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Short communication

Effects of microfractures on permeability in carbonate rocks based on digital core technology

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Abstract:
Carbonate reservoirs develop many different types of microfractures that play an important role in increasing the effective reservoir space and permeability. Thus, the qualitative and quantitative characterisation of the effect of microfractures on permeability in rocks is essential. In this study, a quantitative method for evaluating the impact of different microfracture parameters on carbonate rock permeability was proposed. Lattice Boltzmann simulations were carried on two carbonate digital cores with different types of artificially added microfractures. Based on the simulation results, a partial least squares regression analysis was used to investigate the impact of microfractures on the permeability of the cores. Increases in the fracture length, aperture, and density were found to linearly increase the permeability of the carbonate rocks, and as the fracture length increased to penetrate the whole core, an exponential increase in permeability was observed. Additionally, the effect of microfractures on the digital core permeability was more significant in cores with high permeability compared to that in low-permeability cores. Although both fractures and matrix permeability contribute to the permeability of the digital cores, the former were found to have a greater effect on the permeability.

1. Introduction

As a result of complex sedimentation, diagenesis, and tectonic movements, pores, solution cavities and fractures widely exist in carbonate reservoirs (Guerriero et al., 2013; Rong et al., 2016). During oil and gas production, fractures play an important role in unconventional reservoirs by significantly improving effective permeability and transforming the flow pattern in the rock (Jones, 1975). Therefore, the qualitative and quantitative characterisation of the effects of fractures in rocks is an essential aspect when studying the development of fractured reservoirs.

Microfracture characteristics mainly include length, aperture, angle, density, and roughness (Neuman, 2008). Researchers have studied the influence of various fracture properties on the flow capacity of rocks, such as the effects of fracture size on rock permeability (Sagar and Runchal, 1982). The effects of fracture roughness, width, and tortuosity on hydraulic conductivity (Akhavan et al., 2012; Ju et al., 2017) and the effects of different fracture lengths and angles on the effective thermal conductivity (Yang et al., 2019) in digital cores have also been studied. However, only a few systematic and comprehensive studies have been conducted on the influence of different fracture parameters on rock permeability.

With advancement in technology, digital cores equipped

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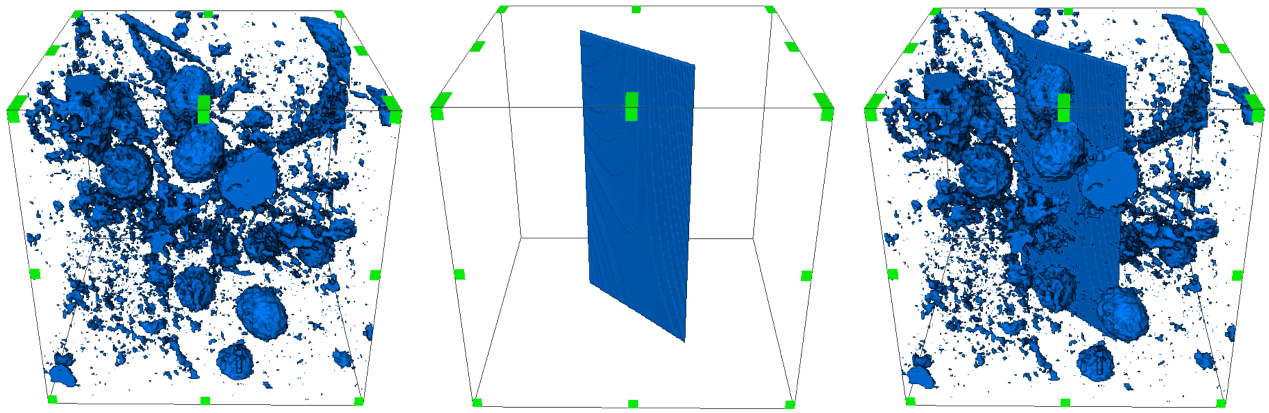


(a) original digital core (b) fracture system (c) final digital core with fracture

Fig. 1. Schematic of adding fractures to a digital core.

with advantages of non-destructive visualisation and digitalisation have been widely used in studies involving porous media (Nie et al., 2019; Wang et al., 2019; Wang et al., 2021). In this study, carbonate digital cores with different pore structures were constructed, and the effects of different fracture parameters were studied via the lattice Boltzmann method (LBM). Subsequently, a quantitative evaluation method derived from a partial least squares (PLS) regression analysis was used to quantitate the influence of different microfracture parameters on carbonate rock permeability.

