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Study on Rock-Electric Characteristics of Cracked Porous Rocks by the Novel Multifactor Conductivity Model

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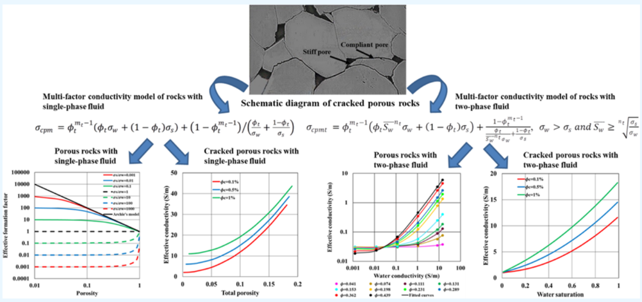
ABSTRACT: Due to the influence of multiple factors on the conductive properties of rocks, the Archie's formula, considering only a single factor, makes it difficult to reasonably explain rock-electric characteristics of cracked porous rocks. In order to better describe the conductive mechanism of cracked porous rocks, a generalized multifactor conductivity model was proposed by considering and introducing multiple influencing factors such as the series-parallel structure, conductive matrix, cracks, and fluids, which is conducive to more accurate research on the conductive mechanism of rocks. It should be noted that the developed model is not only applicable to cracked porous rocks but also useful for porous rocks. Through the study and analysis of various influencing factors, it is demonstrated by the simulation results that both the conductive matrix and cracks improve the conductive ability, which are crucial factors resulting in the non-Archie behavior and low-resistivity pay zone, and rock conductivity is more sensitive to the conductive matrix and cracks in tight reservoirs with porosity below 10%. Furthermore, experimental data are available to validate the novel multifactor conductivity model, and the comparison results show its advantages in predicting and explaining the conductive properties of cracked porous rocks.



1. INTRODUCTION

Rock conductivity plays an important role in interpreting well-logging data, analyzing the microstructure, and evaluating the fluid saturation. The development of theoretical models for rock conductivity is beneficial to accurately analyzing experimental data and providing information concerning reservoir evaluation. Although many conductivity models have been published,[1−3] the most widely used method for the rock-electric analysis is Archie's equation,[4−7] which was derived from experimental data. However, due to the ignorance of multiple factors, Archie's law could not be utilized to explain the reported non-Archie behavior.[8−11] According to relevant studies, it is found out that the main influencing factors resulting in the non-Archie phenomenon involve water salinity, conductive matrix, pore structure, clay, and crack.[12−24]

As for rocks containing the conductive minerals, Archie's formula could overestimate the water saturation. In order to accurately evaluate the water saturation, Givens[12] derived a rock matrix model based on the parallel conductive network. Furthermore, Glover et al.[13] assumed that every component conforms to the form of Archie's law, and extended Archie's equation to porous media with two conducting phases. Glover's formula has been used successfully in the modeling of porous media that have significant matrix conductivity.[25]

In addition, fractured reservoir evaluation has been one of the major challenges in petroleum exploration. The challenge for the fractured reservoir evaluation lies in the coexistence of cracks and pores.[26] The accurate saturation evaluation in fractured rocks requires an understanding of the dual-porosity system.[27,28] Generally, it is assumed that matrix pore and crack are parallel in their equivalent resistant circuit;[29,30] hence, the dual-porosity model can be used to describe rock-electric characteristics in fractured reservoirs.[31−33]

As for the above models, several problems exist because of the neglect of some influencing factors. First, those porous models are suitable for clean sandstones, but they may fail in reservoirs containing conductive minerals. Second, those single-porosity models cannot be applied to fractured reservoirs due to the neglect of the coexistence of pores and cracks. Last but not least, the aforementioned porous models only considered the simplified parallel configuration, which is not representative of realistic field conditions.[34] Therefore, there needs to be an electrical conductivity model that allows for the configuration of series and parallel conductance and the influence of the conductive matrix and cracks. In this paper,

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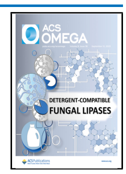

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the novel multifactor conductivity model that satisfies these requirements is developed to study the conductive mechanism of rocks. The unified model is applicable to both porous and cracked porous rocks and is verified using experimental data.

2. METHODOLOGY

2.1. Multifactor Model with Series and Parallel Conductive Structure. As for research on the conductive mechanism of rocks, the widely used method is to treat rocks as parallel or series conductive structures. It is assumed that every component consists of laminated stripes parallel or perpendicular to the applied field. For a two-component mixture, it gives the rock conductivities of parallel and series configurations using Ohm's law

$$\sigma_{par} = \phi\sigma_w + (1-\phi)\sigma_s \tag{1}$$

$$\frac{1}{\sigma_{ser}} = \frac{\phi}{\sigma_w} + \frac{1-\phi}{\sigma_s} \tag{2}$$

where σ_{par} and σ_{ser} represent the rock conductivities with parallel and series structures, σ_w and σ_s represent water and matrix conductivities, and ϕ denotes the matrix porosity.

