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Further Study on the Parametric Variation Trend of the Relative Permeability Curve

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Abstract— The relative permeability curves are the key parameters of mechanics of fluid flowing through porous media multiphase flow, which was influenced by many factors. However, only few study on the correlativity between relative permeability curves and porous media parameters were conducted, which is unfavorable for actual application. The capillary pressure and the relative permeability curve testing experiments were measured simultaneously for the same core samples, which could be used for theoretical and mathematical statistics analysis. The fractal theoretical model was used to analyze the capillary pressure curve and the fractal dimensions could be obtained through regression. Theoretical analysis and mathematical statistics were used for analyze the correlation between the relative permeability parameters and the physical property parameters of the porous media. The most significant finding is that the better the physical property parameters are, the lower the irreducible water saturation and the residual oil saturation are, and the higher the wetting phase endpoint values are. But the correlation between the oil phase index and water phase index were not good enough with the physical property parameters, however satisfied with the fractal dimension. The parametric variation trend of the relative permeability curve could be not only used for the development effect improvement, but also the porous media parameters control for other engineering fields application.

Keyword —relative permeability, capillary pressure, fractal theoretical model;

I. INTRODUCTION

Mechanics of fluid flowing through porous media mainly studies on the mechanism and models describing fluid transporting through porous media. It gains more and more extensive application, and gradually becomes a theoretical basis for multiple engineering technologies. Besides being widely used in underground resources exploitation such as petroleum, natural gas, underground water and geo-thermal development etc., currently it's also applied to environment field, bioengineering field including carbon dioxide storage and pollutant dispersion analysis. The relative permeability curves are the key parameters of multiphase flow, which was influenced by many factors. Many scholars have discussed the influencing factors, which include lithology, porous media parameters, crack development degree, wettability, oil-water viscosity ratio, displacement velocity, and saturation order etc., on the relative permeability curves [1-14]. Few study on the correlativity between the relative permeability curves and the porous media parameters has been conducted. The current research are only qualitative but not quantitative.

In order to figure out the variation trend of the relative permeability parameters and its correlativity with the porous media parameters, a large number of core samples under different physical properties were chosen. The correlation between relative permeability parameters and porous media physical parameters was analyzed, and the correlativity between porous media physical parameters and the endpoint value of the relative permeability parameters were found, however unsatisfied relationship with the other characterization parameters (morphological parameters). Therefore, the capillary pressure curves testing experiments were designed for further analysis. The morphological parameters of the relative permeability curves were given based on the theoretical model of the relative permeability curves, and the fractal dimension was introduced for pore throat characterization based on the capillary pressure curve. Based on the theoretical analysis and mathematical statistics, the correlation function between the relative permeability parameters and the porous media physical property parameters were obtained, therefore laying a foundation for the further analysis of the relationship between the macroscopic seepage law and the microscopic porous media parameters.

II. METHODS

2.1 THE ANALYTICAL MODEL AND CHARACTERISTIC PARAMETERS OF THE RELATIVE PERMEABILITY CURVES

The relative permeability curves could be describes by a variety of forms, and the analytical model was the mostly wide used. The characteristic parameters of the relative permeability curves mainly include the endpoint value parameters (irreducible water saturation S_{wi}, residual oil saturation S_{or}, relative permeability of aqueous phase with residual oil saturation $K_{rw(Sor)}$) and the morphological parameters (including the water phase index n_w and the oil phase index n_o), seeing Fig. 1.

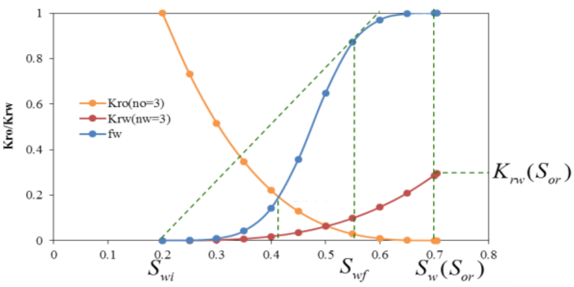

Fig. 1. The typical relative permeability curve and the corresponding characteristic parameters