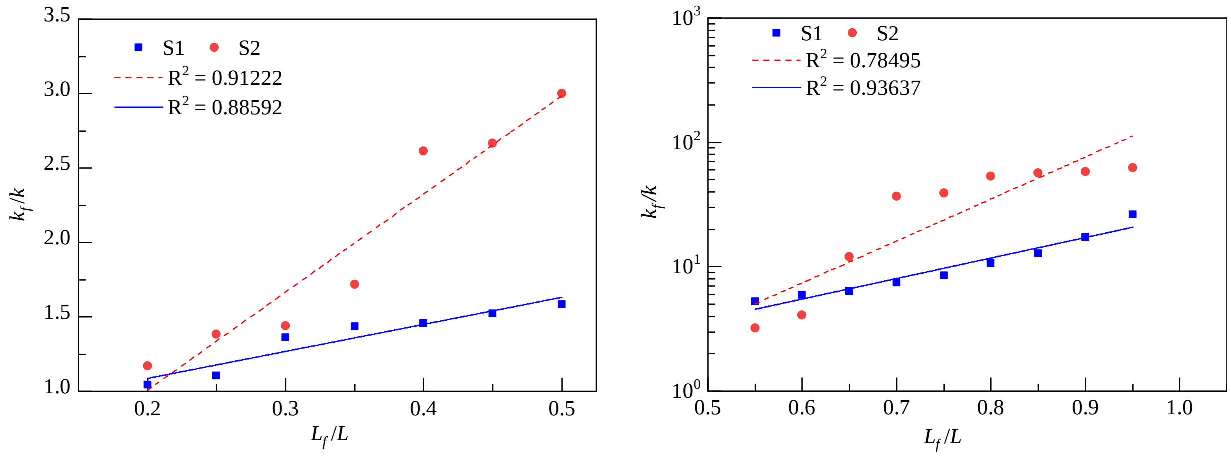
2. Methodology

Two types of carbonates acquired from computed tomography scanning of real carbonate rocks, namely S1 and S2, were used to study the effect of microfractures on permeability (Fig. S1). Sub-volumes ($L^3 = 200 \times 200 \times 200$ voxels^3, 4.32 μm/voxel) were extracted from the digital cores to quantify the different microfractures. The extracted digital cores and pore structure parameters obtained by pore network modelling (Blunt et al., 2013) are shown in Fig. S2 and Table S1.The porosity and conductivity properties of the S2 pore structure was better than that of S1. Finally, a series of digital cores with different fracture properties, including length (L_f = 40–200 pixels), aperture (W_f = 1–5 pixels), angle (θ_f = 0°, 30°, 45°, 60°, and 90°) and density (N = 1–5), were generated for evaluating the influence of different microfracture parameters on carbonate rock permeability. The angle of fractures represents the angle between the direction of fractures and seepage flow, while density represents fracture number in a digital core. Fig. 1 depicts the process of adding microfractures to a digital core. Subsequently, the LBM with a D3Q19 discrete velocity model was applied to obtain the permeability of the three-dimensional digital cores with fractures. The lattice Bhatnagar–Gross–Krook collision approximation was applied to simplify the quantitation (Pradipto and Purqon, 2017). Grain walls were considered as non-slip solid surfaces, and a fixed pressure gradient of 0.00005 was set across the cores. Flow simulations were terminated when the system reached an equilibrium state, and the permeability value was recorded. The detailed instructions of the methods used in this study can be found in the Supporting Information.