Generally, the above parallel and series models correspond to the maximum and minimum conductivities that are possible in the rocks, which could not exactly describe the conductive property of complex rocks. In the case of a random distribution of components, the common assumption that the rock behaves like an electric circuit fully composed of resistances in series or in parallel is unreasonable. The combined configuration of series and parallel conductance is considered to be closer to a real rock structure.

2.2. Multifactor Model Considering Series-Parallel and Dual-Porosity Structure. In fractured or tight reservoirs, there usually exist both stiff and compliant pores, as shown in Figure 1. Considering that cracks are easily compressed, they are treated as compliant pores. Generally, well-developed cracks play an important role in the electrical conductivity of rocks, especially in fractured and tight rocks.

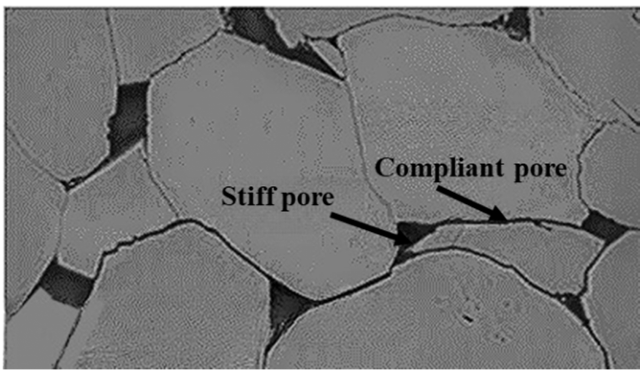

Figure 1. Schematic diagram of cracked porous rocks.

Some rock components, including pores, cracks, fluids, and matrix, contribute to rock conductivity, and the total porosity ϕ_t consists of both matrix porosity ϕ and crack porosity ϕ_c, namely, $\phi_t = \phi + \phi_c$. The series and parallel conductive equations can be extended to cracked porous rocks

$$\sigma_{par,cpm} = \phi\sigma_w + \phi_c\sigma_w + (1-\phi_t)\sigma_s = \phi_t\sigma_w + (1-\phi_t)\sigma_s \tag{3}$$

$$\frac{1}{\sigma_{ser,cpm}} = \frac{\phi}{\sigma_w} + \frac{\phi_c}{\sigma_w} + \frac{1-\phi_t}{\sigma_s} = \frac{\phi_t}{\sigma_w} + \frac{1-\phi_t}{\sigma_s} \tag{4}$$

where ϕ_c and ϕ_t represent crack porosity and total porosity, $\sigma_{par,cpm}$ and $\sigma_{ser,cpm}$ denote the parallel and series conductivities of cracked porous rocks, respectively.

For cracked porous rocks with complex structures, they characterize rock conductivity through a suitable combination of series and parallel conductance. Next, rock conductivity is characterized by a combination of series and parallel conductance

$$\sigma_{cpm} = \lambda\sigma_{par,cpm} + (1-\lambda)\sigma_{ser,cpm} \tag{5}$$

where $\sigma_{par,cpm}$ and $\sigma_{ser,cpm}$ represent parallel and series conductivities for cracked porous rocks.

The weighting factor λ can be regarded as a morphological parameter that determines intermediate behavior between two configurations (series and parallel structure). In order to obtain an analytical expression for λ, a specific boundary condition needs to be employed to determine a weighting factor for the series-parallel conductivities of cracked porous rocks. It is assumed that the expression for the boundary condition in the limit $\sigma_s/\sigma_w \to 0$ possesses a form similar to that of Archie's formula. Next, the boundary condition for cracked porous rocks is given based on Aguilera's equation.

According to Aguilera's study,[31] cracks and background porous parts are assumed to be conductive in parallel. Based on the parallel conductive model and Ohm's law, it gives the conductivity of cracked porous rocks

$$\sigma = (1-\nu\phi_t)\sigma_p + \nu\phi_t\sigma_w \tag{6}$$

where σ is the conductivity of cracked porous rocks free of the conductive matrix, σ_p is the conductivity of the matrix system, and ν is the partition coefficient, which is equal to the crack porosity divided by the total porosity, namely, $\nu = \frac{\phi_c}{\phi_t}$.

Both cracked porous rock and matrix system are assumed to conform to the form of Archie's law, and eq 6 is rewritten as follows:

$$\phi_t^{m_t}\sigma_w = (1-\nu\phi_t)\phi^m\sigma_w + \nu\phi_t\sigma_w \tag{7}$$

where m_t is the effective cementation exponent of cracked porous rocks and m is the cementation exponent of the matrix system.