The analytical models of the relative permeability are as follows:

$$K_{rw} = K_{rw}(S_{or})S_{wd}^{n_w} \tag{1}$$

$$K_{ro} = K_{ro}(S_{wc})(1-S_{wd})^{n_o} \tag{2}$$

$$S_{wd} = \frac{S_{we}-S_{wc}}{1-S_{wc}-S_{or}} \tag{3}$$

The main influencing factors of the relative permeability curves are lithology, physical property, pore structure, and oil/water viscosity ratio. Porous media physical property parameters can be characterized by *RQI*, *FZ1* or *R35*, but the pore structure parameters (geometry, size, and distribution and connectivity) need to be introduced into the pore throat distribution function, the fractal dimension, or other parameters for characterization. Capillary pressure curves could reflect the pore throat distribution of porous media. The capillary pressure is directly related to the phase saturation according to the test procedure, same as the relative permeability curves, keeping consistent in nature. Therefore, it's theoretically feasible to establish the relationship between the capillary pressure curve and the relative permeability curves through proper function conversion.

2.2 THE THEORETICAL ANALYSIS AND CALCULATION MODEL OF THE RELATIVE PERMEABILITY CURVES BASED ON THE CAPILLARY PRESSURE CURVES

Many scholars studied on the calculation method of relative permeability curves based on the capillary pressure curve, and proposed several models. Burdine [1] proposed a model by introducing the concept of tortuosity. Wyllie and Gardner [2] derived models to calculate the relative permeability of the oil/water and oil/gas phase based on the concept of curvature rate. Brooks and Corey [3] obtained the relative permeability expressions by introducing the porosity distribution index. Kewen Li and Horne proposed the Li-Horne model based on the fractal theory [4]. Besides, some other theoretical calculation methods [5-14] were studied on based on the fractal geometry theory. The most common used calculation methods are as shown in Tab. 1:

TABLE I. COMMON CALCULATION MODELS OF THE RELATIVE PERMEABILITY CURVES BASED ON CAPILLARY PRESSURE CURVES

Models	Mathematical Method	Note
Purcell Model	$k_{rw} = \int_0^S \frac{dS}{p_c^2} / \int_0^1 \frac{dS}{p_c^2}$ $k_{ro} = \int_S^1 \frac{dS}{p_c^2} / \int_0^1 \frac{dS}{p_c^2}$	
Burdine Model	$k_{rw} = \tau_{rw}^2 \frac{\int_0^S \frac{dS}{p_c^2}}{\int_0^1 \frac{dS}{p_c^2}}$ $k_{rnw} = \tau_{rnw}^2 \frac{\int_S^1 \frac{dS}{p_c^2}}{\int_0^1 \frac{dS}{p_c^2}}$	$\tau_{rw} = \frac{S_w - S_{wc}}{1-S_{wc}-S_{or}} = S_w^*$ $\tau_{rnw} = \frac{1-S_w-S_{or}}{1-S_{wc}-S_{or}} = 1-S_w^*$
Brooks-Corey Model	$k_{rw} = \left(S_w^*\right)^{\frac{2+3\lambda}{\lambda}}$ $k_{rnw} = \left(1-S_w^*\right)^2\left[1-\left(S_w^*\right)^{\frac{2+\lambda}{\lambda}}\right]$	$p_c = p_{\max}\left(S_w^*\right)^{-1/\lambda}$
Li Model	$k_{rw} = \frac{1-\left(1-bS_w^*\right)^{\frac{2+\lambda}{\lambda}}}{1-\left(1-b\right)^{\frac{2+\lambda}{\lambda}}}$ $k_{rnw} = \frac{\left(1-bS_w^*\right)^{\frac{2+\lambda}{\lambda}} - \left(1-b\right)^{\frac{2+\lambda}{\lambda}}}{1-\left(1-b\right)^{\frac{2+\lambda}{\lambda}}}\left(1-S_w^*\right)^2$	$p_c = p_{\max}\left(1-bS_w^*\right)^{-1/\lambda}$
He Chengzu Model	$k_{rw} = (S_w{}')^{\frac{11-3D}{3-D}}$ $k_{rnw} = (1-S_w{}')^2(1-S_w{}'^{\frac{5-D}{3-D}})$	$P_c = P_{\min}(S_w)^{\frac{1}{D-3}}$ $S_w{}' = \frac{S_w - S_{wc}}{1-S_{wc}}$