3. Results and discussion

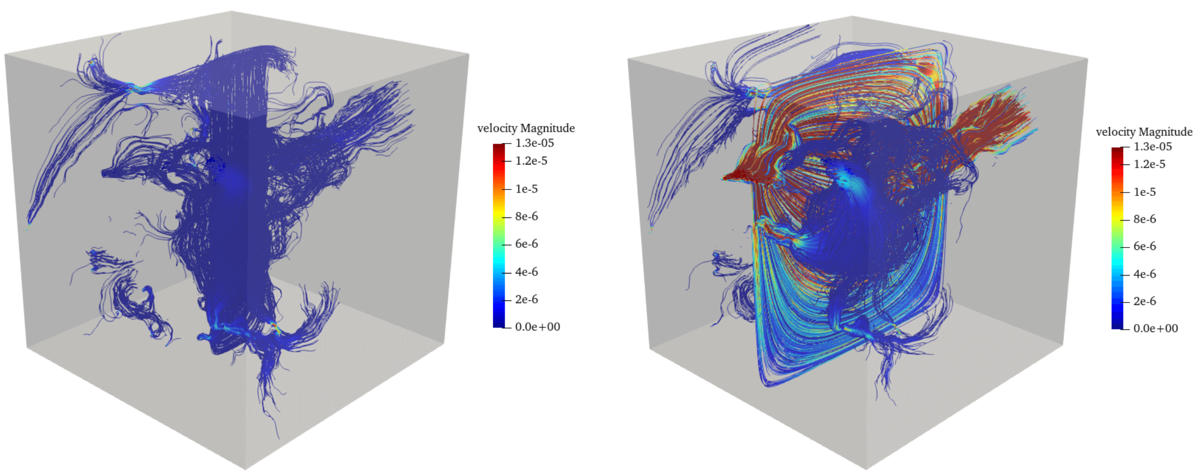
The effect of microfracture length on the permeability of the digital cores was found to be divided into two stages (Figs. 2 and 3). When fracture length L_f extends beyond a threshold (the dimensionless fracture length $L_f/L > 0.5$, L is the length of the rock along flow direction), the variation in permeability enhancement ratio k_f/k, which is defined as the ratio of core permeability after the addition of microfractures to that without fractures, transitions from a linear to an exponential trend. When the fracture length is short (in this paper, $L_f/L < 0.5$), as shown in Figs. 2(a) and 3(a), the effect of the fracture on the matrix permeability is not obvious, and the permeability enhancement ratio shows a linear relationship with the dimensionless fracture length L_f/L. In addition, a short fracture is more effective in improving the permeability of cores with well-developed matrix pores and high permeability. The primary reason is that there are more matrix pores connected to the fracture, resulting in the obvious enhancement of the seepage performance. When the fracture length is relatively long and almost penetrates the core completely, as seen in Figs. 2(b) and 3(b), the fracture becomes the main seepage channel. Several high-speed seepage channels are formed at the meeting point of the fractures and pores; hence, the overall permeability increases significantly.

Similarly, the effect of fracture aperture on the permeability of the digital cores was also quantitated (Fig. 4). It is important to note that the fracture aperture increases in a direction perpendicular to the flow direction. When microfracture is not long enough to penetrate the whole core, the aperture and permeability show a linear relationship. In addition, the permeability enhancement ratio in the high-permeability core is larger than that in the low-permeability core. This indicates that the effect of fracture aperture on permeability is also related to matrix properties. When a fracture connects the two boundaries ($L_f/L = 1$), it becomes the main seepage channel; the seepage velocity in the matrix pores tends to be close



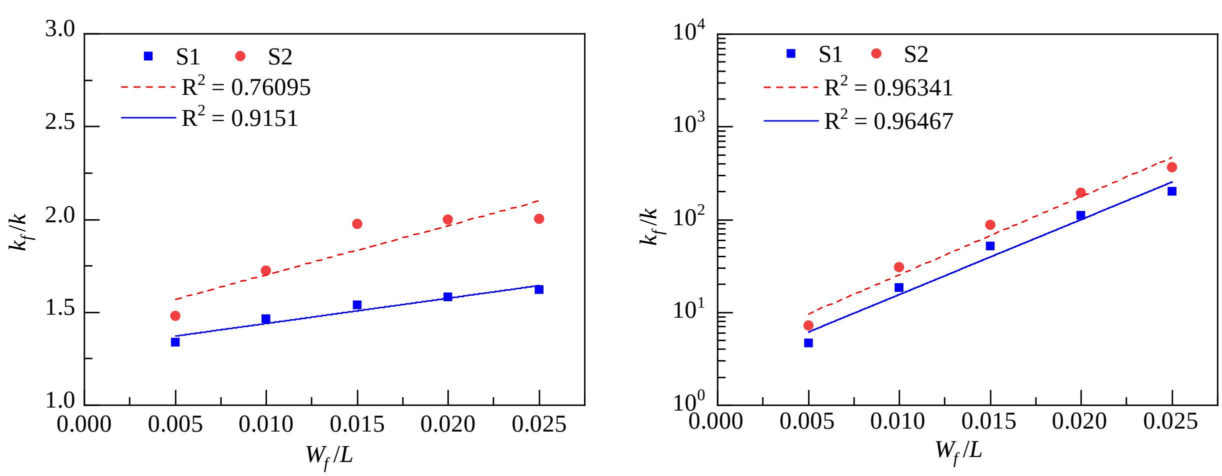
(a) $L_f/L \leq 0.5$, $W_f = 4$, $\theta_f = 0°$, $N = 1$ (b) $L_f/L > 0.5$, $W_f = 4$, $\theta_f = 0°$, $N = 1$

