 compared with other locations (see Fig. 5). As shown in Fig. 5d and i, it gas flow is much more
268 difficult ~~for gas to flow~~ if the micro-fracture network is connected by narrower channels ~~(with~~
269 width less than 5 μm). Another interesting phenomenon is that the special micro-fracture
270 morphology ~~makes determines~~ the time ~~when that~~ the flow simulation reaches the steady state
271 ~~greatly different,~~ which varies from 5711 to 130561 ~~showing greatly different. It can be found~~
272 ~~indicated~~ This result means that the time for the simpler micro-fracture network ~~takes ajs~~ much
273 shorter time to reach the steady state, while the micro-fracture network with a more special
274 shape (see e.g., the orthogonal type in Fig. 5i and Fig. 6) and a more complex distribution (see
275 Fig. 5g) takes longer to reach steady state. ~~Assuming that~~ The equilibrium time listed in Fig. 5
276 is used as the standard to evaluate the difficulty of fluid flow in micro-fracture network, it can
277 ~~be seen that~~ the orthogonal micro-fracture is the most unfavorable for flow capability, and the
278 most favorable network is the reticular type. And in between are the dendritic and filamentous
279 types are in between the orthogonal and reticular types. The dendritic type with more branches
280 will cause more obstacles to flow. The filamentous type is connected by has a lot of narrow

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281 ~~throats, so it~~ throats, which result in is more difficult to flow in filamentous structure more difficult than
282 that in the dendritic structure type with fewer branches. ~~More clearly, Fig. 6 indicates displays~~
283 ~~that~~ the simulated flow process of the orthogonal micro-fracture network ~~is not easy for gas~~
284 flow. At the beginning of the flow process, the gas will extend in three directions after meeting
285 the bifurcation. As time goes on, the gas will flow further following with the branches. At this
286 time, the upward and downward flow directions do not match the main flow direction; therefore,
287 the gas in the up and down directions will gradually disappear. When the simulation reaches
288 the steady state, the gas only passes in the main flow direction. The computation time also
289 becomes longer due to the special angle (e.g., orthogonal type) of the branches ~~in of~~ the natural
290 micro-fracture network.

291 The fracture dimension values calculated by BCM are displayed in Fig. 7 ~~and, which~~ ranges
292 from 1.321 ~~to~~ 1.584. The larger the value is, the more complicated ~~the~~ distribution of the
293 natural micro-fracture network [16]. Besides, Fig. 8b reveals that there is an obvious positive
294 correlation between the fractal dimension and the fracture porosity. This phenomenon may be
295 ascribed to two causes: the first is that micro-fracture network with larger fracture porosity will
296 have a greater chance of being more complicated ~~in~~ distribution, which is consistent with ~~the~~
297 ~~conclusion of~~ Wu et al. [36]. Secondly, ~~it is not significant that~~ the micro-fracture network
298 ~~obtained by optical microscopy is~~ filled with minerals is poor developed, thus there is no
299 complex trend that is similar to the relationship between porosity and fractal dimension [35].

300 As shown in Fig. 8a, there is a significant inverted U-shaped relationship between fractal
301 dimension and permeability with the correlation coefficient of 0.86. The permeability increases
302 as fractal dimension increases from 1.321 ~~to~~ 1.472, and then decreases as fractal dimension

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303 exceeds 1.472. The permeability is 0.147 D when the fractal dimension is 1.321, while it
304 increases to 0.345 D as fractal dimension reaches to 1.472. The reason for this increasing trend
305 is that lower fractal dimension normally corresponds to lower fracture porosity, resulting in
306 lower permeability ~~for methane~~. As the fractal dimension increases, the fracture porosity also
307 increases, and the permeability is improved when the connectivity of the micro-fracture
308 network is better. However, when the fractal dimension exceeds 1.472, ~~it means that~~ the
309 micro-fracture network becomes more complex. Meanwhile, due to the strong heterogeneity of
310 the CBM reservoir and poor connectivity [1, 26, 42], the natural micro-fracture network is
311 connected by the narrow throat, leading to difficult gas flow ~~of methane~~ and thus lower
312 permeability ~~(as shown in Fig. 9)~~. Fig. 9 shows that the methane still flows through the micro-
313 fracture network branch f1 (see f2) at the beginning of the flow process, but methane will not
314 pass through these channels as time increases. Hence, under the premise of only one flow
315 direction, ~~the flow time~~ will undoubtedly ~~make take the flow time~~ longer if many branches
316 exist in the micro-fracture network. And if the extension direction of these branches is different
317 from the flow direction, ~~they will be not~~ would constrained ~~constrain~~ ~~contributed to the~~
318 permeability.

319 4.2 Effects of pressure on flow capacity

320 The trend of permeability together with outlet pressure is shown in Fig. 10. ~~Fig. 10, which~~
321 illustrates that the permeability decreases sharply as pressure increases from 0.1 MPa to 5 MPa,
322 and then the ~~change of~~ permeability tends to be gentle stable as pressure exceeds 5 MPa. In
323 other words, the natural micro-fracture network is more sensitive to changes in permeability at
324 low pressure. ~~This is because~~ ~~because at low pressure~~, the distance between the rarefied gas

325 molecules is far away and the attractive force is weak at low pressure [29]. The decreasing trend
326 of decreasing permeability with increasing pressure is consistent with the production of shale
327 gas production [27, 43]. But in this study However, when the permeability is larger than 5 MPa,
328 there is no similar trend similar to that in CBM production concluded by Shi and Durucan [44].
329 During the production of CBM production, the permeability initially declines and then
330 increases with increasing pressure [6, 44]. The reason for this phenomenon is that the shrinkage
331 of the coal matrix due to gas desorption, a unique a unique characteristic of coal reservoir,
332 counteracts the decrease in permeability decrease with pressure drop during the production [4,
333 45]. Therefore, a model considering matrix swelling/shrinkage can accurately describe gas
334 actual flow characteristics. Due to its extremely challenging nature, coal matrix
335 swelling/shrinkage response during gas flow will-should be considered into our the permeability
336 model in the near future.

337 4.3.3 Effects of temperature on flow capacity capability

338 Three sets of temperatures were simulated to study the effects of changes of temperature
339 changes including 300K, 330 K and 360 K on coal permeability, including 300K, 330 K and
340 360 K. From Fig. 10, it can be seen exhibits that the permeability will increase with increasing
341 temperature for at the constant pressure. The increase of temperature will aggravate the thermal
342 motion of gas molecules, leading to the average kinetic energy of the molecules increasing and
343 thereby increasing the permeability, which is in accordance with the research conclusion of
344 Yuan et al previous research [29]. And at low pressure, the influence of temperature on
345 permeability is more sensitive at low pressure. For realistic CBM production, the effect of
346 temperature on coal permeability is related to many factors, such as coal rank and pore-fracture

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347 structure [39, 42]. For instance, Cai et al. [39] revealed that different rank coals have different
348 trends in permeability changes caused by temperature. And Liu et al. [42] ~~studied found that~~
349 the ~~effect of~~ temperature has obvious impact on the mechanical properties and acoustic
350 emission characteristics in coal, and ~~found that~~ the pore-fracture structures were promoted and
351 the permeability was significantly improved under ~~the impact of~~ temperature treatment.
352 ~~Therefore, the micro fracture morphology, pressure and temperature have an comprehensive~~
353 ~~complex influence on the gas flow capability, which generally follows the dominated micro-~~
354 ~~fracture morphology, supplemented by pressure and temperature. The comprehensive~~
355 ~~mechanism is shown in Fig. 11.~~ CBM reservoirs normally have the characteristics of complex
356 pore-fracture structure, strong heterogeneity, and abundant mineral types, which ~~may~~ cause a
357 series of physical and chemical changes in the process of temperature increase [46]. ~~Even,~~
358 ~~different~~ Different components in coal have different shrinking and swelling ability under the effect of
359 temperature [42]. ~~For example, the temperature stress will aggravate the expansion of fractures~~
360 ~~and weaken the mechanical properties of coal [42]. XX and XX.~~ Moreover, during the
361 exploitation of CBM, the reservoir temperature also changes dynamically with produced gases;
362 thus, the effect of temperature on permeability ~~must should~~ be cautiously considered [47].
363 ~~Therefore, the micro-fracture morphology, pressure and temperature have a comprehensive~~
364 ~~complex influence on gas flow capability, which generally follows the dominated micro-~~
365 ~~fracture morphology, supplemented by pressure and temperature. The comprehensive~~
366 ~~mechanism is as shown in Fig. 11.~~
367 Although the detailed work on the morphology effect of micro-fracture network on
368 permeability has been revealed, the process of fluid-solid coupling has yet to confirm, ~~which~~

369 ~~may include the response mechanism of the coal matrix in the gas transmission process and~~
370 ~~heat transmission~~. Therefore, the flow response in micro-nano scale natural pore-fracture
371 structure during the ~~exploitation of~~ CBM development will be our next ~~focus in the following~~
372 work.

373 5.4. Conclusions

374 In this study, natural micro-fracture morphologies of selected Chinese coals from the Ordos
375 Basin were characterized by the optical microscope. And the box-counting method together
376 with the lattice Boltzmann method was adopted to quantify the complexity of the micro-fracture
377 network and ~~to investigate the~~ flow behaviors in these natural micro-fracture networks. Besides,
378 factors affecting the flow ~~capacity capability~~ in these natural micro-fracture networks were
379 discussed. The following conclusions can be ~~summarized~~ made:

380 1) The ~~existence of~~ dominant channels in the natural micro-fracture network will greatly
381 improve the permeability. Besides, ~~the~~ flow characteristics ~~of in the~~ micro-fracture networks
382 with different morphologies are quite different, ~~which presents that the orthogonal type is~~
383 ~~unfavorable for flow capability, and the most favorable network is reticular, with dendritic and~~
384 ~~filamentous types in between, and the orthogonal type is not conducive to the flow capacity.~~

385 2) An obvious inverted U-shaped relationship exists between the fractal dimension and
386 permeability. ~~When the fractal dimension is lower than 1.472, the larger fractal dimension~~
387 ~~means the greater fracture porosity, and thus the permeability of well-connected natural micro-~~
388 ~~fractures will be increased. When As~~ the fractal dimension exceeds 1.472, the distribution of
389 natural micro-fracture network is ~~complicated~~ complicated, ~~which presents reticular and~~
390 ~~dendritic types~~ XX. ~~And~~ the connected narrow throats normally lead to a permeability decrease.

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391 3) Pressure and temperature have opposite influence on coal permeability. The permeability
392 increases with decreasing gas? pressure, which is caused by due to the rarefied gas caused
393 by due to the declining pressure. But-However, the methane-gas at high temperatures of XX360
394 K will lead to a gentle increase of permeability.

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535 **Captions for Figures and Tables**

536 **Fig. 1.** Different micro-fracture morphologies of selected samples obtained by optical
537 microscope, which varied involving dendritic, reticular, filamentous and orthogonal etc. The
538 red dotted lines are the dominant channels mentioned in section 4.1.

539 **Fig. 2.** The results after threshold segmentation and the discrete velocity of D2Q9 model. (a) is
540 the initial image; (b) and (c) are images before and after noise reduction, respectively. Careful
541 observation shows that the noise in the red rectangular frame of (c) is significantly less than
542 that in (b), and the edge of the micro-fracture in (c) is smoother after noise reduction. (d) is the
543 discrete velocity of D2Q9 model.

544 **Fig. 3.** The verification of the box-counting method. (a) is the Sierpinski Carpet image and (b)
545 is the value estimated by the box-counting method.

546 **Fig. 4.** Normalized streamwise velocity profiles with different lattice sizes.

547 **Fig. 5.** The velocity distribution results of dimensionless lattice unit when the simulation
548 reaches equilibrium with different micro-fractures morphologies and the schematic diagram of
549 the gas flow model. t is the time for the simulation to reach convergence. (a)- (i) are the velocity
550 distribution results and (j) is the schematic diagram of the gas flow model. Simulation
551 conditions include $T = 300$ K, outlet pressure = 10 MPa and pressure gradient = 0.1 MPa/m.

552 **Fig. 6.** Velocity distribution of sample F9 under different time steps. t is the time step. The
553 length of the arrow indicates how far the gas flows. At the beginning of the flow process, the
554 gas will extend in three directions after meeting the bifurcation. As time goes on, the gas will
555 flow further following with the branches. At this time, the upward and downward flow
556 directions do not match the main flow direction, so the gas in the up and down directions will

557 gradually disappear. When the simulation reaches equilibrium, the gas only passes in the main
558 flow direction. The equilibrium time also becomes longer due to the special angle (orthogonal
559 type) of the branches of the microfracture network. Simulation conditions include $T = 300$ K,
560 outlet pressure = 10 MPa and pressure gradient = 0.1 MPa/m.

561 **Fig. 7.** Results of fractal dimension calculated by the box-counting method

562 **Fig. 8.** Relations between permeability, fracture porosity and fractal dimension. (a) fractal
563 dimension versus permeability and (b) fractal dimension versus fracture porosity. $T = 300$ K,
564 outlet pressure = 10 MPa and pressure gradient = 0.1 MPa/m.

565 **Fig. 9.** Velocity distribution of sample F7 under different time steps. t is the time step. (a) is the
566 initial image of F7 and (b)-(e) are the velocity distribution under different time steps [during](#)
567 [simulation](#). $f1$ and $f2$ are the original image of the branch and the changes that occurred [in the branch](#)
568 during the flow [process, respectively](#).

569 **Fig. 10.** Relations between pressure, temperature and permeability in different samples.
570 Pressure gradient = 0.1 MPa/m.