The relative permeability curve can be obtained based on the capillary force curve:

S_{wi}: The minimum wetting-phase saturation could be obtained through the mercury intrusion or the semi-permeability clapboard experiments, but it depends on the displacement pressure. If the displacement pressure is too small (mainly referring to the semi-permeable partition experiments), and the tail end of capillary force curve is not upward, the S_{wi} gained would be relatively large. If the displacement pressure is large (mainly referring to the mercury intrusion experiments), the obtained S_{wi} will be relatively small. The displacement velocity also affects the irreducible saturation. Generally, when the displacement pressure is close, the irreducible water saturation gained in the capillary pressure experiment will also be relatively closer to the irreducible water saturation obtained from the relative permeability experiment.

S_{or}: The residual non-wetting phase saturation could be obtained from the mercury ejection curves or suction curves from the semi-permeable partition experiments.

$K_{rw(Sor)}$: By substituting the tortuosity coefficient into the Burdine model, The value of $K_{rw(Sor)}$ could be determined by(S_{wmax}-S_{wi})/(1-S_{wi}), leading to $K_{rw\,(Sor)}$<1 .

n_o and n_w: The corresponding n_o and n_w values could be obtained through different calculation models based on the capillary pressure curves, Seeing Table I. The calculation process is as follows:

1) The data section of the capillary pressure curves were chosen for analysis, as shown in Fig. 2. The pore throat distribution parameters, the fractal dimension, or other parameters for pore structure characterization could be obtained through data fitting.

2) The relative permeability curves could be calculated based on different calculation models, as shown in Table I.

3) The normalized relative permeability curves was then calculated and fitted to get the n_o and n_w, as shown in Fig.3.

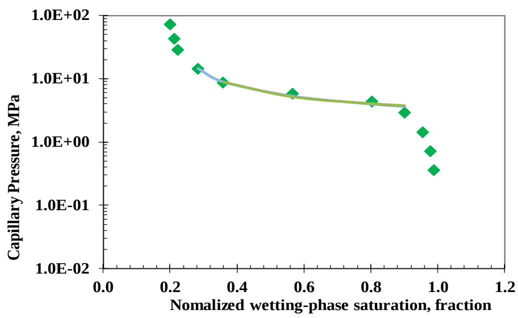

Fig. 2. The capillary pressure curve and the chosen data section

From the calculation process, it could be concluded that parameters n_o and n_w mainly depended on the pore structure parameters, which could be described by the pore throat distribution parameter, the fractal dimension, or other parameters for characterization.

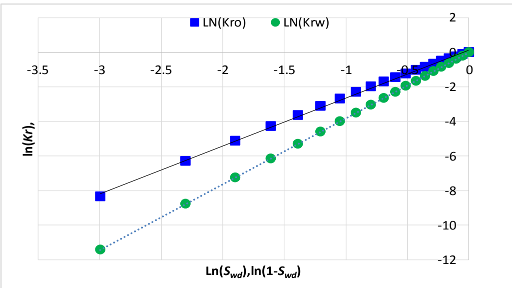

Fig.3. The n_o and n_w fitting results

III. Results and Discussions

3.1 The Correlativity between the Relative Permeability Parameters and the Porous Media Parameters

In order to verify the above analysis, the capillary pressure and the relative permeability curve testing experiments were measured simultaneously for the same core samples (Sandstone core samples chosen from a same reservoir), which could be used for theoretical and mathematical statistics analysis. The *RQI* and fractal dimension were chosen for the correlativity analysis between the relative permeability parameters and pore structure characterization parameters, seeing Fig.4-Fig.9.