Then, the effective cementation exponent m_t of cracked porous rocks can be calculated by taking logarithms on both sides of eq 7

$$m_t = \frac{\log((1-\nu\phi_t)\phi^m + \nu\phi_t)}{\log\phi_t} \tag{8}$$

As for crack porosity $\phi_c = 0$, it indicates the porous rock without cracks; thus,$\nu = \frac{\phi_c}{\phi_t} = 0$ and $\phi_t = \phi$; the above eq 8 can ultimately be simplified as $m_t = m$, and when $\phi = 0$, it represents the cracked rock, thus $\phi_t = \phi_c$, $m_t = m_c$, and m_c denotes the cementation exponent of cracks. Aguilera[29] pointed out that compared with the porous part, the cracked part has a much smaller cementation exponent, which is equal to 1 in the condition that cracks are parallel to current. In this work, m_c is assumed to be 1.

In the limit approximation, $\sigma_s/\sigma_w \to 0$, $\sigma_{ser,cpm} \to 0$, $\sigma_{par,\,cpm} \to \phi_t\sigma_w$, and $\sigma_{cpm} \to \lambda\phi_t\sigma_w$. Furthermore, σ is assumed to be

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Table 1. Commonly Used Models for Electrical Conductivity

models	equations	conducting phases	application condition
series model	$\frac{1}{\sigma_e} = \sum_{i=1}^{n} \frac{\phi_i}{\sigma_i}$	many	multiphase conductive media
parallel model	$\sigma_e = \sum_{i=1}^{n} \phi_i \sigma_i$	many	multiphase conductive media
Archie model	$\sigma_e = \sigma_w \phi^m$	1	single-phase conductive porous media
Glover model	$\sigma_e = \sigma_w \phi^m + \sigma_s (1-\phi)^p$	2	two-phase conductive porous media
Aguilera model	$\sigma_e = \sigma_w \nu \phi_t + \sigma_p (1 - \nu \phi_t)$	2	two-phase conductive cracked porous media
this work	$\sigma_e = \phi_t^{m_t-1}(\phi_t\sigma_w + (1-\phi_t)\sigma_s) + (1-\phi_t^{m_t-1})/\left(\frac{\phi_t}{\sigma_w} + \frac{1-\phi_t}{\sigma_s}\right)$	3	multiphase conductive porous and cracked porous media

equal to σ_{cpm} under the condition $\sigma_s/\sigma_w \to 0$. Therefore, the weighting factor for cracked porous rocks is solved as

$$\lambda = \frac{\sigma_{cpm}(\sigma_w \gg \sigma_s) - \sigma_{ser,cpm}}{\sigma_{par,cpm} - \sigma_{ser,cpm}} = \frac{\phi_t^{m_t}\sigma_w}{\phi_t \sigma_w} = \phi_t^{m_t-1} \quad (9)$$

eq 9 implies that the resulting weighting factor λ is a function of the geometrical factors. Substituting eqs 9 into 7 could obtain the following formula

$$\sigma_{cpm} = \phi_t^{m_t-1}(\phi_t\sigma_w + (1-\phi_t)\sigma_s) + (1-\phi_t^{m_t-1}) \Big/ \left(\frac{\phi_t}{\sigma_w} + \frac{1-\phi_t}{\sigma_s}\right) \quad (10)$$

It is clearly found that multiple factors are incorporated into the conductive model, which can be used for the comprehensive description of the conductive property. When the crack porosity is equal to zero, eq 10 is reduced to the case of porous rocks. In addition, when the matrix conductivity is much smaller than the water conductivity, eq 10 is further simplified into the classic Archie's law. Therefore, compared to existing models, this work unifies single-phase, two-phase, and three-phase conductive models and is applicable to both porous and cracked porous rocks. Table 1 compares and summarizes the commonly available conductivity models.

2.3. Multifactor Model for Cracked Porous Rocks with Two-phase Fluid. When the pore space is filled up with immiscible two-phase fluid instead of single-phase fluid, the equivalent conductivity of the mixed fluid is treated as the parallel conductance between fluids

$$\sigma_w' = \overline{S_w}\sigma_w + (1 - \overline{S_w})\sigma_h \quad (11)$$

where σ_w' and σ_h represent the conductivities of the mixed fluid and hydrocarbon, respectively, and $\overline{S_w}$ denotes the average water saturation.

Generally, the hydrocarbon conductivity σ_h is much lower than the water conductivity σ_w, namely, $\sigma_h/\sigma_w \to 0$, then, $\sigma_w' \approx \overline{S_w}\sigma_w$. Without considering the influence of the fluid distribution, the equivalent water conductivity is considered as the possible maximum. According to the Archie's law, the equivalent water conductivity that involves the fluid distribution can be defined as follows:

$$\sigma_w' = \overline{S_w}^{n_t}\sigma_w \quad (12)$$

where n_t denotes the effective saturation exponent of cracked porous rocks.

Replacing σ_w with σ_w' in eqs 3 and 4, series and parallel conductive equations can be rewritten as

$$\sigma_{par,cpmt} = \phi_t\sigma_w' + (1-\phi_t)\sigma_s \quad (13)$$

$$\frac{1}{\sigma_{ser,cpmt}} = \frac{\phi_t}{\sigma_w'} + \frac{1-\phi_t}{\sigma_s} \quad (14)$$

where $\sigma_{par,cpmt}$ and $\sigma_{ser,cpmt}$ represent parallel and series conductivities for cracked porous rocks saturated with two-phase fluid.