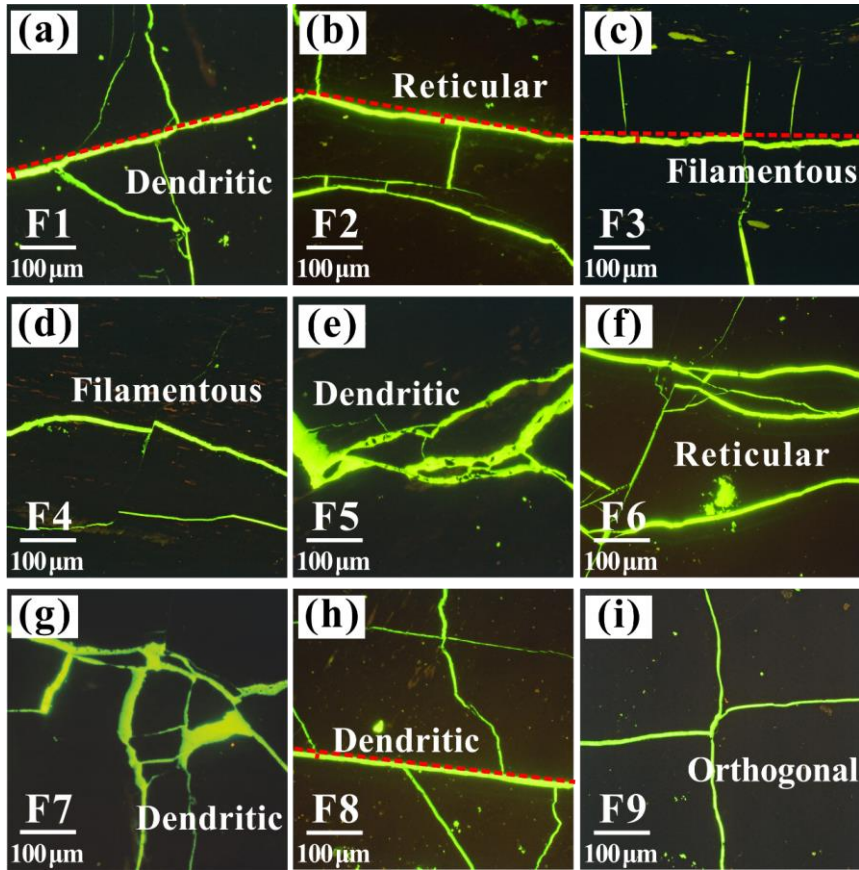
571 **Fig. 11.** Diagram of the influence mechanism of different factors on permeability, including the
572 micro-fracture morphology, pressure and temperature. The positive and negative signs (“+” and
573 “-”) in the figure represent the promotion and inhibition effects, respectively.

574 **Table 1** Sample information and basic parameters of the selected coals.

575 [Table 2 Statistics of the length and width of the dominant channel of micro-fractures in Fig. 1.](#)

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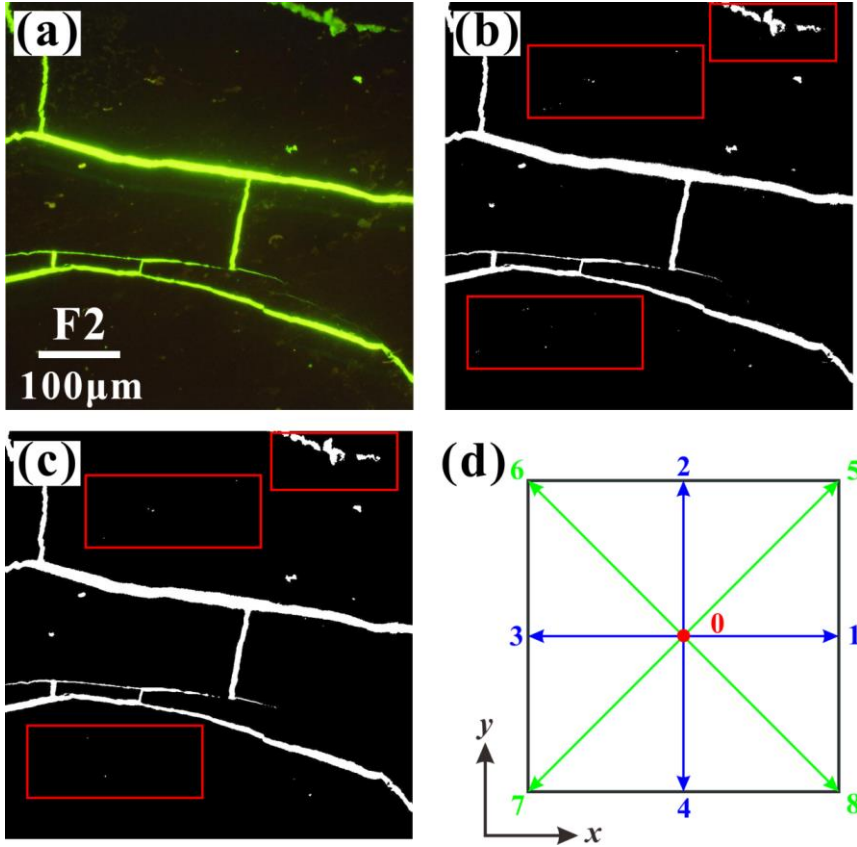
579 **Fig. 1.** Different micro-fracture morphologies of selected samples obtained by optical microscope,

580 which varied involving dendritic, reticular, filamentous and orthogonal etc. The red dotted lines are

581 the dominant channels mentioned in section 4.3.1.

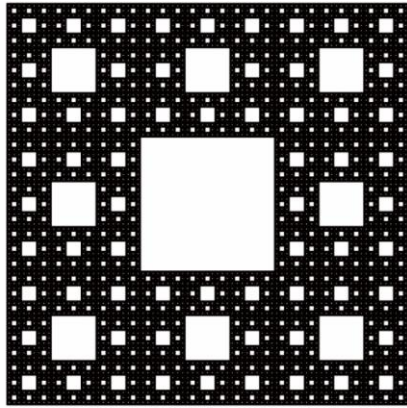
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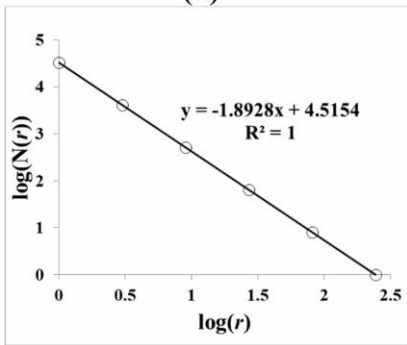


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585 **Fig. 2.** The results after threshold segmentation and the discrete velocity of D2Q9 model. (a) is the
 586 initial image; (b) and (c) are images before and after noise reduction, respectively. Careful
 587 observation shows that the noise in the red rectangular frame of (c) is significantly less than that in
 588 (b), and the edge of the micro-fracture in (c) is smoother after noise reduction. (d) is the discrete
 589 velocity of D2Q9 model.



(a)



(b)

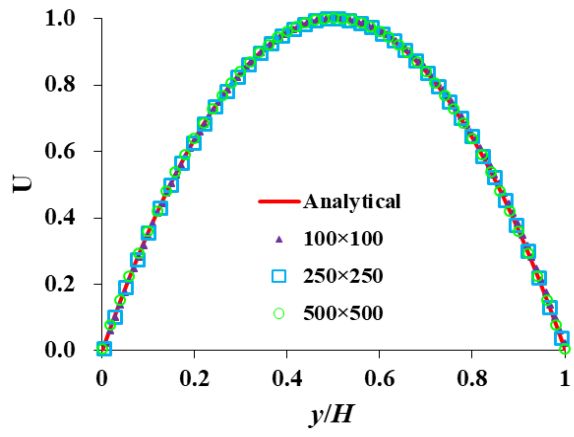
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591 **Fig. 3.** The verification of the box-counting method. (a) is the Sierpinski Carpet image and (b) is

592 the value estimated by the box-counting method.

593

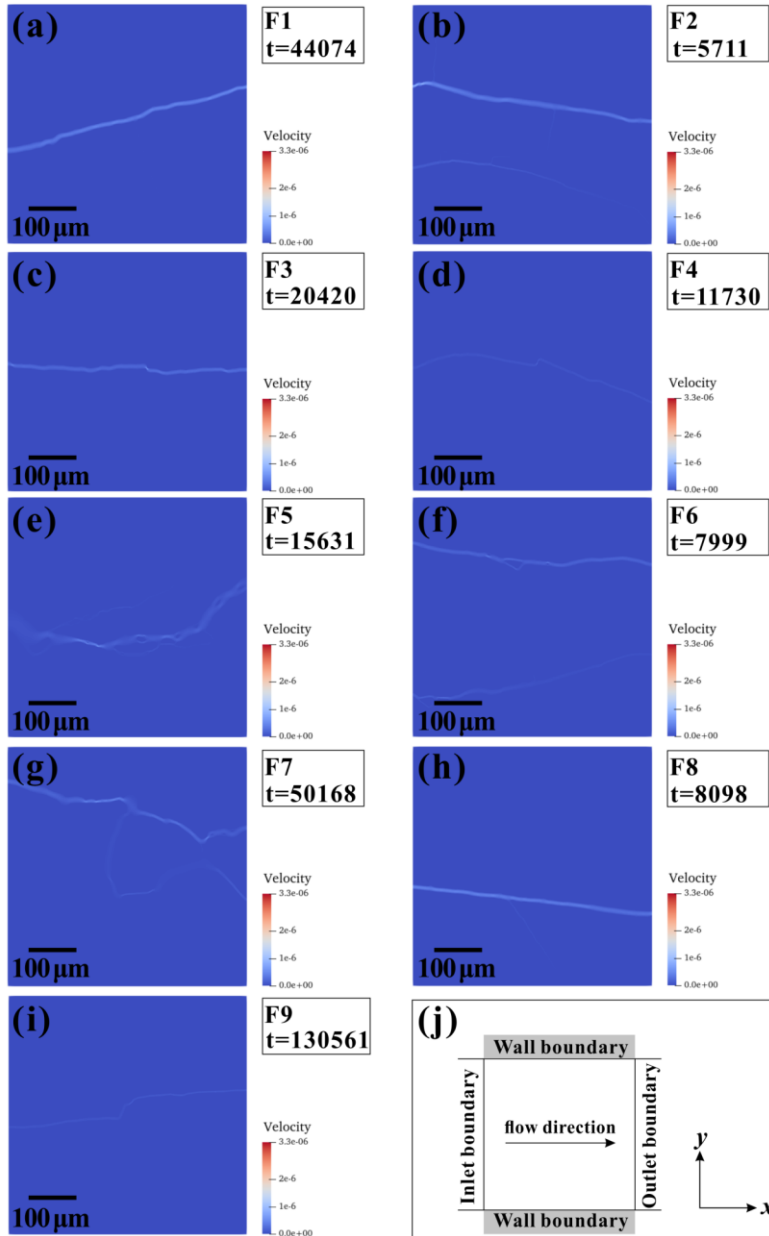
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596 **Fig. 4.** Normalized streamwise velocity profiles with different lattice sizes.

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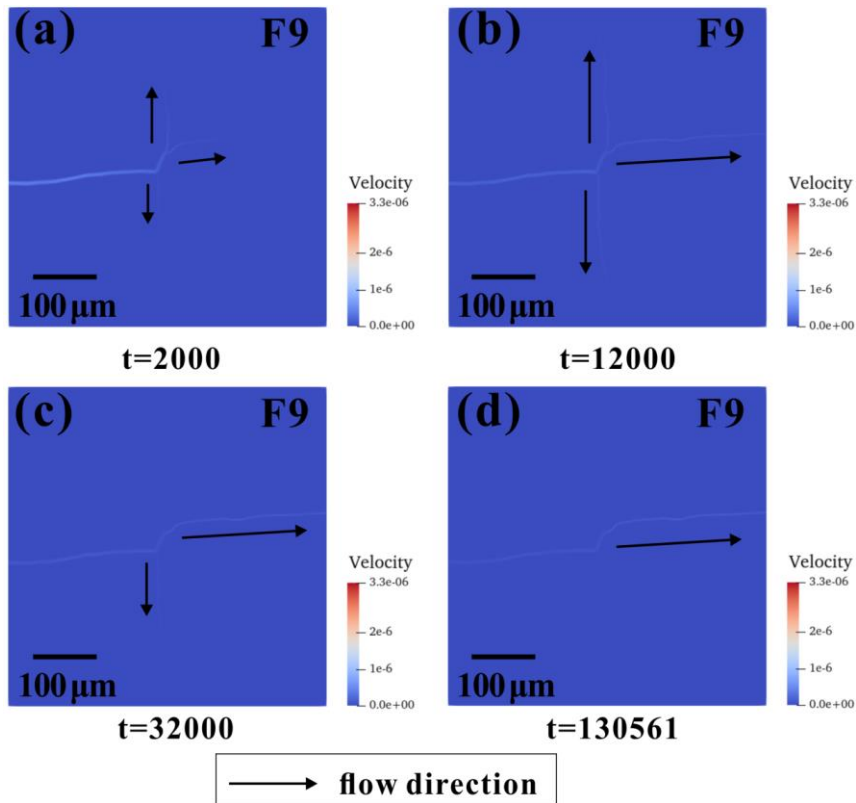
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Fig. 5. The velocity distribution results of dimensionless lattice unit when the simulation reaches equilibrium with different micro-fractures morphologies and the schematic diagram of the gas flow model. t is the time for the simulation to reach convergence. (a)- (i) are the velocity distribution results and (j) is the schematic diagram of the gas flow model. Simulation conditions include $T = 300$ K, outlet pressure = 10 MPa and pressure gradient = 0.1 MPa/m.