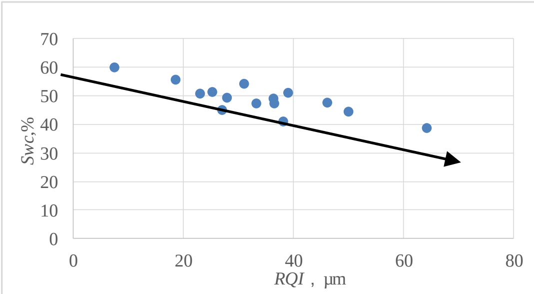

Fig. 4. The correlation between *RQI* and the relative permeability characteristic parameters S_{wc}

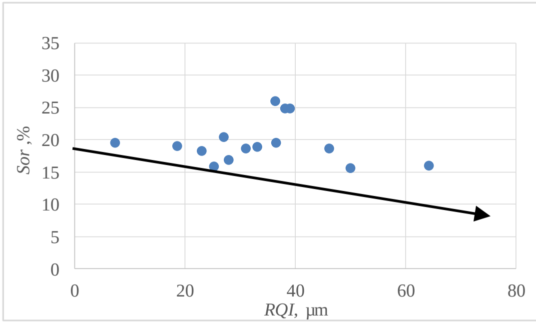

Fig. 5. The correlation between *RQI* and the relative permeability characteristic parameters S_{or}

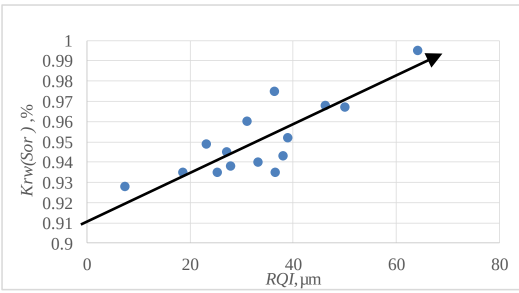

Fig. 6. The correlation between *RQI* and the relative permeability characteristic parameters $K_{rw(Sor)}$

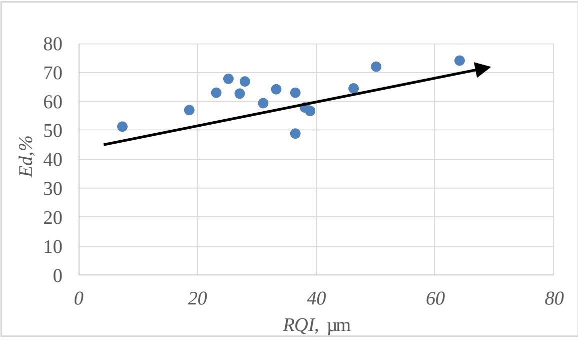

Fig. 7. The correlation between *RQI* and E_d

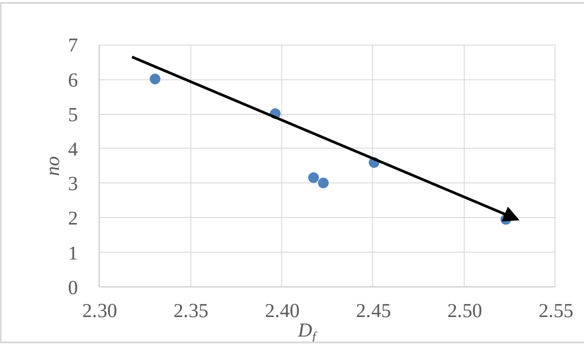

Fig. 8. The correlation between D_f and the relative permeability characteristic parameters n_w

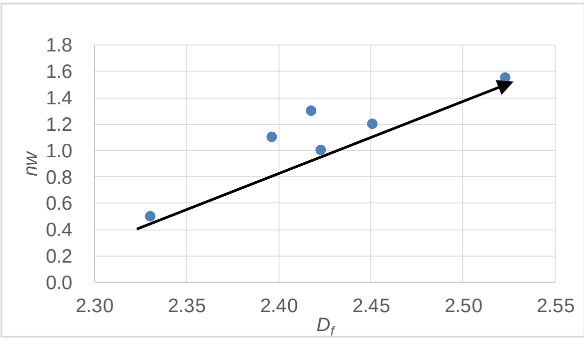

Fig. 9. The correlation between D_f and the relative permeability characteristic parameters n_o

Figs.4-Fig.9. present the correlativity between the relative permeability parameters and the porous media parameters for the dolomite samples. It could be concluded that the *RQI* has a good correlation with the endpoint value parameters of the relative permeability curves (S_{wi}, S_{or} and $K_{rw(Sor)}$) and the sweep efficiency E_d, but has a poor correlation with the morphological parameters (n_o and n_w). The fractal dimension, which determines the pore throat distribution has a good correlation with n_w and n_o.