Similarly, based on a linear combination of series and parallel conductance, the effective conductivity for cracked porous rocks could be determined by choosing a suitable weighting factor

$$\sigma_{cpmt} = \lambda_t\sigma_{par,cpmt} + (1-\lambda_t)\sigma_{ser,cpmt} \quad (15)$$

where σ_{cpmt} and λ_t denote the effective conductivity and weighting factor for cracked porous rocks with two-phase fluid.

As for cracked porous rocks with two-phase fluid, regardless of the fluid distribution in cracks, the boundary condition in eq 6 can be revised as follows

$$\sigma_t = (1-\nu\phi_t)\sigma_{p,t} + \nu\phi_t\overline{S_w}\sigma_w \quad (16)$$

where σ_t denotes the effective conductivity for cracked porous rocks free of the conductive matrix and $\sigma_{p,t}$ represents the conductivity of the matrix system with two-phase fluid.

The conductivities of both cracked porous rock and matrix porosity part are assumed to satisfy Archie's second equation. Therefore, eq 16 is rewritten as

$$\phi_t^{m_t}\overline{S_w}^{n_t}\sigma_w = (1-\nu\phi_t)\phi^m\overline{S_w}^{n}\sigma_w + \nu\phi_t\overline{S_w}\sigma_w \quad (17)$$

where n_t indicates the effective saturation exponent of cracked porous rocks and n represents the saturation exponent of the matrix system.

Then, taking logarithms on both sides of eq 17 yields the effective saturation exponent n_t of cracked porous rocks

$$n_t = \frac{\log((1-\nu\phi_t)\phi^m\overline{S_w}^{n} + \nu\phi_t\overline{S_w}) - \log(\phi_t^{m_t})}{\log \overline{S_w}} \quad (18)$$

In the case $\phi_c \to 0$, it denotes the porous rock saturated with two-phase fluid; thus, $\phi_t \to \phi$, $m_t \to m$, and $n_t \to n$; in the condition $\phi \to 0$, it becomes the cracked rock filled with two-phase fluid; thus, $\phi_t \to \phi_c$, $n_t \to n_c = 1$, thereby eq 18 is a generalization of porous rocks, and the development of cracks could decrease the effective saturation exponent.

As stated above, the weighting factor is a morphological parameter related to the microstructure; it is assumed that the fluid distribution only affects the equivalent water conductivity, but it could not lead to the change of the weighting factor. Thus, we obtain

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$$\lambda_t = \lambda \tag{19}$$

As for rocks with two-phase fluid, the suitable weighting factor is associated with the relative magnitude of the equivalent water and matrix conductivities, and when water conductivity is larger than matrix conductivity, the relative size of the equivalent water and matrix conductivities relies on the water saturation. Through the analysis, it follows that when $\sigma'_w > \sigma_s$, $\overline{S_w} > \sqrt[n_t]{\frac{\sigma_s}{\sigma_w}}$, σ and $\lambda_t = \phi_t^{m_t-1}$.

Then, the effective conductivity of cracked porous rocks with two-phase fluid can be expressed as

$$\sigma_{cpmt} = \phi_t^{m_t-1}(\phi_t \overline{S_w}^{n_t}\sigma_w + (1-\phi_t)\sigma_s) + \frac{1-\phi_t^{m_t-1}}{\frac{\phi_t}{\overline{S_w}^{n_t}\sigma_w} + \frac{1-\phi_t}{\sigma_s}}, \quad \sigma_w > \sigma_s \text{ and } \overline{S_w} \geq \sqrt[n_t]{\frac{\sigma_s}{\sigma_w}} \tag{20}$$

As crack porosity decreases to zero, eq 20 could degenerate into the case of porous rocks. Figure 2 illustrates the construction process of the multifactor conductivity model in this work.

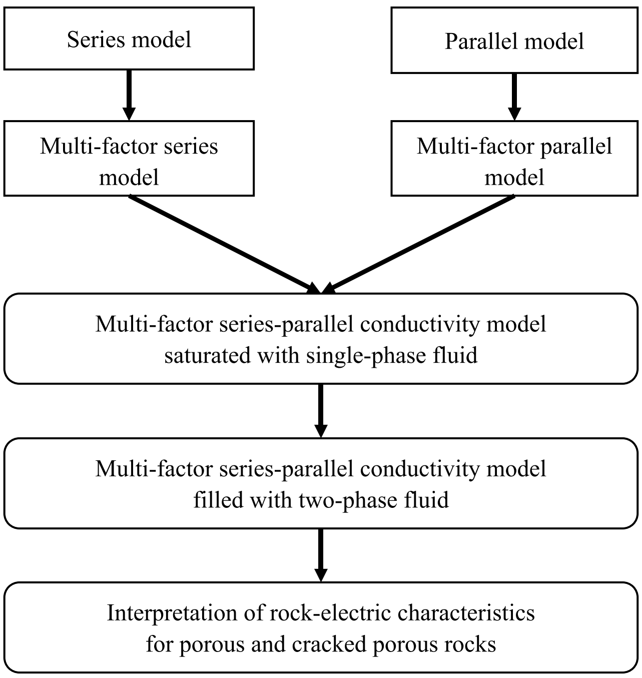

Figure 2. Interactive flowchart for constructing the multifactor conductivity model.