Fig. 2. Relationship between fracture length and permeability enhancement ratio.



(a) $L_f/L = 0.25$ (b) $L_f/L = 0.9$

Fig. 3. Velocity field distribution of different fracture lengths.



(a) $L_f/L = 0.5$, $\theta_f = 0°$, $N = 1$ (b) $L_f/L = 1$, $\theta_f = 0°$, $N = 1$

Fig. 4. Relationship between fracture aperture and permeability enhancement ratio.

to zero and has no contribution to the overall permeability, and the flow capacity in this case is entirely influenced by the fracture. The relationship between fracture aperture and permeability shows an exponential relationship.

Similarly, the effects of density and angle of the fracture on the permeability of the digital cores were also quantitated (Fig. 5). For fracture density, as the fracture number increases (all fractures are parallel to the flow direction), the ratio of permeability of dual fracture-pore system to matrix permeability shows a linear increase. Since the fractures added in this case are short ($L_f/L = 0.5$), the influence of microfractures is mainly a function of the initial rock structure, and the more discrete the macropores, the more obvious the permeability change. For the fracture orientation, the cosine value of the fracture angle and the permeability show a linear relationship, wherein permeability decreases with an increase in the fracture angle. This is because with the increase in the fracture angle, the projected length of the fracture along the direction of flow ($L_f * \cos\theta_f$) will decrease. In terms of permeability enhancement ratio, although inclined fractures can enhance permeability to a certain extent, the effect is not significant.

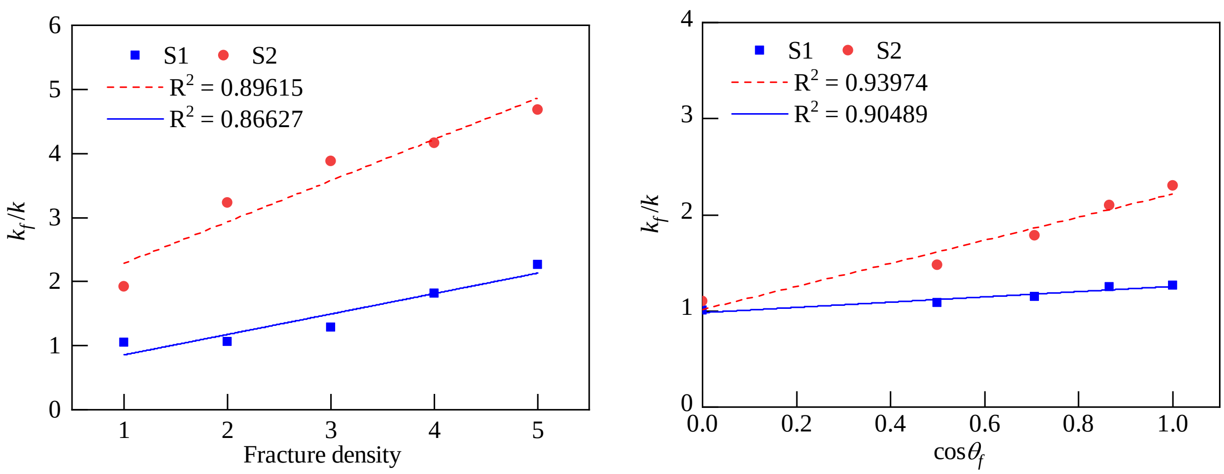
To rapidly and directly investigate the influence of structural parameters of fractures on permeability, PLS method was used to perform a regression analysis (Geladi and Kowalski, 1986), with the following assumptions:

1) The fracture and seepage directions in the core are consistent.
2) The fractures in the core are short, and the fractures do not penetrate the core.