604

605 **Fig. 6.** Velocity distribution of sample F9 under different time steps. t is the time step. The length

606 of the arrow indicates how far the gas flows. At the beginning of the flow process, the gas will

607 extend in three directions after meeting the bifurcation. As time goes on, the gas will flow further

608 following with the branches. At this time, the upward and downward flow directions do not match

609 the main flow direction, so the gas in the up and down directions will gradually disappear. When

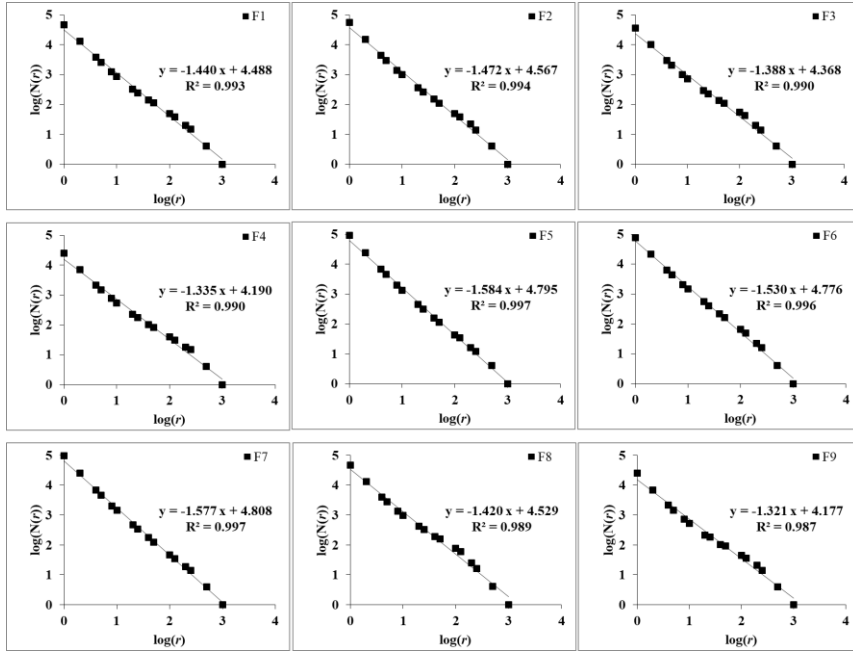
610 the simulation reaches equilibrium, the gas only passes in the main flow direction. The equilibrium

611 time also becomes longer due to the special angle (orthogonal type) of the branches of the

612 microfracture network. Simulation conditions include $T = 300$ K, outlet pressure = 10 MPa and

613 pressure gradient = 0.1 MPa/m.

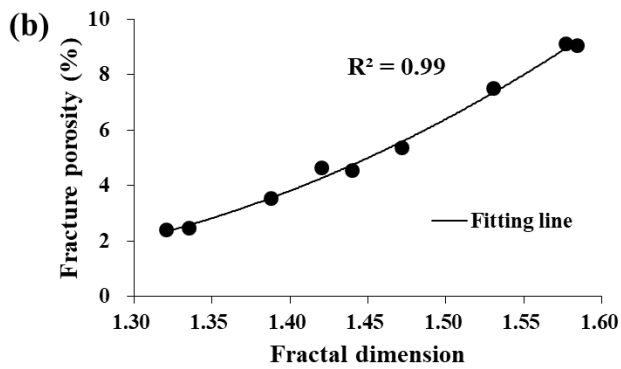
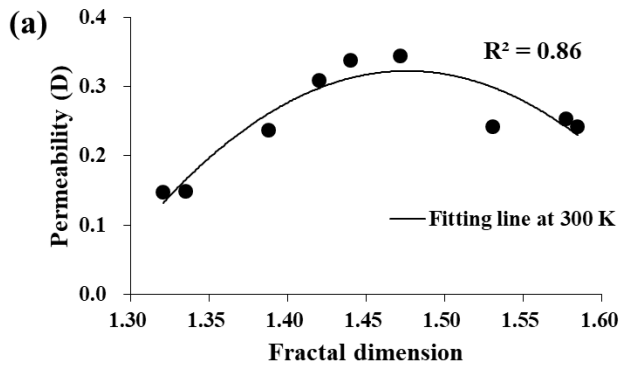
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615

616 **Fig. 7.** Results of fractal dimension calculated by the box-counting method

617



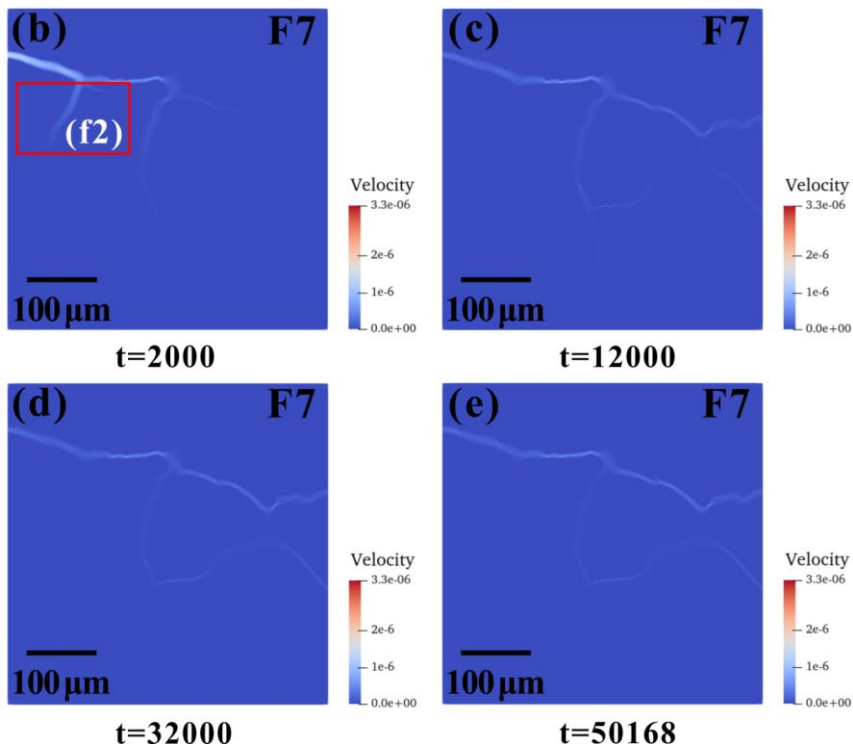
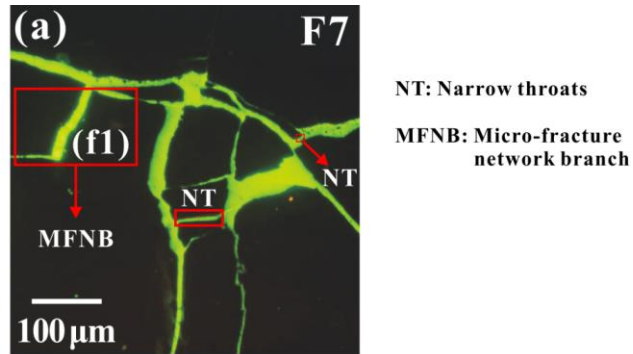
618

619 **Fig. 8.** Relations between permeability, fracture porosity and fractal dimension. (a) fractal

620 dimension versus permeability and (b) fractal dimension versus fracture porosity. T = 300 K, outlet

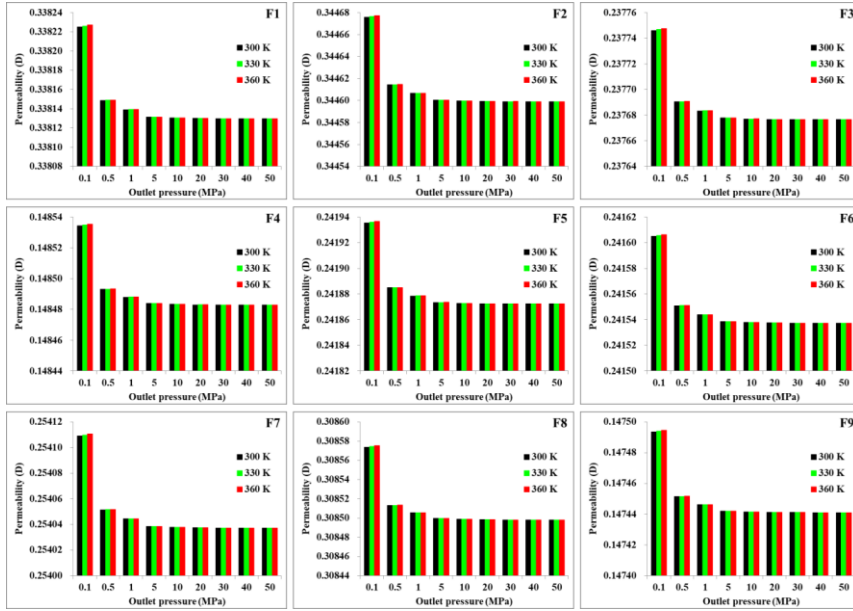
621 pressure = 10 MPa and pressure gradient = 0.1 MPa/m.

622



623
 624 **Fig. 9.** Velocity distribution of sample F7 under different time steps. t is the time step. (a) is the
 625 initial image of F7 and (b)-(e) are the velocity distribution under different time steps during
 626 simulation. f1 and f2 are the original image of the branch and the changes that occurred in the branch
 627 during the flow process, respectively.

628

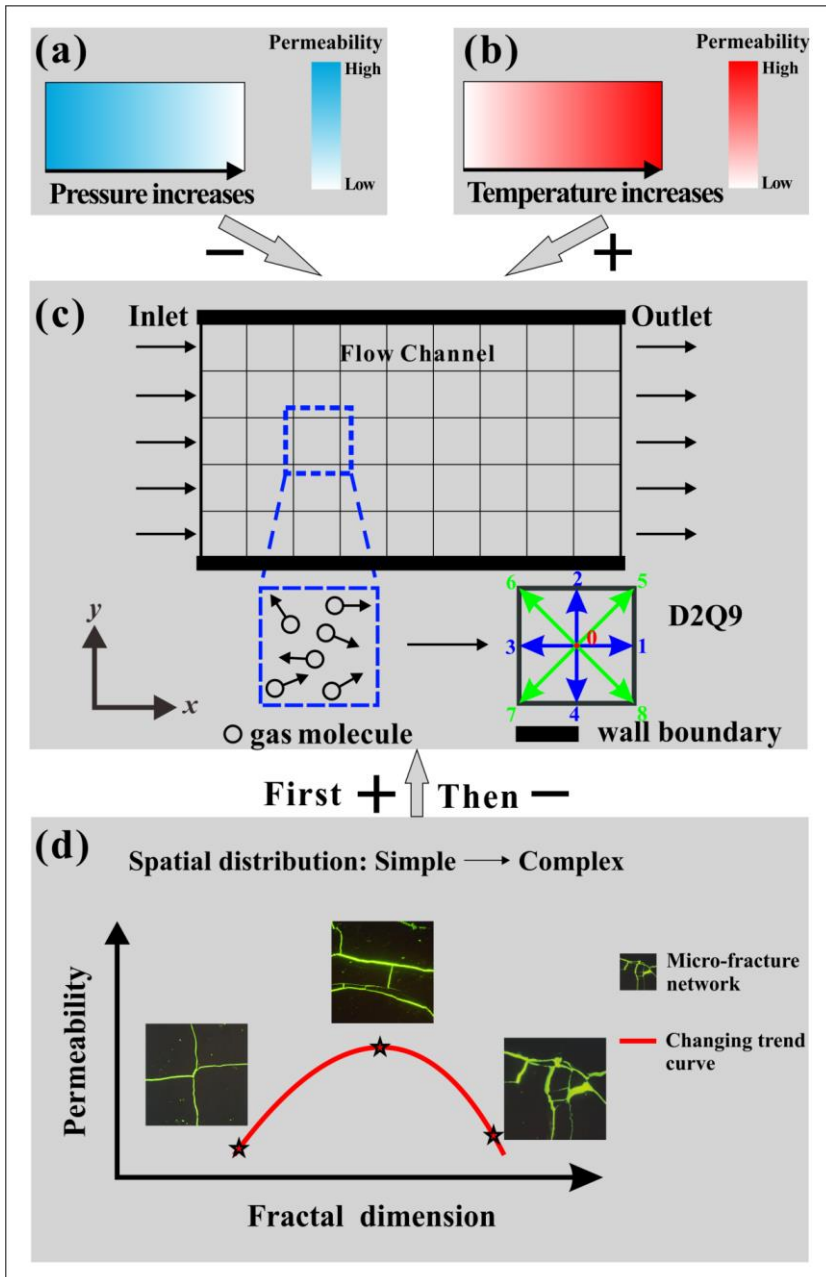


629

630 **Fig. 10.** Relations between pressure, temperature and permeability in different samples. Pressure

631 gradient = 0.1 MPa/m.

632



633
 634 **Fig. 11** Diagram of the influence mechanism of different factors on permeability, including the
 635 micro-fracture morphology, pressure and temperature. The positive and negative signs (“+” and “-”)
 636 in the figure represent the promotion and inhibition effects, respectively.

637

638 **Table 1** Sample information and basic parameters of the selected coals

Sample no.	Basin	R _{o,max} (%)	Maceral and mineral (%)				Fracture porosity (%)
			Vitrinite	Inertinite	Exinite	Mineral	
F1		0.62	65.4	21	5.3	8.3	4.53
F2		0.65	66.2	24.9	1.4	7.5	5.35
F3		0.68	90.1	4.5	4.4	1	3.54
F4		0.89	66.9	25.6	5.9	1.6	2.45
F5	Ordos	1.27	90.2	8.3	0	1.5	9.05
F6		1.27	82.3	14.7	0	3	7.50
F7		1.36	82.2	15.2	2.4	0.2	9.11
F8		1.58	84.0	11.6	0.6	3.8	4.64
F9		1.78	84.4	7.9	3.1	4.6	2.41

639

640 **Table 2** Statistics of the length and width for the dominant channel of micro-fractures in Fig. 1.