3. RESULTS AND DISCUSSION

It is noticed that the established multifactor model can be applied to cracked porous rocks and used for the description of rock-electric characteristics in porous rocks. In the following section, the multifactor model is utilized to model the effective conductivities for both porous and cracked porous rocks, and experimental data are available to validate the proposed method.

3.1. Rock-Electric Characteristics of Porous Rocks. According to Archie's law, the effective formation factor of porous rocks with the conductive matrix is defined as $F\left(\phi, m, \frac{\sigma_s}{\sigma_w}\right) = \sigma_w/\sigma_{cpm}$. In contrast to Archie's first equation, in addition to the porosity and cementation exponent, the effective formation factor depends on the conductivity ratio of matrix to water. The effective formation factors at different conductivity ratios of matrix to water calculated by the multifactor method are plotted in Figure 3 and are compared

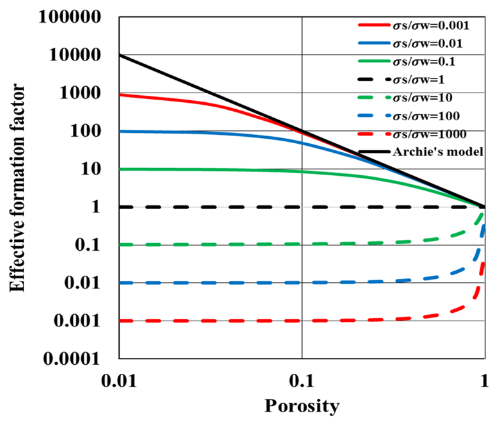

Figure 3. Relation between the effective formation factor and porosity at different conductivity ratios of matrix to water calculated by the multifactor model, and the formation factor calculated by Archie's model.

with the results computed by Archie's equation. The comparison implies that as the matrix conductivity increases, the nonlinear degree of the effective formation factor increases greatly, which means that the conductive matrix is a crucial factor resulting in the non-Archie behavior; on the other hand, the increasing matrix conductivity significantly leads to the decreasing resistivity of porous rocks, especially for tight reservoirs with low porosity, which indicates that the conductive matrix is also an important factor resulting in a low-resistivity pay zone. Furthermore, the matrix conductivity σ_s is set to 1 S/m, the cementation exponent m of the matrix porosity part free of cracks is set to 2, and the effective conductivities for water-saturated porous rocks, at different water conductivities ranging from 0.1 to 1000 S/m, are inferred from the multifactor model, and are compared with the results obtained from Glover's model and Archie's model, as shown in Figure 4. The results demonstrate that the multifactor method approaches Archie's model in the condition of high water conductivity and achieves a stable result in the condition of low water conductivity, which is consistent with known experimental rules. Then, the effective conductivities and corresponding parameters of 10 core samples with the conductive matrix (copper oxide) obtained by Glover[13] are used to verify the proposed method, and the fitting curves displayed in Figure 5 are in good agreement with measured data, which proves that the multifactor method can be utilized to well-interpret real data.

Next, when some brine is displaced by hydrocarbon with high resistivity, a rock with single-phase fluid is changed to a rock with two-phase fluid. The effective conductivity curves at different water saturations and porosities are plotted in Figure 6, and the matrix and brine conductivities are set to 1 and 100 S/m, respectively. In addition, the changes of the effective conductivity with water conductivity at different water saturations are displayed in Figure 7, and the porosity is set

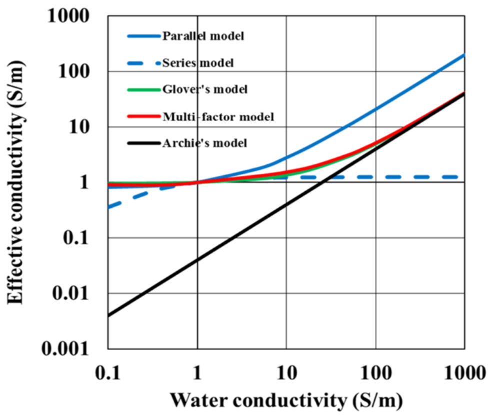

Figure 4. Comparison of theoretical results at different water conductivities calculated by the multifactor model, Glover's model, and Archie's model, respectively.