The relationship between the volume fraction of fracture and the length, aperture, and density is given as follows:

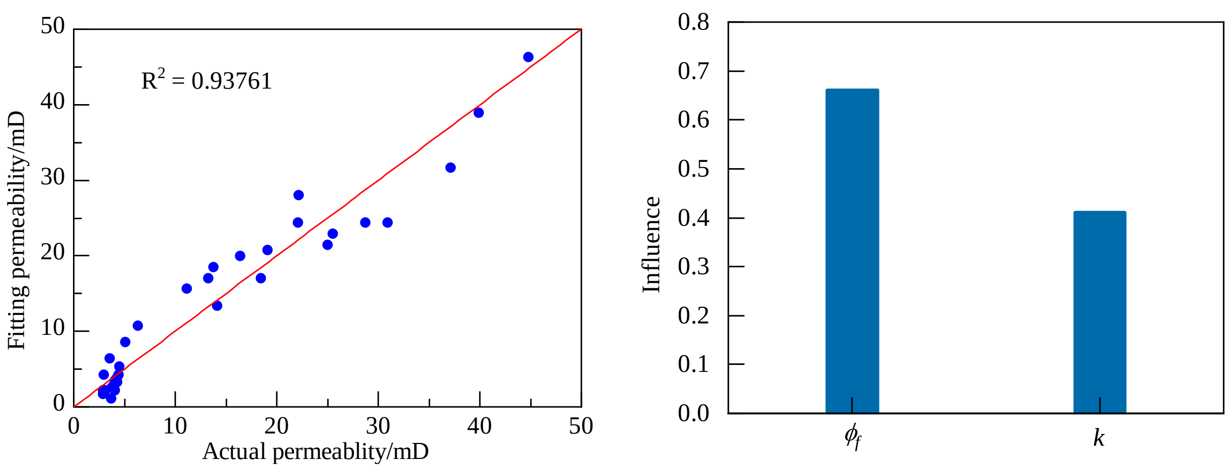
$$\phi_f = \frac{L_f}{L}\frac{W_f}{W}N \tag{1}$$

where ϕ_f represents the volume fraction of fracture porosity; and W_f/W represents the dimensionless fracture width in the core.



(a) $L_f/L = 0.5$, $W_f = 2$, $\theta_f = 0°$ (b) $L_f/L = 0.5$, $W_f = 4$, $N = 1$

Fig. 5. Relationship between fracture density, angle, and permeability enhancement ratio.



(a) relationship between fitting value and simulation value (b) degrees of influence of fracture parameters

Fig. 6. Fitting results of PLS regression.

The fitting equation for predicting the permeability k_f of the dual fracture-pore medium is given as follows:

$$k_f = k(152.16\phi_f + 1.44) - 4.05 \tag{2}$$

The fitting diagram and the degree of influence of the parameters in the Equation are shown in Fig. 6, where ϕ_f and k_f were obtained from a series of digital cores with different fracture properties. Fig. 6(b) shows the degree of influence of fracture volume fraction and matrix permeability, both of which are positively related with the permeability of the final system. However, the fracture plays a dominant role in enhancing the permeability of the matrix pore space.

4. Conclusions

Microfractures can significantly increase the permeability of carbonate rocks. As the fracture length increases, the effect of fracture length on the permeability of the system transitions from linear to exponential. Fracture aperture, density, and angle have similar influences on rock permeability. A relationship between the permeability enhancement ratio and the permeability of matrix pores also exists. The greater the permeability of the matrix pores, the greater the effect of microfractures on enhancing the permeability of the entire system. Both fractures and matrix permeability influence the final permeability of the digital cores, and the former have a greater effect on enhancing the permeability.

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Supplementary file

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Conflict of interest

The authors declare no competing interest.

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