Figure ID	Fig 1(a)	Fig 1(b)	Fig 1(c)	Fig 1(h)	Average
Length (μm)	506.66	495.61	493.68	497.10	498.26
Width (μm)	13.63	10.19	11.13	8.88	10.96

641

642

643 **Nomenclatures**

644 r : length of boxes

645 D : fractal dimension

646 $N(r)$: the number of boxes required to completely cover the image

647 FP: fracture porosity

648 f : distribution function

649 x : position of the particles

650 t : time

651 δ_x : lattice size

652 δ_t : time step

653 τ : relaxation time

654 e_i : the discrete propagation velocity vector in i direction

655 $f_i^{(eq)}$: the equilibrium distribution function

656 ρ : density

657 \mathbf{u} : fluid velocity

658 ν : kinematic viscosity

659 n : spatial dimension

660 b : number of discrete velocity vectors

661 c_s : sound speed

662 c : lattice velocity

663 R : gas constant

664 T : temperature

665 ω_i : weight coefficient

666 K : intrinsic permeability with physical unit

667 K_{LBM} : permeability simulated by LBM

668 L : the real scale of coal sample

669 L_{LBM} : the scale of LBM

670 U : normalized streamwise velocity

1 Effects of natural micro-fracture morphology, temperature and pressure on
2 fluid flow in coals through fractal theory combined with lattice Boltzmann
3 method

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10 **Abstract**

11 The fluid flow behaviors during the production of coalbed methane (CBM) are generally
12 restricted by the pre-existing natural fractures in coal seams. To better understand the effect of
13 natural micro-fracture morphology on the flow capability, nine coals collected from Ordos
14 Basin were subjected to optical microscope observations to obtain micro-fractures morphology.
15 And then, an improved box-counting method (BCM) was used to quantify the complexity of
16 the micro-fracture network planar distribution. Besides, the lattice Boltzmann method (LBM)
17 was adopted to simulate the flow in the complex micro-fracture network under different
18 pressures and temperatures. Finally, factors affecting the flow capability in micro-fracture were
19 elaborated. The results show that the micro-fractures generally present dendritic, reticular,
20 filamentous and orthogonal structures. The natural micro-fracture morphology has a
21 remarkable impact on flow behavior, in which the presence of dominant channels with a length

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22 of $\sim 498.26 \mu\text{m}$ and a width of $\sim 10.96 \mu\text{m}$ has a significant contribution to permeability, while
23 the orthogonal micro-fracture network normally is not conducive to fluid flow. The fractal
24 dimension extracted from the nine coals varies from 1.321-1.584, and the permeability
25 calculated from LBM method varies from 0.147 to 0.345 D; in contrast to other studies, a non-
26 monotonic change, an inverted U-shaped, of permeability on fractal dimension was observed.
27 Moreover, permeability decreases as pressure increases and increases with increasing
28 temperature due to the physical properties of methane and coal matrix. Therefore, this work
29 may contribute to understanding the process of hydrofracturing and hydrothermal methods for
30 improving CBM reservoirs during enhancing CBM recovery.

31 **Keywords:** Coal; Micro-fractures morphology; Permeability; Fractal theory; Lattice
32 Boltzmann method

33

34 **1. Introduction**

35 Coalbed methane (CBM) is an essential component of the unconventional energy system due
36 to its huge reserves, the reservoir of which is deemed as a dual-porous medium with pores in
37 matrix and fractures/cleats [1-3]. Pores are generally associated with the processes of gas
38 storage, desorption and diffusion [4]. For fractures, composed by micro-fractures and macro-
39 fractures, they are the most important physical attribute governing gas flow in a CBM reservoir
40 [5, 6]. Generally speaking, natural fractures primarily contributed to the permeability of coal,
41 while the pores in coal matrix have very limited influence on coal permeability [7]. Extensive
42 works including experiments and numerical simulations have been conducted to understand the
43 performance of micro-fracture with the width at micron scale due to its importance on CBM

44 production [8-24]. Multiple experimental methods can be used to characterize micro-fractures
45 properties, including low-field nuclear magnetic resonance (NMR) [8, 9], X-ray computed
46 micro-tomography (X-ray μ CT) [10-12] and the classic optical microscopy [13]. NMR is a non-
47 destructive measurement and has been adopted successfully to detect and quantify the pore-
48 fracture structure of coals [8], where the T_2 spectrum larger than 100 ms represents micro-
49 fracture [9]. However, the detailed morphological features of micro-fracture are not accessible
50 through NMR. X-ray μ CT can provide realistic three-dimensional digital images and different
51 components reconstruction [10-12]. Jenkins et al. [12] utilized X-ray μ CT to dynamically
52 measure the deformation behavior of tested rock under various loading conditions. However,
53 X-ray μ CT is expensive and time-consuming. Compared with the above techniques, the micro-
54 fracture morphology observation by optical microscopy is not only economically suitable but
55 also easy to obtain clear morphologies [13]. Besides, the fractal dimension can extend the
56 qualitative description of the micro-fracture network to a quantitative description, which
57 quantifies its complexity of distribution [14, 15]. The box-counting method (BCM) is one of
58 the most popular algorithms [16, 17] to acquire the complexity, namely fractal dimension,
59 through the images of pore-fracture structure. Herein, the BCM will be utilized to quantify the
60 complexity of micro-fractures. On the other hand, direct numerical methods including finite
61 difference method (FDM) [18], finite element method (FEM) [19] and finite volume method
62 (FVM) [20] can be effectively adopted to simulate the flow behavior in micro-fracture networks.
63 But these traditional simulation methods on the basis of Navier-Stokes equations require
64 complicated meshing process to define the simulation domain and are challenging to solve
65 complex geometric boundaries and have low parallel efficiency [18-20]. The lattice Boltzmann

66 method (LBM), as a typical mesoscopic method, has a strong advantage in simulating the flow
67 behavior of porous media with irregular boundaries [21, 22]. For example, Wang et al. [23]
68 decomposed the three-dimensional fracture geometry into primary and secondary roughness
69 through wavelet analysis, and investigated the role of the latter in the flow of rock fractures
70 using LBM. And Zhao et al. [24] adopted LBM to discuss the effect of structure, surface
71 roughness and aperture on flow in constructed fracture networks with rough surfaces.

72 The previous works on coal fractures/cleats can be classified into two parts: characterization of
73 micro-fracture networks [8-13] and the exploration of gas flow behavior in the micro-fracture
74 networks [18-24]. It is significant for understanding the effect of natural fracture network on
75 permeability through investigating the characteristics and distribution of natural fractures in
76 coal. Besides, owing to the complexity of the natural fracture network in coal, much related
77 work has performed flow simulation in the fracture network constructed by algorithms such as
78 Voronoi tessellations method [24, 25] and Fracture Pipe Network Model (FPNM) [26], whereas
79 rare researches have been conducted on the real complex natural fracture networks with specific
80 morphologies. Many studies adopted an idealistic tube model with a circular cross-section to
81 simplify the flow simulation [27, 28]. However, in most cases, the shape of micro-fractures is
82 non-circular and irregular in coal, which is much complicated. Therefore, Yuan et al. [29]
83 compared the realistic shape with the permeability characteristics of circle, square and
84 equilateral triangular cross-sections, which found that the permeability of the network with
85 circle cross-section is the highest, followed by the realistic shape, and the final are square and
86 equilateral triangular. This finding corroborates the importance of accurately acquiring
87 morphological features in micro-fracture networks.

88 In this study, we aim to investigate the flow behavior in natural micro-fractures with various
89 morphologies under different pressures and temperatures. To detailed address the flow behavior
90 in micro-fractures, the specific morphologies of natural micro-fractures were firstly obtained
91 by optical microscopy. And then, the BCM was used to quantify the complexity of the natural
92 micro-fracture network. Finally, the LBM was applied to simulate the flow behavior in the
93 natural micro-fracture network with specific morphologies in coals, and the controlling factors
94 were revealed. This study may provide insights into the flow mechanisms of natural micro-
95 fracture networks with complex morphologies in unconventional reservoirs.

96 **2. Methodology and validation**

97 **2.1 Coal sampling and basic analysis**

98 Nine coal blocks ($30 \times 30 \times 30 \text{ cm}^3$) with different coal ranks were selected from the eastern
99 Ordos Basin, north China. The maximum vitrinite reflectance ($R_{o, \max}$) and maceral composition
100 were carried out with a Leitz MPV-III microscope photometer following the Chinese National
101 Standard of GB/T 6948–1998. The $R_{o, \max}$ varies from 0.62% to 1.78% as shown in [Table 1](#),
102 which may indicate the variable inner micro-fractures existed [\[30\]](#). Coal macerals were tested
103 by the point counting technique according to the scheme of the International Committee for
104 Coal and Organic Petrology [\[31\]](#). The coal composition differs, with vitrinite of 65.4-90.2%,
105 inertinite of 4.5-25.6%, exinite of 0-5.9% and mineral being 0.2-8.3%. Natural micro-fractures
106 of coals selectively develop in macerals/submacerals, for example, micro-fractures develop
107 well in the telocollinites while others including the desmocollinite, vitrodetrinite, inertodetrinite
108 and semifusinite are not conducive to micro-fractures development [\[30\]](#).

109 **2.2 Micro-fractures characterization by optical microscopy**

110 The morphological characteristics of the natural micro-fractures can be clearly observed by
111 optical microscopy. The specific preparation process of used coals is as follows: first a certain
112 proportion of resin and paraffin was melted, and then was poured into the micro-fractures of
113 coal. After that, the coals were cut and polished into the blocks with the area of $\sim 3 \times 3 \text{ cm}^2$. To
114 the end, LABORLUX 12 POL optical microscopy (Leitz Company of Germany) was utilized
115 to observe the natural micro-fractures performance including the morphological characteristics.
116 Natural micro-fractures morphologies with the image resolution of $0.4937 \mu\text{m}$ were achieved,
117 which contain various shapes involving dendritic, reticular, filamentous and orthogonal
118 structure as shown in Fig. 1. The natural dendritic micro-fracture network is mostly composed
119 of a backbone and several branches extending out (see Fig. 1a, e, g and h). The natural reticular
120 micro-fracture network can be divided into regular type (Fig. 1b) and disorganized type (Fig.
121 1f), which have the common feature of more than two main channels and the part of branches
122 connecting the main channels, and their difference is whether the channel is curved and
123 disorganized. The natural filamentous micro-fracture network primarily has a channel similar
124 to a ribbon with weak connectivity. Comparatively, the orthogonal micro-fracture network is
125 easy to distinguish, which has a pair of orthogonal channels.

126 After collecting the images, these images need to be preprocessed including noise reduction
127 and image segmentation. First to reduce noise, which normally due to the limitations of the
128 experimental equipment, herein the median filter is chosen to reduce the noise for studied
129 images (Fig. 2). And then the images need to be segmented by Otsu algorithm, which has been
130 proved to be an effective and conciseness threshold segmentation method [16, 32]. After
131 thresholding, the micro-fractures were distinguished from the background in the selected coals.

132 As shown in Fig. 2c, black is the micro-fracture and white is the coal matrix in the binary
133 images. Detailed observation shows that the noise in the red rectangular frame of Fig. 2c is
134 significantly less than that in Fig. 2b; what's more the edge of the micro-fracture in Fig. 2c is
135 smoother after noise reduction.

136 **2.3 Fractal theory applied for micro-fractures network**

137 The fractal theory proposed by Mandelbrot [33] can be used to evaluate the natural porous
138 properties such as coals and shales. The fractal dimension, the characteristic parameter of fractal
139 theory, can effectively quantify the complexity of pore-fracture structure. For a two-
140 dimensional (2D) system, the fractal dimension changes from 1 to 2; a larger the fractal
141 dimension represents a more complicated fracture system. Previous research has been
142 demonstrated that fractal dimensions of pore-fracture structure can be acquired from images by
143 the box-counting method [16, 17, 34, 35]. In this study, the fractal dimensions of obtained 2D
144 micro-fracture images were determined by the BCM to quantify the complexity of the micro-
145 fracture distribution. The details of BCM have been listed in our latest work [35], and the
146 following is a brief description:

147 By covering a binary image with boxes of length r , the fractal dimension D can be estimated
148 as:

$$149 \quad D = -\lim_{r \rightarrow 0} \frac{\log(N(r))}{\log(r)} \quad (1)$$

150 where $N(r)$ is the number of boxes required to cover the complete image. The side length r
151 of the box needs to be assigned a series of values, and the number of boxes $N(r)$ required to
152 cover the image is counted. Then a set of $[\log(r), \log(N(r))]$ values of each sample are plotted
153 in the coordinate system with the abscissa of $\log(r)$ and the ordinate of $\log(N(r))$. The slope is

154 determined by the least square fitting method, which is the fractal dimension D .
 155 Within the calculation process, we adopted the method proposed by Wu et al. [36] to avoid
 156 boundary effects, using the common divisors of the length and width of the image as a series
 157 of box sizes.
 158 In addition, the fracture porosity (FP) of each sample was calculated following Eq. (2), as listed
 159 in Table 1.

$$160 \quad FP = \frac{\text{fracture pixel}}{\text{total pixel}} \times 100\% \quad (2)$$

161 2.4 Flow simulation using lattice Boltzmann method

162 The flow simulation was carried out based on the Bhatnagar Gross Krook (BGK) model [37],
 163 which is the most widely used model. The distribution functions f_i can be expressed as:

$$164 \quad f_i(x + \mathbf{e}_i \delta_t, t + \delta_t) - f_i(x, t) = -\frac{1}{\tau} [f_i(x, t) - f_i^{(eq)}(x, t)] \quad (3)$$

165 where x is the position of the particles; t is time; δ_t is the time step; τ is the relaxation time;
 166 \mathbf{e}_i is the discrete propagation velocity vector in i direction, $f_i^{(eq)}$ is the equilibrium
 167 distribution function of \mathbf{e}_i for density ρ and fluid velocity \mathbf{u} .

168 The relaxation time τ is adopted:

$$169 \quad \tau = \frac{\nu}{c_s^2 \delta_t} + \frac{1}{2} \quad (4)$$

170 where ν is the kinematic viscosity; $c_s = \sqrt{RT} = c / \sqrt{3}$ is the sound speed, in which R is
 171 the gas constant and T is the temperature.