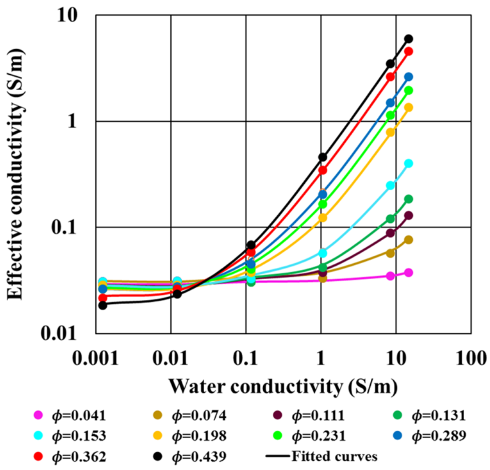

Figure 5. Glover's data and fitted curves by the multifactor model.

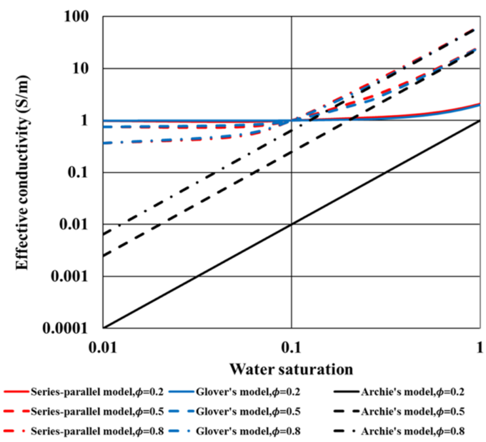

Figure 6. Comparison of the effective conductivities at different water saturations and porosities calculated by the multifactor model, Glover's model, and Archie's model.

to 20%. A comparison indicates that as for porous rocks with the conductive matrix, the deviation caused by Archie's second equation is larger in the lower water saturation, and lower porosity or water conductivity can significantly increase the deviation. Therefore, in tight reservoirs with low porosity and water saturation, the matrix conductivity plays a more important role, and hydrocarbon saturation evaluation using

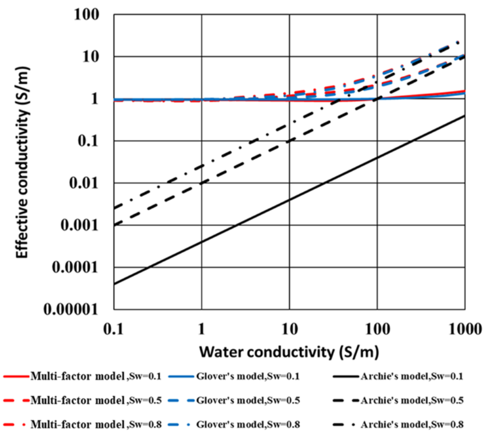

Figure 7. Comparison of the effective conductivities at different water conductivities and saturations calculated by the multifactor model, Glover's model, and Archie's model.

Archie's equation can lead to an error. Besides, the simulation results obtained by the multifactor model in Figures 6 and 7 get a good match with that of Glover's model.

3.2. Rock-Electric Characteristics of Cracked Porous Rocks. Because of the coexistence of pores and cracks in real reservoirs, especially in fractured reservoirs, the single-porosity model may not accurately describe the conductive properties in cracked porous rocks. Therefore, the multifactor model for porous rocks is further extended to cracked porous rocks, which can be applied to the simulation and interpretation of the conductive properties in dual-porosity rocks. As for brine-saturated cracked porous rocks with relatively low porosity, the effective conductivities and cementation exponents calculated by eqs (10)and (8) at different crack porosities are displayed in Figure 8a,b; among them, matrix and brine conductivities are set to 1 and 1000 S/m, respectively. The effective rock conductivity in Figure 8a increases with increasing crack porosity, which reveals that the development of cracks greatly contributes to the conductive ability, and the decreasing cementation exponent with increasing crack porosity in Figure 8b is consistent with the results in Figure 8a. Furthermore, as the total porosity increases, the effective rock conductivities at different crack porosities are gradually close to each other in Figure 8a, which indicates that the contribution of cracks to rock conductivity is significant in tight reservoirs.

When cracked porous rocks are filled with two-phase fluid, the effective rock conductivities and saturation exponents calculated by eqs (20) and (18) at different crack porosities are displayed in Figure 9a,b. The total porosity is set to 10%, and matrix and brine conductivities are set to 1 S/m and 1000 S/m, respectively. In hydrocarbon-saturated rocks ($S_w = 0$), the total pore space has no contribution to rock conductivity, and only the conductive matrix contributes to rock conductivity, thus, when the total porosity holds constant, the effective conductivity is not related to crack porosity and only influenced by the conductive matrix, which is consistent with the results in Figure 9a. As the water saturation increases, the effective conductivity increases, and the contribution of cracks to rock conductivity also increases. In Figure 9b, the saturation exponent decreases with increasing crack porosity, which also validates the results in Figure 9a.