3.2 The Variation Trend of Relative Permeability Parameters with Porous Media Parameters

1) The higher the *RQI* parameter is, the lower the irreducible water saturation and residual oil saturation are. The higher the *RQI* parameter is, the larger the pore size is, and the lower the percentage influenced by rock walls is, leading to the lower irreducible water saturation. The higher the *RQI* parameter is, the harder the oil phase is traped, leading to lower residual oil saturation.

2) The higher the *RQI* parameter is, the higher $K_{rw(Sor)}$ is. The higher the *RQI* parameter is, the lower the irreducible water saturation and residual oil saturation are, the higher percentage of water phase located in the geometric center of the pores.

3) The higher the D_f is, the lower the n_o is and the higher the n_w is. The higher the D_f is, the more complicated the geometrical morphology of the pores is, the more percentage of water phase influence by the rock walls is, and the larger the seepage resistence of water phase is under same water saturation, leading to higher $n_{w,}$ because the main component of sandstone is quartz (a king of oleophilic mineral) leading to hydrophile. However, the relative seepage resistence rate is lower, leading to lower n_o, because the oil phase mainly located in the the geometric center of the pore in sand stone resevoirs.

3.3 Disscussions

The above conclusions were obtained based on the statistical analysis results based on sandstone core samples under certain oil/water viscosity ratio, there is some uncertainty for the above conclusions.

1) The mineral component is different for different lithology, and the interaction between the rock and fluid is different, leading to different influence on the relative permeability curves.

2) Wettability is an overall characteristic parameter by the interaction between rocks and reservoir fluids. The wettability exerts a great influence on the characteristics of relative permeability curve. The parametric variation trend of the relative permeability maybe chang under different wettability.

3）The complexity of the pore structure(related with average pore radius, pore throat ratio, coordination number, and shape factor) has a great influence on the relative permeability curves. Different pore structure lead to different seepage space, different seepage resistence, leading to differnet relative permeability. And the parametric variation trend maybe become more complicated under complicated pore structure.

IV. Conclusions

1) The physical parameters of porous media has a good correlation with the endpoint value parameters of relative permeability curve and displacement efficiency. The better the physical property of the porous media, the lower the irreducible water saturation and residual oil saturation, and the larger the wetting phase endpoint value as well as the displacement efficience.

2) The physical parameters of porous media but is poorly correlated with the morphological parameters(n_o and n_w) of relative permeability curves. Through calculation models analysis of the relative permeability curves based on the capillary pressure curves The fractal dimension D_f, which determines pore throat distribution, has a good correlation with the morphological parameters of relative permeability curves. The higher the fractal dimension is, the higher the wet phase index is, the lower the non-wet phase indexis.

3) The influencing of porous media parameters on relative permeability curves was through the interaction between rock and the fluid in porous media. Different lithology, different wettability and the complexity of the pore structure maybe lead to more complicated parametric variation trend.

4) The parametric variation trend of the relative permeability curve could be not only used for experiments count decreasing, dynamic performance forecasting accuracy increasing and the development effect improving, but also the porous media parameters control for other engineering fields application.

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NOMENCLATURES

K_{rw}, water relative permeability, f;

K_{ro}, oil relative permeability, f;

$K_{rw}(S_{or})$, water relative permeability at the residual oil saturation, f;

$K_{ro}(S_{wc})$, oil relative permeability at the connate water saturation, f;

S_w, water saturation, f;

S_{wf}, water saturation of the water flood front, f;

S_{wc}, irreducible water saturation, f;

S_{or}, residula oil saturation, f;

S_{we}, water saturation at the exit end, f;

RQI, FZ1, R35, porous media physical property parameters.

n_w, water phase index of the relative permeability, f;

n_o, oil phase index of the relative permeability, f;

P_c, capillary pressure, 10^{-1}Mpa;

S_w, wet saturation, f;

D_f, fractional dimension, f;

λ ,b, Pore throat distribution parameters;

P_{max}, maxinum capillary pressure, 10^{-1}Mpa;

P_{min}, maxinum capillary pressure, 10^{-1}Mpa;

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