172 The DnQb model (n is the spatial dimension and b is the number of discrete velocity vectors)
 173 proposed by Qian et al. [38] is the most representative. We utilize the D2Q9 model (see Fig.
 174 2d), and its equilibrium distribution function $f_i^{(eq)}$ can be expressed as:

175
$$f_i^{(eq)} = \omega_i \rho \left[1 + \frac{\mathbf{e}_i \cdot \mathbf{u}}{c_s^2} + \frac{(\mathbf{e}_i \cdot \mathbf{u})^2}{2c_s^4} - \frac{\mathbf{u} \cdot \mathbf{u}}{2c_s^2} \right] \quad (5)$$

176 where $c = \delta_x / \delta_t$ is the lattice velocity, and both the lattice size δ_x and time step δ_t are
 177 set to 1. The \mathbf{e}_i and weight coefficient ω_i are defined as:

178
$$\mathbf{e}_i = c \begin{bmatrix} 0 & 1 & 0 & -1 & 0 & 1 & -1 & -1 & 1 \\ 0 & 0 & 1 & 0 & -1 & 1 & 1 & -1 & -1 \end{bmatrix}$$

$$i = 0, 1, \dots, 8$$

 179
$$\omega_i = \begin{cases} 4/9 & i = 0 \\ 1/9 & i = 1-4 \\ 1/36 & i = 5-8 \end{cases} \quad (6)$$

180 For isothermal gas flow, the macroscopic parameters, such as density and momentum, can be
 181 determined as:

182
$$\rho = \sum_i f_i, \quad \rho \mathbf{u} = \sum_i \mathbf{e}_i f_i \quad (7)$$

183 The pressure boundary conditions are applied to the inlet and outlet. The stationary non-slip
 184 boundary is drawn on the solid wall. We default the simulation to reach a steady state when the
 185 velocity change of each grid between two time steps is less than 0.0001%. Note that the fact
 186 that the isothermal boundary condition has been adopted in the above deduction.

187 The lattice units are used in the above-mentioned parameters. Therefore, it is necessary to
 188 convert the studied physical quantity (e.g. permeability) from the lattice unit to the physical
 189 unit. The permeability can be determined by Eq. (8) following the theoretical model of capillary
 190 model.

191
$$\frac{K}{K_{LBM}} = \left(\frac{L}{L_{LBM}} \right)^2 \quad (8)$$

192 where K and K_{LBM} are the intrinsic permeability with physical unit and the permeability
 193 simulated by LBM, respectively. L is the real scale of coal sample and L_{LBM} is the scale of LBM.

194 Other physical property parameters such as kinematic viscosity required for methane under
195 different pressure and temperature conditions can be obtained from the open source software
196 called Peace software.

197 **2.5 Validation of Box-counting and lattice Boltzmann methods**

198 **2.5.1 Box-counting method**

199 Sierpinski Carpet as a classic figure (as shown in Fig. 3a) in fractal theory can be used to verify
200 the accuracy of our calculation program. The definition of fractal dimension determines
201 Sierpinski Carpet's theoretical fractal dimension $D = \frac{\ln 8}{\ln 3} \approx 1.8928$. As presented in Fig. 3b,
202 the actual result we calculated is also 1.8928, which indicates that the actual result is in good
203 agreement with the theoretical value. In other words, this comparison confirms that our program
204 is feasible.

205 **2.5.2 Lattice Boltzmann method**

206 The second validation is carried out by simulating the flow of two-dimensional Poiseuille with
207 different lattice sizes including 100×100 , 250×250 and 500×500 . The normalized
208 streamwise velocity profiles $U = u / u_{\max}$ are compared with the analytical solution as shown
209 in Fig. 4, which shows that the simulation results based on a series of lattice sizes are highly
210 consistent with the analytical solutions. This consistency also confirms that the LBM is suitable
211 for understanding the flow capability.

212 **3. Results and discussion**

213 Micro-fracture morphology, pressure and temperature are three of the important factors
214 affecting permeability and thus enhancing CBM recovery [39-41]. This section captured the
215 flow characteristics of methane under different micro-fractures morphologies, different

216 pressures and temperatures based on the D2Q9 model. The pressure gradient was set to 0.1
217 MPa/m in the simulation along the flow direction.

218 **3.1 Effects of micro-fracture morphology on flow capability**

219 The pre-existing natural fractures characteristics are of importance on the hydraulic fracturing
220 stimulation effect [7]. Herein, the effect of pre-existing natural fracture morphology on methane
221 flow in coal will be discussed in detail. The velocity distribution results with different micro-
222 fractures morphologies are displayed in Fig. 5 as the simulation reaches steady state (i.e. the
223 velocity change of each grid between two time steps is less than 0.0001%). Fig. 5 demonstrates
224 that the pressure-driven methane migration in various micro-fracture networks is different. It is
225 easy to find out that the existence of dominant channels is conducive to the gas flow, that is,
226 there is a wide channel connecting the inlet to the outlet in the micro-fracture network as shown
227 in Fig. 1. The length and width of the dominant channel was listed in Table 2, which has the
228 average length and width of ~498.26 μm and 10.96 μm , respectively. The velocity in the
229 dominant channel is much larger compared with other locations (see Fig. 5). As shown in Fig.
230 5d and i, gas flow is much more difficult if the micro-fracture network is connected by narrower
231 channels with width less than 5 μm . Another interesting phenomenon is that the special micro-
232 fracture morphology determines the time that the flow simulation reaches the steady state,
233 which varies from 5711 to 130561 showing greatly different. This result means that the time
234 for the simpler micro-fracture network is much shorter to reach the steady state, while the
235 micro-fracture network with a more special shape (e.g., the orthogonal type in Fig. 5i and Fig.
236 6) and a more complex distribution (see Fig. 5g) takes longer to reach steady state. The
237 equilibrium time in Fig. 5 is used as the standard to evaluate the difficulty of fluid flow in

238 micro-fracture network, the orthogonal micro-fracture is unfavorable for flow capability, and
239 the most favorable network is reticular. And the dendritic and filamentous types are in between
240 the orthogonal and reticular types. The dendritic type with more branches will cause obstacles
241 to flow. The filamentous type has a lot of narrow throats, which result in flow in filamentous
242 structure more difficult than that in the dendritic structure with fewer branches. Fig. 6 displays
243 the simulated flow process of the orthogonal micro-fracture network. At the beginning of the
244 flow process, the gas will extend in three directions after meeting the bifurcation. As time goes
245 on, the gas will flow further following with the branches. At this time, the upward and
246 downward flow directions do not match the main flow direction; therefore, the gas in the up
247 and down directions will gradually disappear. When the simulation reaches the steady state, the
248 gas only passes in the main flow direction. The computation time also becomes longer due to
249 the special angle (e.g., orthogonal type) of the branches in the natural micro-fracture network.
250 The fracture dimension values calculated by BCM are displayed in Fig. 7, which ranges from
251 1.321 to 1.584. The larger the value is, the more complicated distribution of the natural micro-
252 fracture network [16]. Besides, Fig. 8b reveals that there is an obvious positive correlation
253 between the fractal dimension and the fracture porosity. This phenomenon may be ascribed to
254 two causes: the first is that micro-fracture network with larger fracture porosity will have a
255 greater chance of being more complicated distribution, which is consistent with Wu et al. [36].
256 Secondly, the micro-fracture network filled with minerals is poor developed, thus there is no
257 complex trend that is similar to the relationship between porosity and fractal dimension [35].
258 As shown in Fig. 8a, there is a significant inverted U-shaped relationship between fractal
259 dimension and permeability with the correlation coefficient of 0.86. The permeability increases

260 as fractal dimension increases from 1.321 to 1.472, and then decreases as fractal dimension
261 exceeds 1.472. The permeability is 0.147 D when the fractal dimension is 1.321, while it
262 increases to 0.345 D as fractal dimension reaches to 1.472. The reason for this increasing trend
263 is that lower fractal dimension normally corresponds to lower fracture porosity, resulting in
264 lower permeability. As the fractal dimension increases, the fracture porosity also increases, and
265 the permeability is improved when the connectivity of the micro-fracture network is good.
266 However, when the fractal dimension exceeds 1.472, the micro-fracture network becomes more
267 complex. Meanwhile, due to the strong heterogeneity of the CBM reservoir and poor
268 connectivity [1, 26, 42], the natural micro-fracture network is connected by the narrow throat,
269 leading to difficult gas flow and thus lower permeability. Fig. 9 shows that the methane still
270 flows through the micro-fracture network branch f1 (see f2) at the beginning of the flow process,
271 but methane will not pass through these channels as time increases. Hence, under the premise
272 of only one flow direction, the flow time will undoubtedly take longer if many branches exist
273 in the micro-fracture network. And if the extension direction of these branches is different from
274 the flow direction, it would constrain the permeability.

275 **3.2 Effects of pressure on flow capability**

276 The trend of permeability together with outlet pressure is shown in Fig. 10, which illustrates
277 that the permeability decreases sharply as pressure increases from 0.1MPa to 5 MPa, and then
278 the permeability tends to be stable as pressure exceeds 5 MPa. In other words, the natural micro-
279 fracture network is more sensitive to change in permeability at low pressure because the
280 distance between the rarefied gas molecules is far away and the attractive force is weak at low
281 pressure [29]. The decreasing trend of permeability with increasing pressure is consistent with

282 the shale gas production [27, 43]. However, when the permeability is larger than 5 MPa, there
283 is no similar trend in CBM production by Shi and Durucan [44]. During the CBM production,
284 the permeability initially declines and then increases with increasing pressure [6, 44]. The
285 reason for this phenomenon is that the shrinkage of the coal matrix due to gas desorption, a
286 unique characteristic of coal reservoir, counteracts the permeability decrease with pressure drop
287 during the production [4, 45]. Therefore, a model considering matrix swelling/shrinkage can
288 accurately describe actual flow characteristics. Due to its extremely challenging nature, coal
289 matrix swelling/shrinkage response during gas flow should be considered into the permeability
290 model.

291 **3.3 Effects of temperature on flow capability**

292 Three sets of temperatures were simulated to study the effects of temperature changes including
293 300K, 330 K and 360 K on coal permeability. Fig. 10 exhibits that the permeability increase
294 with increasing temperature at the constant pressure. The increase of temperature will aggravate
295 the thermal motion of gas molecules, leading to the average kinetic energy of the molecules
296 increasing and thereby increasing the permeability, which is in accordance with previous
297 research [29]. And at low pressure, the influence of temperature on permeability is more
298 sensitive. For realistic CBM production, the effect of temperature on coal permeability is related
299 to many factors, such as coal rank and pore-fracture structure [39, 42]. For instance, Cai et al.
300 [39] revealed that different rank coals have different trends in permeability changes caused by
301 temperature. And Liu et al. [42] found that the temperature has obvious impact on the
302 mechanical properties and acoustic emission characteristics in coal, and the pore-fracture
303 structures were promoted and the permeability was significantly improved under temperature

304 treatment. CBM reservoirs normally have the characteristics of complex pore-fracture structure,
305 strong heterogeneity, and abundant mineral types, which cause a series of physical and chemical
306 changes in the process of temperature increase [46]. Different components in coal have different
307 shrinking and swelling ability under the effect of temperature [42]. For example, the
308 temperature stress will aggravate the expansion of fractures and weaken the mechanical
309 properties of coal [42]. Moreover, during the exploitation of CBM, the reservoir temperature
310 also changes dynamically with produced gases; thus, the effect of temperature on permeability
311 should be cautiously considered [47]. Therefore, the micro-fracture morphology, pressure and
312 temperature have a comprehensive complex influence on gas flow capability, which generally
313 follows the dominated micro-fracture morphology, supplemented by pressure and temperature
314 as shown in Fig. 11.

315 Although the detailed work on the morphology effect of micro-fracture network on
316 permeability has been revealed, the process of fluid-solid coupling has yet to confirm.
317 Therefore, the flow response in micro-nano scale natural pore-fracture structure during the
318 CBM development will be our next work.

319 **4. Conclusions**

320 In this study, natural micro-fracture morphologies of selected Chinese coals from the Ordos
321 Basin were characterized by the optical microscope. And the box-counting method together
322 with the lattice Boltzmann method was adopted to quantify the complexity of the micro-fracture
323 network and flow behaviors in these natural micro-fracture networks. Besides, factors affecting
324 the flow capability in these natural micro-fracture networks were discussed. The following
325 conclusions can be made:

326 1) The dominant channels in the natural micro-fracture network will greatly improve the
327 permeability. Besides, flow characteristics in the micro-fracture networks with various
328 morphologies are quite different, which presents that the orthogonal type is unfavorable for
329 flow capability, and the most favorable network is reticular, with dendritic and filamentous
330 types in between.

331 2) An obvious inverted U-shaped relationship exists between the fractal dimension and
332 permeability. When the fractal dimension is lower than 1.472, the larger fractal dimension
333 means the greater fracture porosity, and thus the permeability of well-connected natural micro-
334 fractures increase. As the fractal dimension exceeds 1.472, the distribution of natural micro-
335 fracture network is complicated, which presents reticular and dendritic types. And the
336 connected narrow throats normally lead to a permeability decrease.

337 3) Pressure and temperature have opposite influence on coal permeability. The permeability
338 increases with decreasing gas pressure, which is caused by the rarefied gas due to the declining
339 pressure. However, the gas at high temperatures of 360 K will lead to a gentle increase of
340 permeability.

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459

460 **Captions for Figures and Tables**

461 **Fig. 1.** Different micro-fracture morphologies of selected samples obtained by optical
462 microscope, which varied involving dendritic, reticular, filamentous and orthogonal etc. The
463 red dotted lines are the dominant channels mentioned in section 4.1.

464 **Fig. 2.** The results after threshold segmentation and the discrete velocity of D2Q9 model. (a) is
465 the initial image; (b) and (c) are images before and after noise reduction, respectively. Careful
466 observation shows that the noise in the red rectangular frame of (c) is significantly less than
467 that in (b), and the edge of the micro-fracture in (c) is smoother after noise reduction. (d) is the
468 discrete velocity of D2Q9 model.