Figure 10a further shows the relation between the effective formation factor and crack porosity at different conductivity

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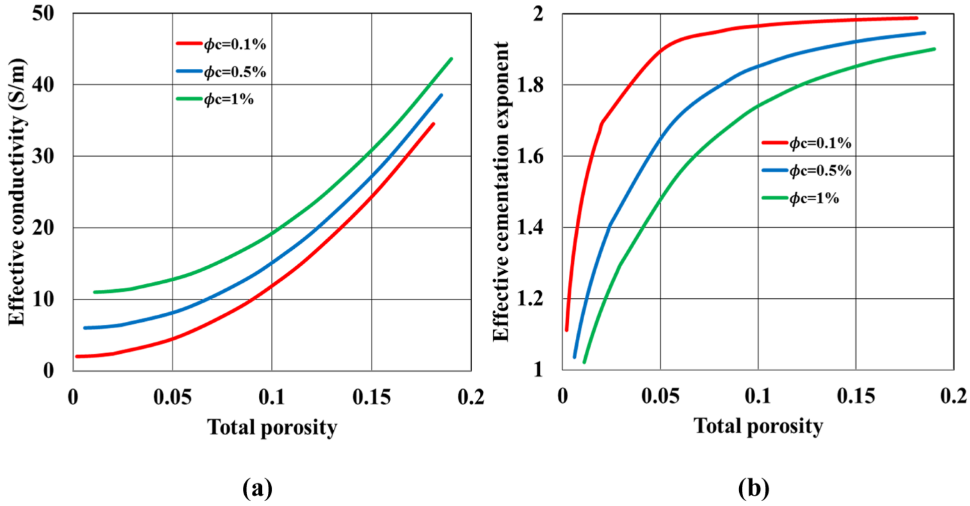

Figure 8. Changes of the effective conductivity (a) and cementation exponent (b) at different crack porosities calculated by the multifactor model in cracked porous rocks.

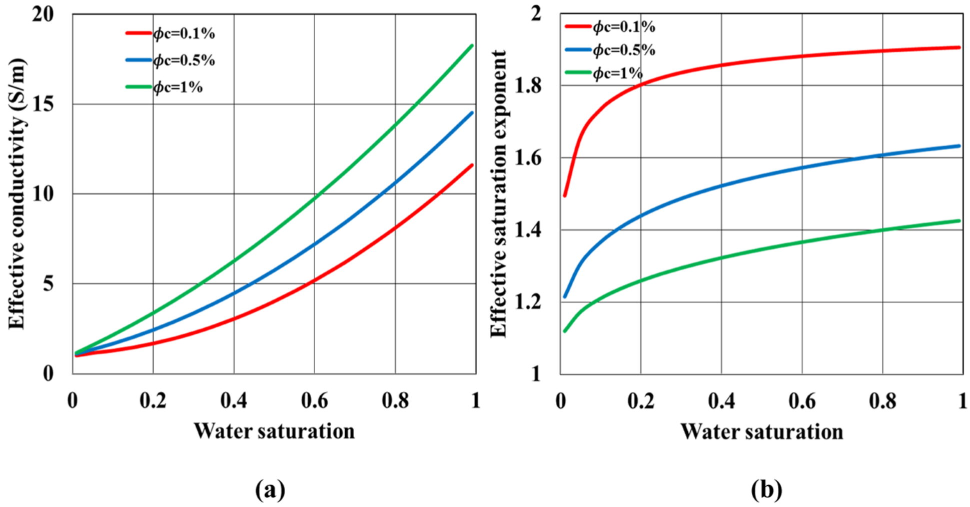

Figure 9. Changes of the effective conductivity (a) and saturation exponent (b) at different crack porosities calculated by the multifactor model in cracked porous rocks.

ratios of matrix to water and total porosities. When the total porosity remains constant and is equal to 10%, with the increase of the proportion of cracks among them, the effective formation factor decreases, and the conductive ability improves. Moreover, compared with Aguilera's model independent of the matrix conductivity, starting from the conductivity ratio of the matrix to water greater than 10^{-4}, the effect of the matrix on the formation factor becomes significant and not negligible. Meanwhile, the conductivity ratio of matrix to water is set to 10^{-5}, the total porosity ranges from 15 to 25%, and the range of the effective formation factor becomes larger in the lower total porosity, which implies that the electrical conductivity is more sensitive to cracks in tight rocks. Then, the multifactor method for cracked porous rocks is further employed to fit experiment data measured by Borai[35] in the groups of ultralow porosity, low porosity, and high porosity, and ϕ_c/ϕ_t is set to 0.058, as shown in Figure 10b−d. It is noted that the multifactor method considers multiple influencing factors, including the series-parallel configuration, conductive matrix, and cracks, and can be simplified into Aguilera's model in the limit $\sigma_s/\sigma_w \rightarrow 0$. Compared with the high-porosity group, since the effective conductivities in ultralow- and low-porosity groups calculated by the multifactor method approach that obtained by Aguilera's model in the condition of the lower conductivity ratio of matrix to water, it proves that the effective conductivities in tight reservoirs are more sensitive to the matrix conductivity. By and large, due to the comprehensive consideration of both conductive matrix and crack, the experiment data ranging from high porosity to ultralow porosity can be well fitted by the presented multifactor method.