469 **Fig. 3.** The verification of the box-counting method. (a) is the Sierpinski Carpet image and (b)
470 is the value estimated by the box-counting method.

471 **Fig. 4.** Normalized streamwise velocity profiles with different lattice sizes.

472 **Fig. 5.** The velocity distribution results of dimensionless lattice unit when the simulation
473 reaches equilibrium with different micro-fractures morphologies and the schematic diagram of
474 the gas flow model. t is the time for the simulation to reach convergence. (a)- (i) are the velocity
475 distribution results and (j) is the schematic diagram of the gas flow model. Simulation
476 conditions include $T = 300$ K, outlet pressure = 10 MPa and pressure gradient = 0.1 MPa/m.

477 **Fig. 6.** Velocity distribution of sample F9 under different time steps. t is the time step. The
478 length of the arrow indicates how far the gas flows. At the beginning of the flow process, the
479 gas will extend in three directions after meeting the bifurcation. As time goes on, the gas will
480 flow further following with the branches. At this time, the upward and downward flow
481 directions do not match the main flow direction, so the gas in the up and down directions will

482 gradually disappear. When the simulation reaches equilibrium, the gas only passes in the main
483 flow direction. The equilibrium time also becomes longer due to the special angle (orthogonal
484 type) of the branches of the microfracture network. Simulation conditions include $T = 300\text{ K}$,
485 outlet pressure = 10 MPa and pressure gradient = 0.1 MPa/m.

486 **Fig. 7.** Results of fractal dimension calculated by the box-counting method

487 **Fig. 8.** Relations between permeability, fracture porosity and fractal dimension. (a) fractal
488 dimension versus permeability and (b) fractal dimension versus fracture porosity. $T = 300\text{ K}$,
489 outlet pressure = 10 MPa and pressure gradient = 0.1 MPa/m.

490 **Fig. 9.** Velocity distribution of sample F7 under different time steps. t is the time step. (a) is the
491 initial image of F7 and (b)-(e) are the velocity distribution under different time steps during
492 simulation. f_1 and f_2 are the original image of the branch and the changes that occurred in the
493 branch during the flow process, respectively.

494 **Fig. 10.** Relations between pressure, temperature and permeability in different samples.
495 Pressure gradient = 0.1 MPa/m.

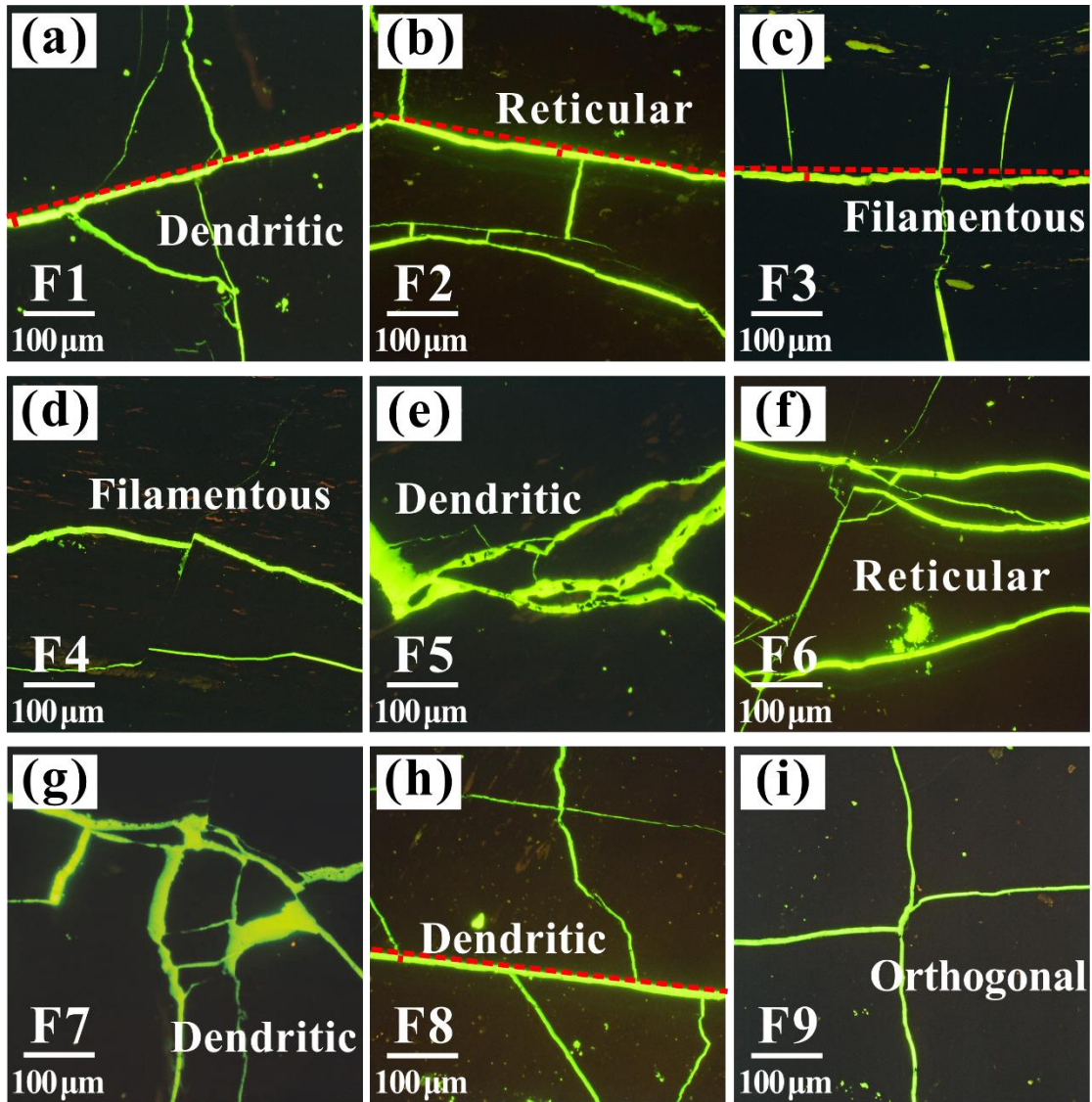
496 **Fig. 11.** Diagram of the influence mechanism of different factors on permeability, including the
497 micro-fracture morphology, pressure and temperature. The positive and negative signs (“+” and
498 “-”) in the figure represent the promotion and inhibition effects, respectively.

499 **Table 1** Sample information and basic parameters of the selected coals.

500 **Table 2** Statistics of the length and width of the dominant channel of micro-fractures in Fig. 1.

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Fig. 1. Different micro-fracture morphologies of selected samples obtained by optical microscope,

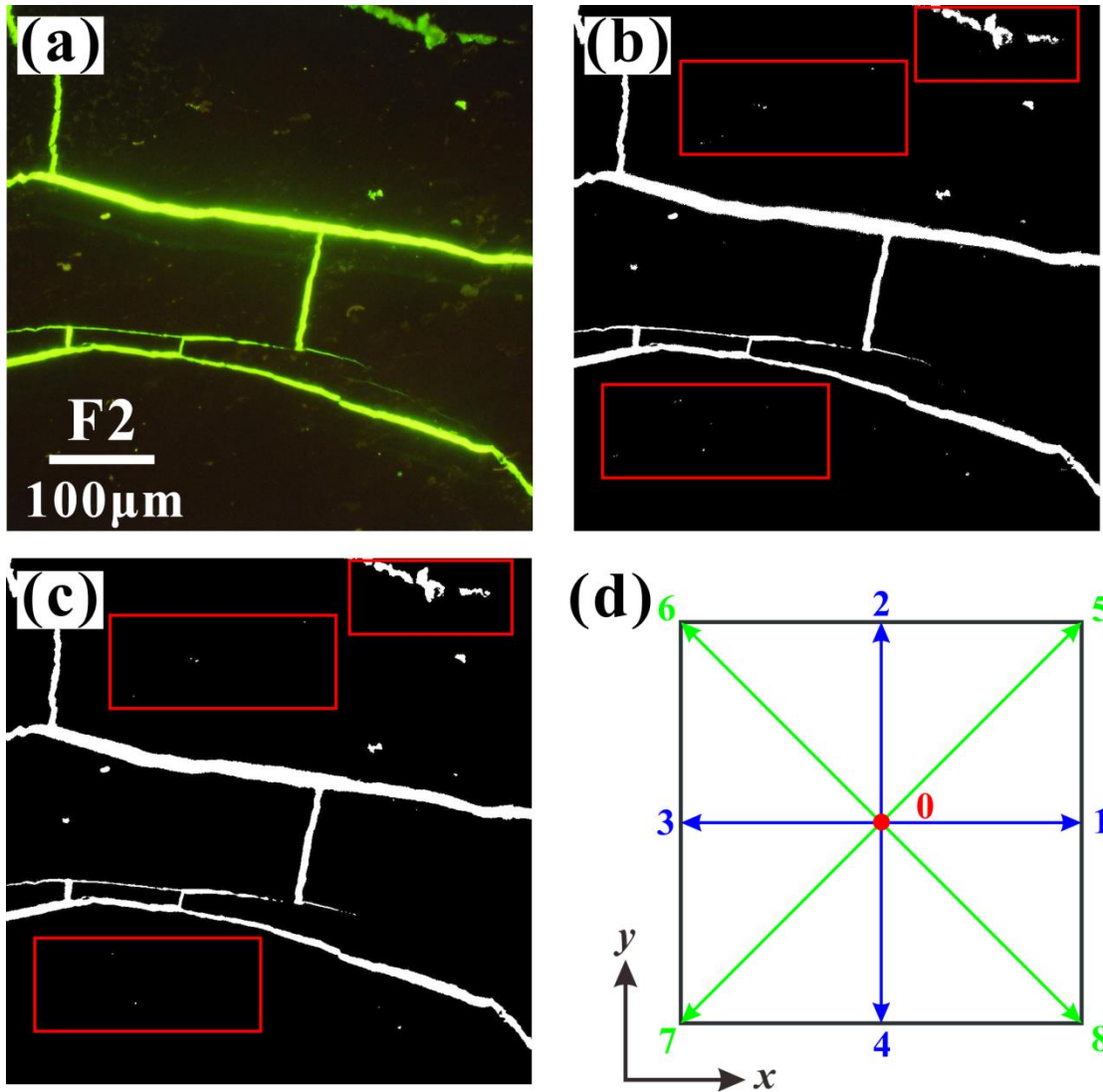
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which varied involving dendritic, reticular, filamentous and orthogonal etc. The red dotted lines are

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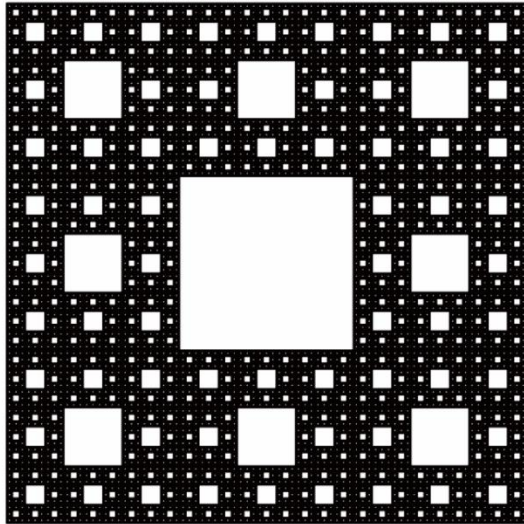
the dominant channels mentioned in section 3.1.

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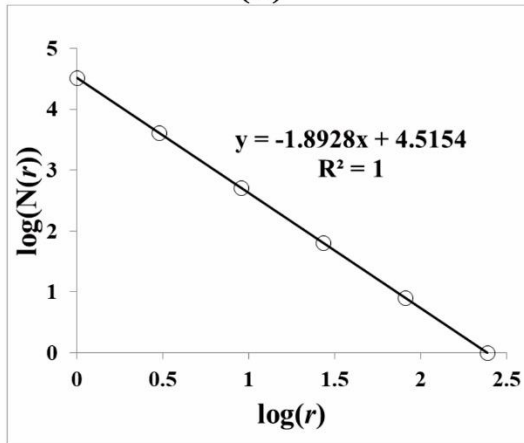


508

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 513 velocity of D2Q9 model.



(a)



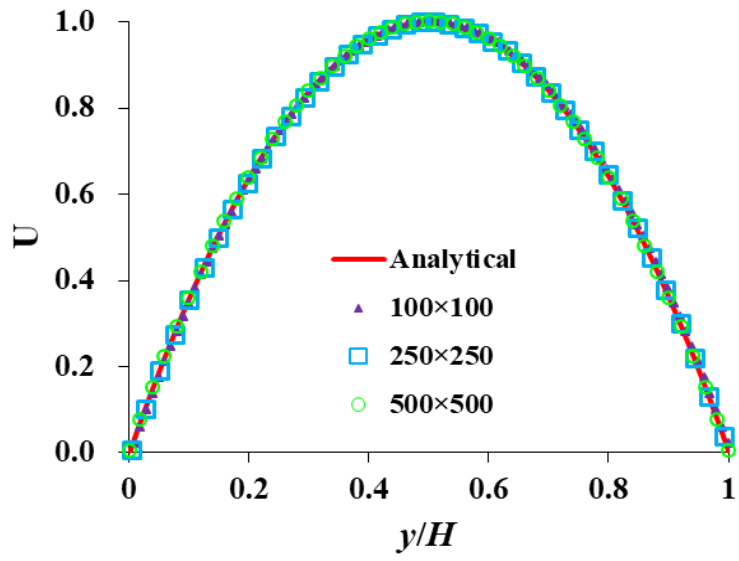
(b)

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515 **Fig. 3.** The verification of the box-counting method. (a) is the Sierpinski Carpet image and (b) is

516 the value estimated by the box-counting method.

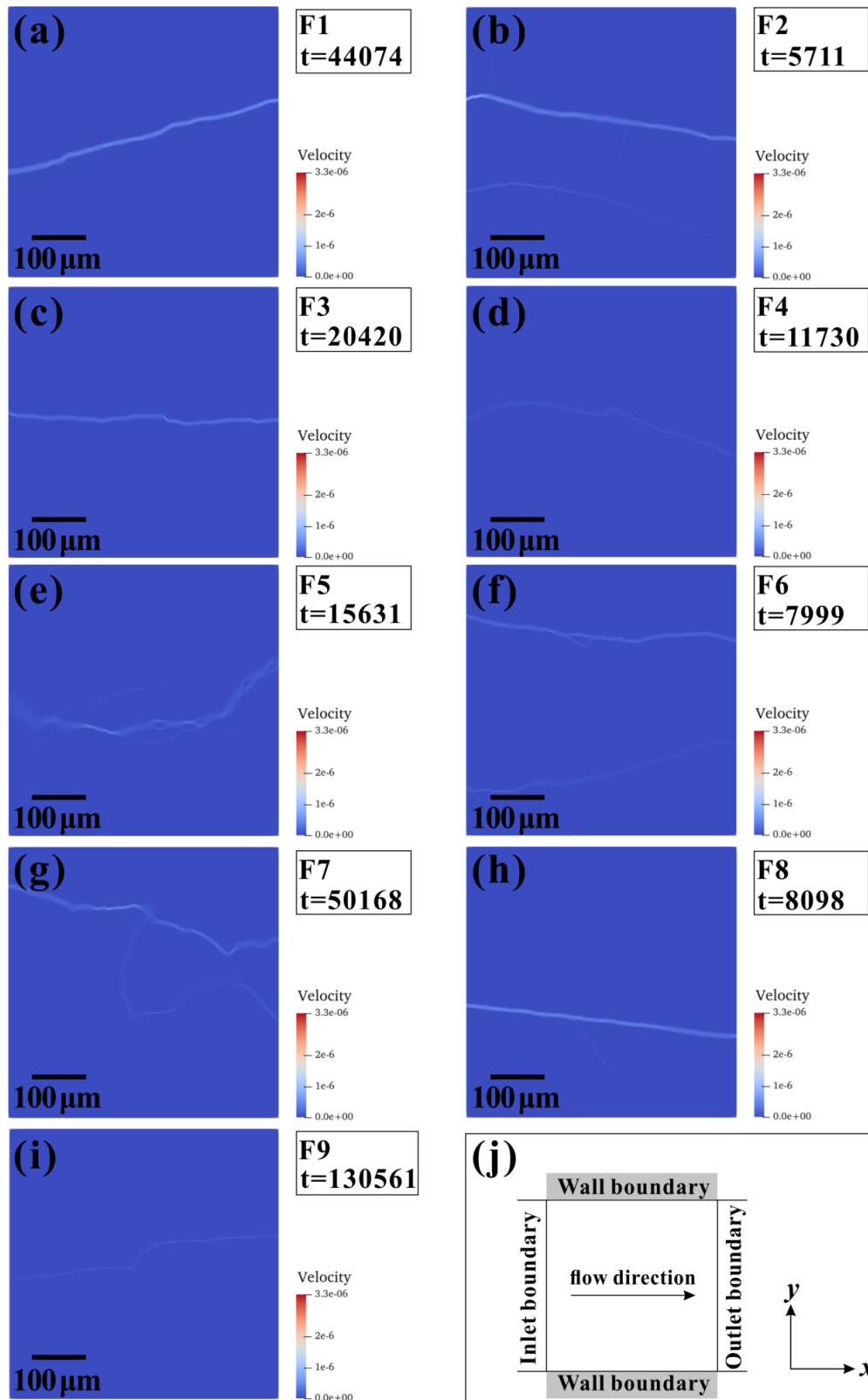
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519 **Fig. 4.** Normalized streamwise velocity profiles with different lattice sizes.

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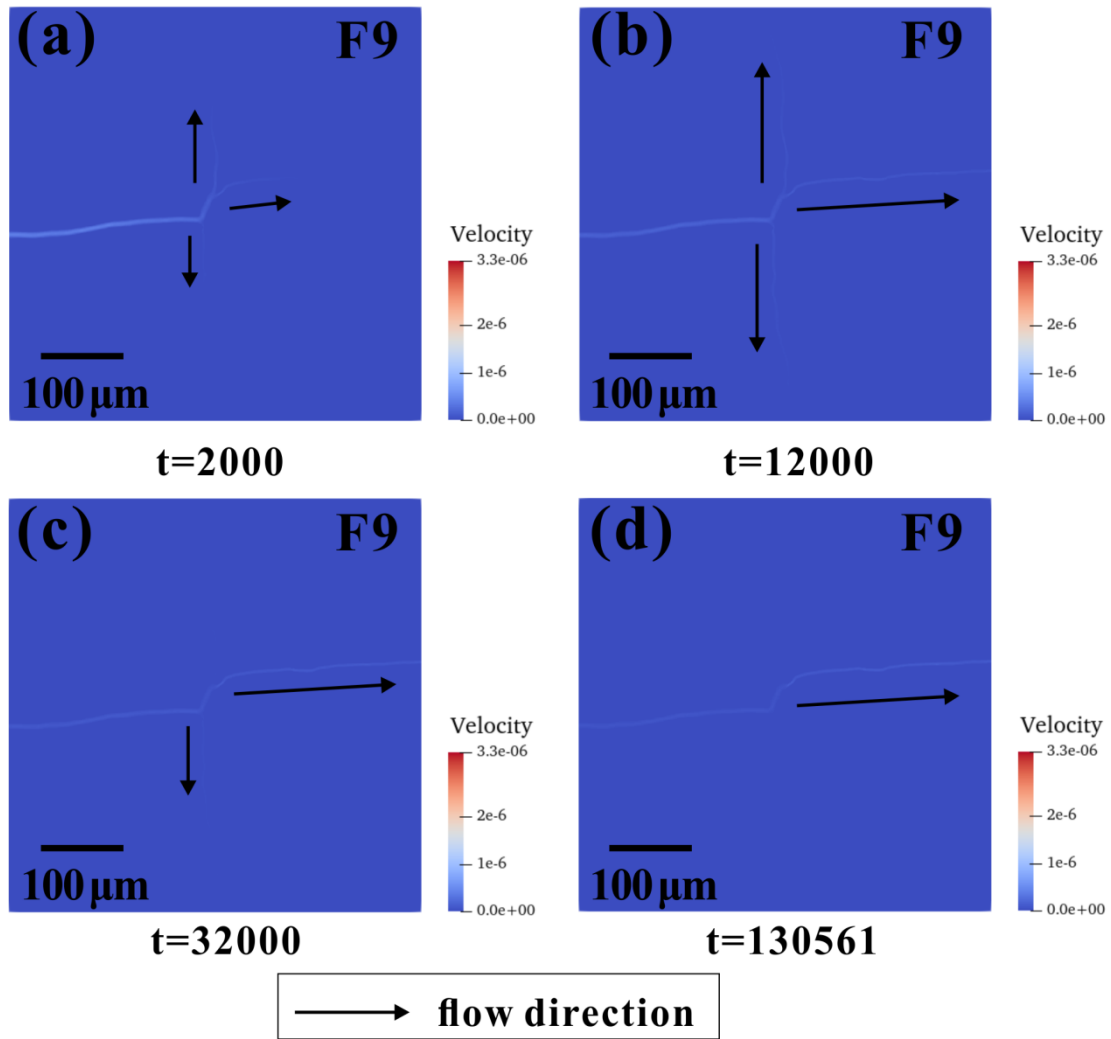
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Fig. 5. The velocity distribution results of dimensionless lattice unit when the simulation reaches equilibrium with different micro-fractures morphologies and the schematic diagram of the gas flow model. t is the time for the simulation to reach convergence. (a)- (i) are the velocity distribution results and (j) is the schematic diagram of the gas flow model. Simulation conditions include $T = 300$ K, outlet pressure = 10 MPa and pressure gradient = 0.1 MPa/m.



527

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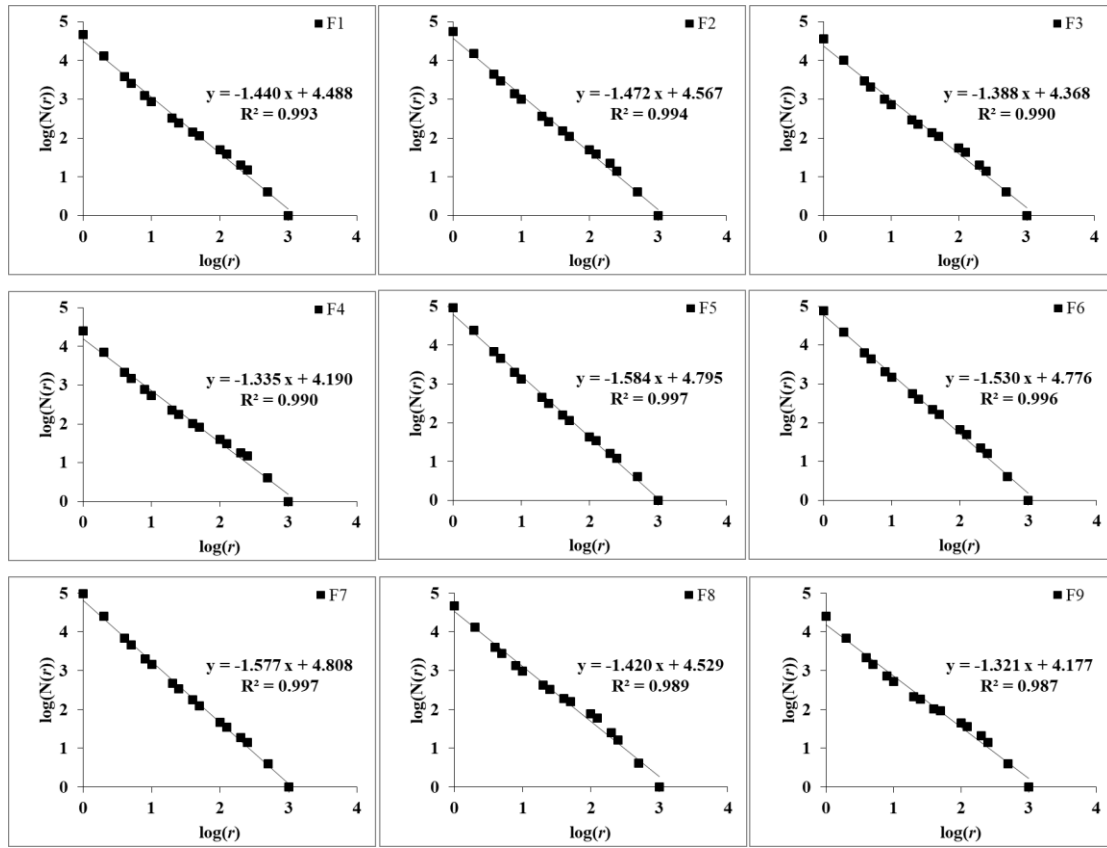
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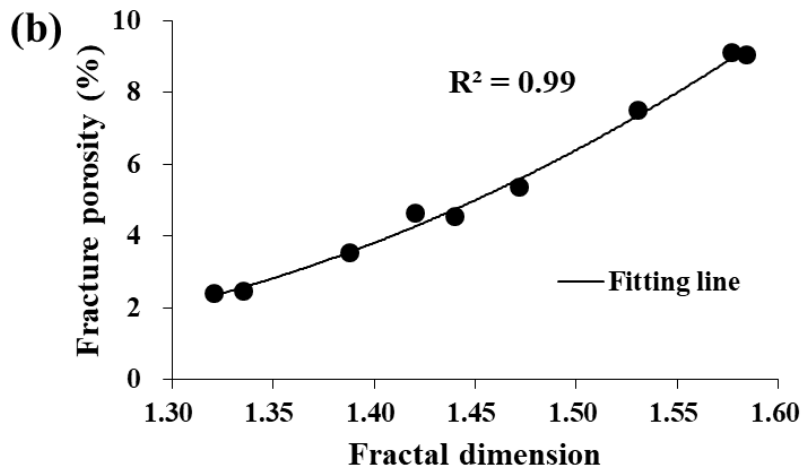
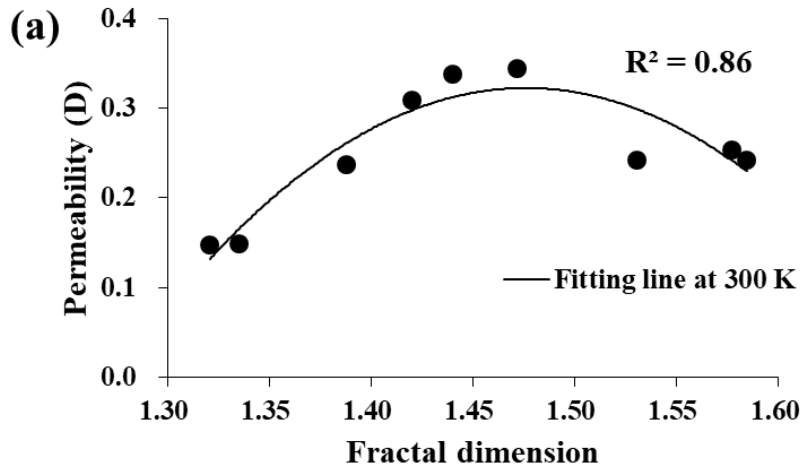
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539 **Fig. 7.** Results of fractal dimension calculated by the box-counting method