4. CONCLUSIONS

The multifactor conductivity model is established to precisely analyze the conductive properties of both porous and cracked porous rocks by the linear combination of series and parallel conductance. The advantages of the proposed method lie in not only consideration of the series-parallel configuration but also the introduction of multiple influencing factors, which is beneficial to the study of the conductive mechanism. To begin with, the derived multifactor conductivity model for porous rocks involves the influence of the conductive matrix. By

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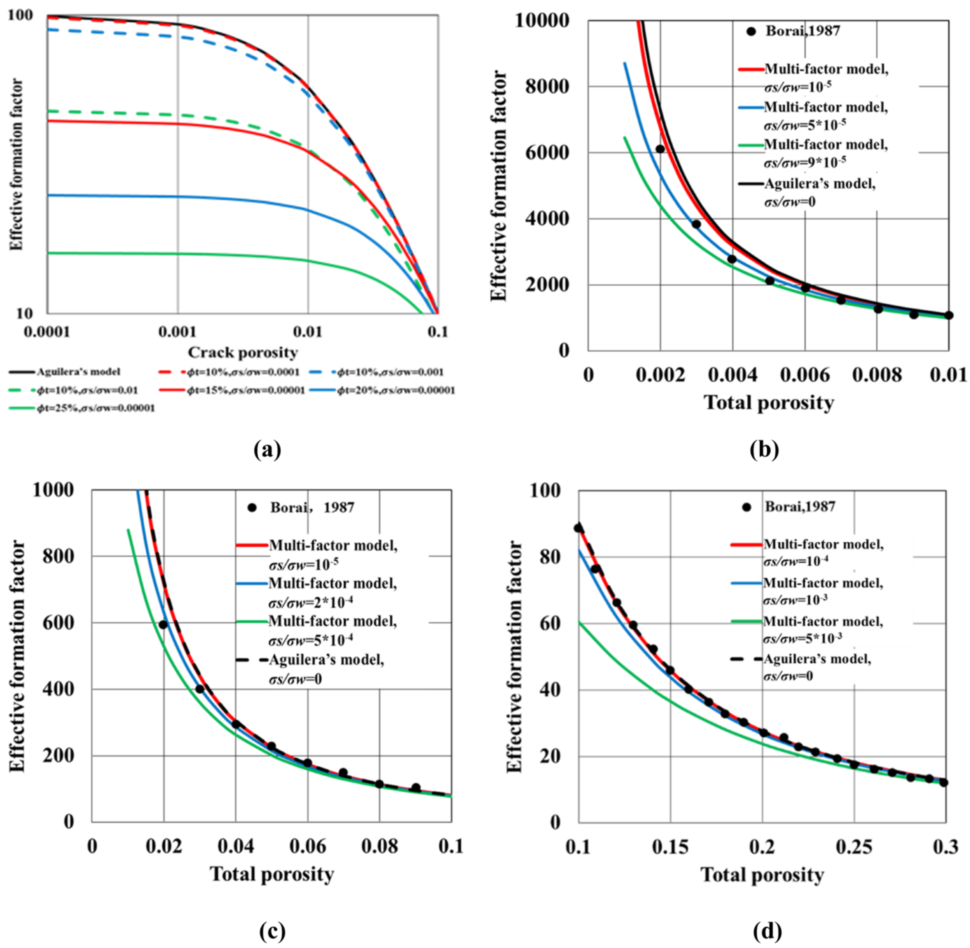

Figure 10. (a) Relation between the effective formation factor and crack porosity at different total porosities and conductivity ratios of matrix to water; (b)−(d) the experimental data from Borai[35] and fitting curves at different conductivity ratios of matrix to water calculated by the multifactor model for cracked porous rocks.

combining with dual-porosity structure, the multifactor model is further generalized to cracked porous rocks, which involves the effect of both conductive matrix and cracks. Besides, in order to describe the conductive property in rocks with two-phase fluid, the multifactor model is further extended to cracked porous rocks saturated with two-phase fluid by replacing water conductivity with equivalent water conductivity. The presented multifactor method indicates that both conductive matrix and cracks may lead to non-Archie phenomenon and low-resistivity pay zone, and the contribution of the conductive matrix and cracks is more significant in tight reservoirs. The proposed method is verified by comparing the theoretical relationship with the experimental results. The good agreement in the comparison validates its accuracy in predicting the electrical conductivity in porous and cracked porous rocks.

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Author Contributions

H.M.: Supervision, conceptualization, writing—original draft, investigation, methodology, and formal analysis. Y.Y.: Writing—review and editing. C.Y. and D.D.: Formal analysis.

Notes

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