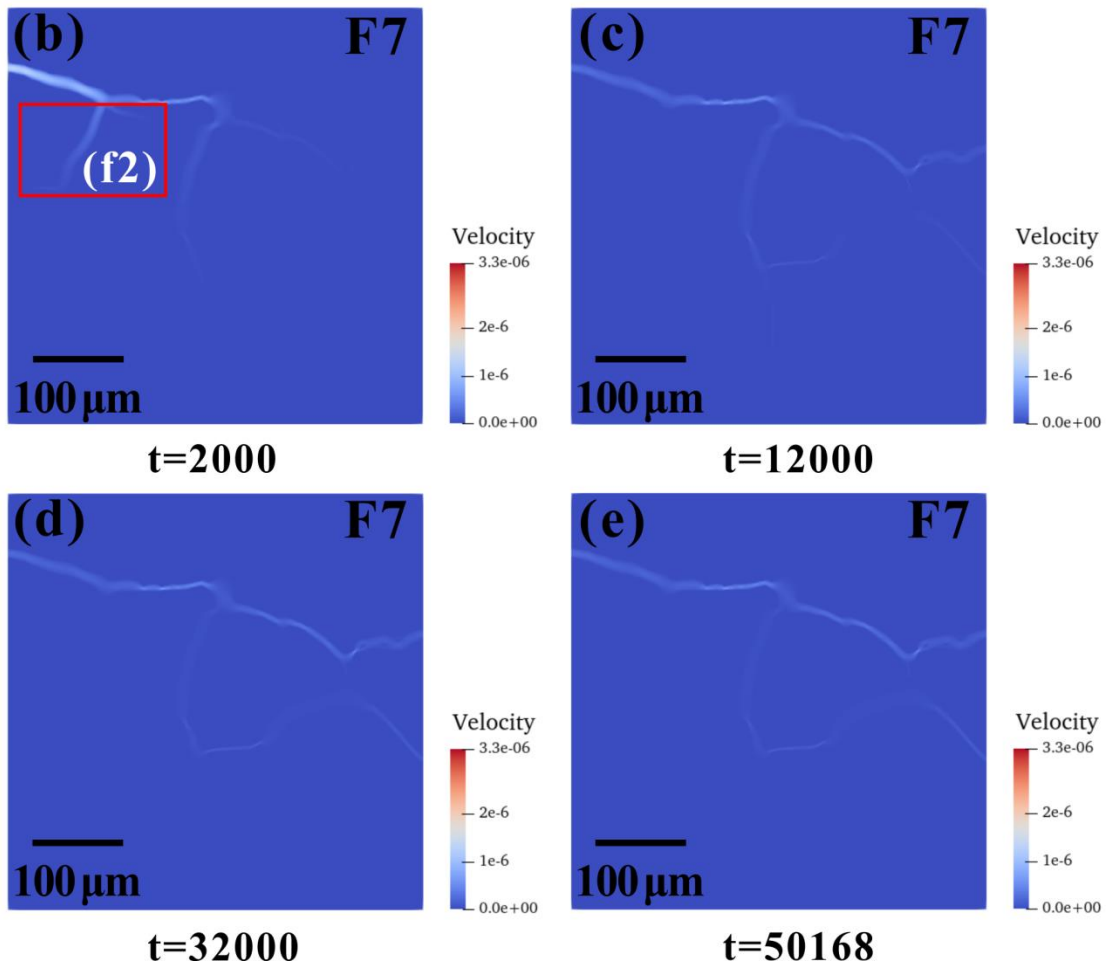
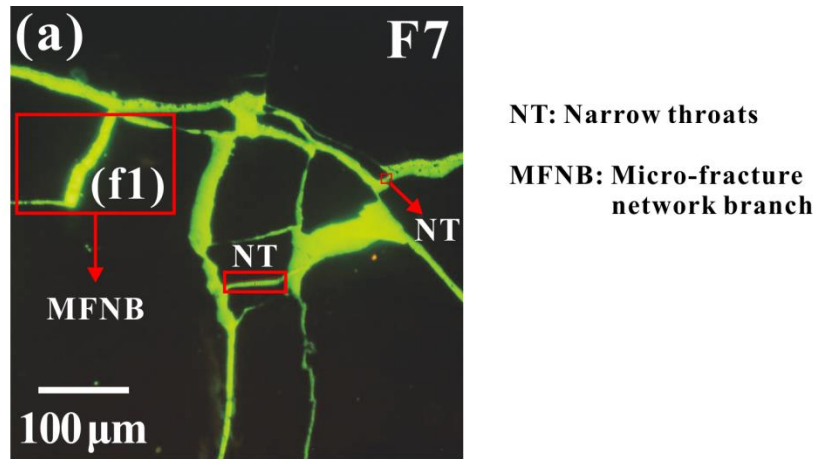
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 544 pressure = 10 MPa and pressure gradient = 0.1 MPa/m.

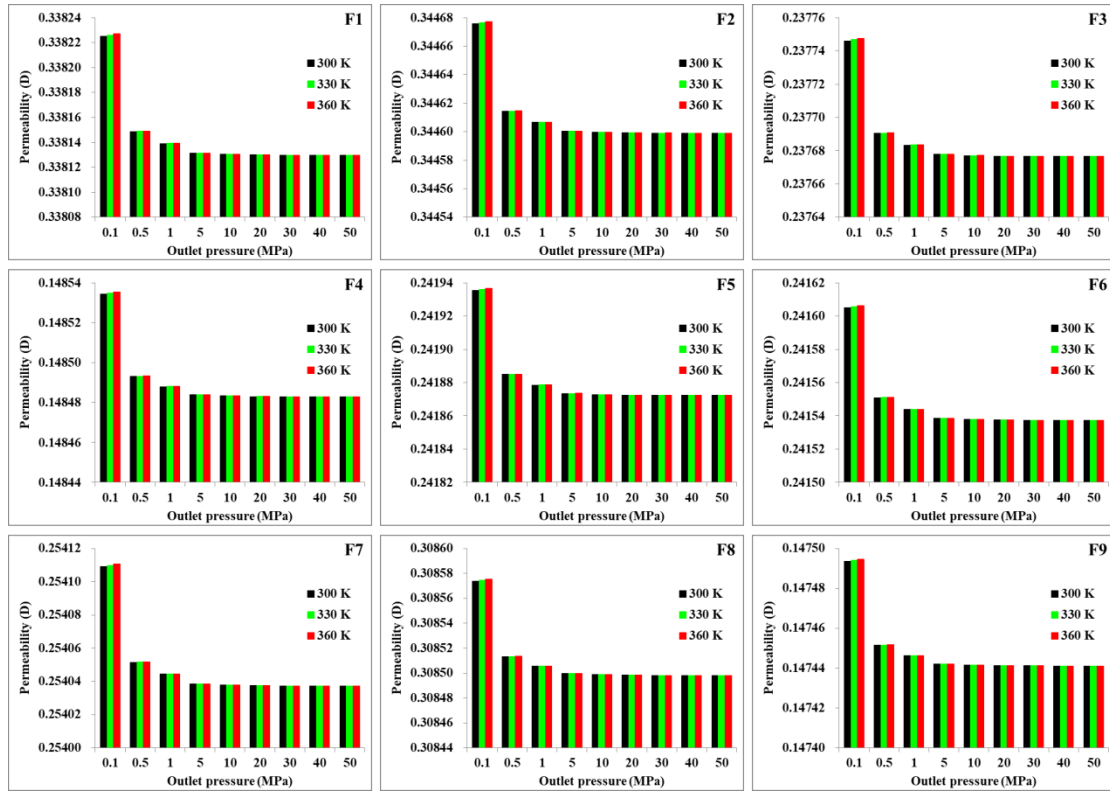
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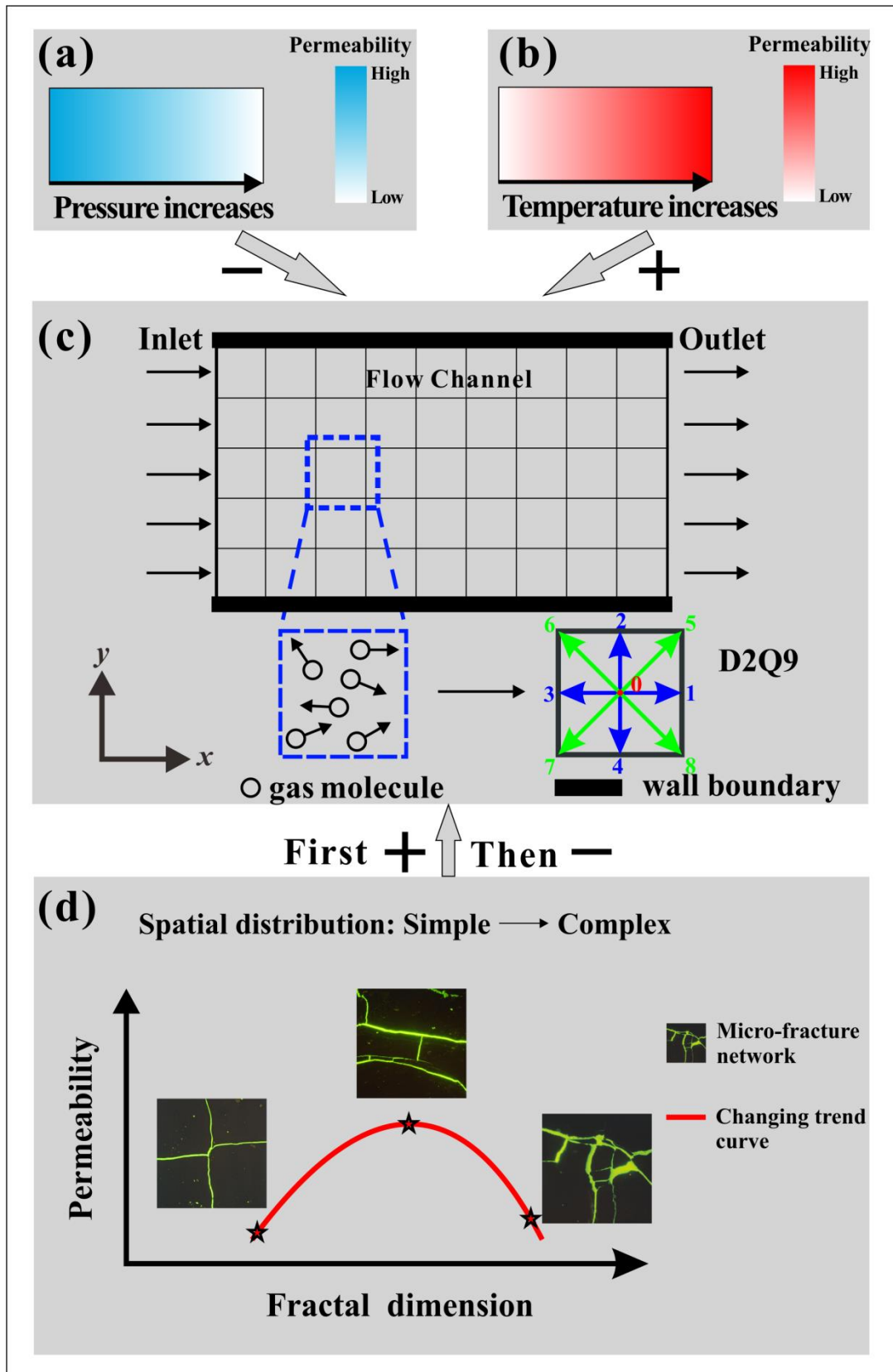


552

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556

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558 micro-fracture morphology, pressure and temperature. The positive and negative signs (“+” and “-”)

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560

561 **Table 1** Sample information and basic parameters of the selected coals

Sample no.	Basin	R _{o,max} (%)	Maceral and mineral (%)				Fracture porosity (%)
			Vitrinite	Inertinite	Exinite	Mineral	
F1		0.62	65.4	21	5.3	8.3	4.53
F2		0.65	66.2	24.9	1.4	7.5	5.35
F3		0.68	90.1	4.5	4.4	1	3.54
F4		0.89	66.9	25.6	5.9	1.6	2.45
F5	Ordos	1.27	90.2	8.3	0	1.5	9.05
F6		1.27	82.3	14.7	0	3	7.50
F7		1.36	82.2	15.2	2.4	0.2	9.11
F8		1.58	84.0	11.6	0.6	3.8	4.64
F9		1.78	84.4	7.9	3.1	4.6	2.41

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578 **Table 2** Statistics of the length and width for the dominant channel of micro-fractures in Fig. 1.

Figure ID	Fig 1(a)	Fig 1(b)	Fig 1(c)	Fig 1(h)	Average
Length (μm)	506.66	495.61	493.68	497.10	498.26
Width (μm)	13.63	10.19	11.13	8.88	10.96

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582 **Nomenclatures**

583 r : length of boxes

584 D : fractal dimension

585 $N(r)$: the number of boxes required to completely cover the image

586 FP: fracture porosity

587 f : distribution function

588 x : position of the particles

589 t : time

590 δ_x : lattice size

591 δ_t : time step

592 τ : relaxation time

593 e_i : the discrete propagation velocity vector in i direction

594 $f_i^{(eq)}$: the equilibrium distribution function

595 ρ : density

596 \mathbf{u} : fluid velocity

597 ν : kinematic viscosity

598 n : spatial dimension

599 b : number of discrete velocity vectors

600 c_s : sound speed

601 c : lattice velocity

602 R : gas constant

603 T : temperature

604 ω_i : weight coefficient

605 K : intrinsic permeability with physical unit

606 K_{LBM} : permeability simulated by LBM

607 L : the real scale of coal sample

608 L_{LBM} : the scale of LBM

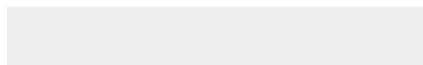
609 U : normalized streamwise velocity



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Declaration of interests

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

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Credit author statement

Qian Li: Writing-original draft, Investigation, Validation.

Dameng Liu: Conceptualization, Methodology.

Yidong Cai: Conceptualization, Funding acquisition, Supervision, Writing-review & editing.

Bo Zhao: Validation.

Yuejian Lu: Writing-review & editing.

Yingfang Zhou: Writing-review & editing.