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Fractal Description of Pores in Low Permeability Sandstone and the Inside Nonlinear Fluid Flow

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Abstract. An integrated analysis was made upon images of casting thin sections taken by SEM and capillary pressure curves measured on the same cores by MIP to reveal the complexity of pore structures and their effect on fluid flowing capacity in low permeability porous media. Based on fractal theory, a concept was defined for the two linear sections of the log-log curve of $S_{Hg} \sim P_c$ as multi-fractal dimension spectrum which further correlate with the non-linear fluid flowing feature of $v \sim \triangle p/L$ through porous media. The integrated analysis here disclosed the physical significance of the multi-fractal dimension spectrum and its coupling pattern between heterogeneous pore distribution and non-linear fluid flowing features inside. It provides a new quantitative description tool to reveal the complexity and correlation between pores and inside non-linear fluid flow for low permeability sandstones, which would give significant theoretical direction to understand the dynamic low permeability reservoir system.

Keywords: low permeability, pore-throat structure, fractal dimension, heterogeneity, mercury intrusion porosimetry

1. Introduction

Recently the low permeability reservoir has taken an important role in the sustainable development of petroleum exploration and production [1]. However, engineers always meet technological difficulties in the building up of effective displacement draw down between injectors and producers which always results in low recovery factor [2]-[3]. It is required to make fine description of low permeability reservoirs and the non-linear fluid flow mechanism inside. While the traditional reservoir description method is not capable of such purpose, a new method is in urgent need to fulfil the quantitative characterization of pore distributing law and non-linear flowing features for low permeability reservoirs. Fractal theory breakthroughs the concept of continuous Euclidean space dimension, indicates the extent of the fractal bodies' complexities and the capability of the fractal units to fill the embedded space, so it can realize the quantitative description of the nonlinear mechanism which is coarse, transilient and intermittent in the development process of a dynamic reservoir system [4]. Pfeifer P. et al [5] has arrived at a conclusion by the molecular absorption method that fractal structures exist at the formation rock. Katz, Thompson [6] used the SEM to study many types of sandstones and their analyses shown fractal characteristics of pore space for the obtained optical data. Angulo Gonzalez [7] have reported a new method to estimate the fractal dimension from the capillary pressure curve by mercury intrusion porosimetry (hereinafter referred to "MIP"). Also by SEM Krohn [8]-[10] found two segments of different sizes of pores, the fractal segment of smaller size and the non-fractal segment of bigger sizes. Shen P [11] et al has analyzed the subdivision of fractal curves of natural cores from DQ oilfield. But

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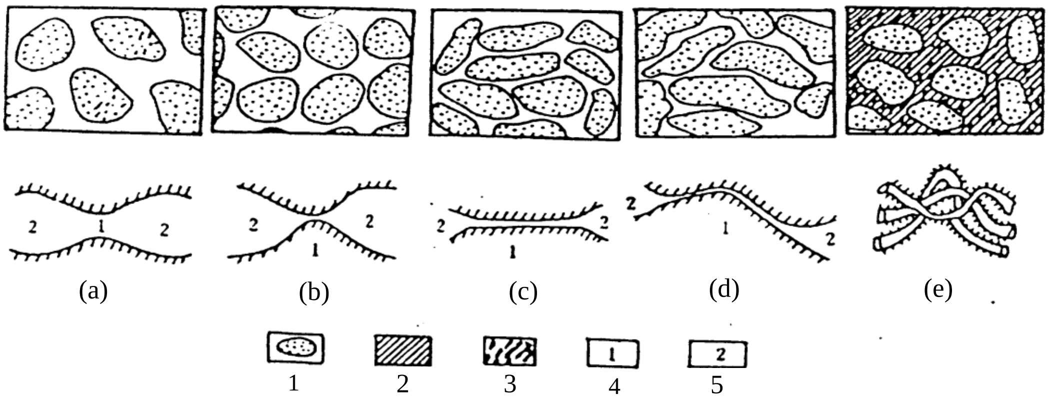
But such studies are primarily based on the medium or high permeability reservoirs and the recognitions acquired are not fit for the complicated pore structures of low permeability formations. Hence, based on the fractal theory, an integrated method including SEM scanned images and MIP measured capillary pressure curves were combined to make a comprehensive analyses of the pore distributing characteristics of low permeability cores and the inside non-linear fluid flow, to reveal the physical meaning of multi-fractal spectrum.

2. Microscopic Pore-throats Structures

The size and structure of pore-throats are determined by particles sizes, shapes and their contact patterns and consolidation types among the sandstone debris. The scanning images on casting thin sections by SEM show 5 patterns of typical pore-throats forms in Fig. 1: (a) throat as the reduced part of a pore, (2) throat as the contracted variable section, (3) throat as the laminated part, (4) bended laminar throat, (5) tubiform throat. While 3 patterns developed in the sandstones of Depression Sanzhao at Songliao Basin as (1) the corroded wide throats which appear in the diminished parts of pore space of sandstones primarily with intergranular pore-space, (2) the compacted small throat about several to tens of micrometers caused by further mechanical compaction or by free crystal growth which makes inter-crystal pores the connecting throats that are then surrounded by regenerated crystal surface, (3) the micro tubiform throat in the high content of matrix and cement which have blocked the primary intergranular pores completely and where many micro pores ($< 0.5\mu m$) take the roles of both pores and also connecting channels that make the corresponding sandstone a extremely low permeability rock less than $0.1\times10^{-3}\mu m^2$.

Researches indicate in the low permeability sandstone reservoir of Fuyang at Songliao basin the corroded wide throats could be observed only at few of local area where the corroded wide intergranular pores develop; the compacted small throats take a certain portion; compaction regenerated throats distribute a lot in the forms of plates and bending plates; micro tubiform throats could be observed. Generally speaking, the configuration between pores and throats show that voluminous micro throats (from several μm to tens of μm) make some pores the dead ones which connect with less than 3 throats. This should be attributed to the important reason of low permeability sandstones.



(a) (b) (c) (d) (e)

1-Particle, 2-Matrix, 3-Micro pore, 4-Throat, 5-Pore

Fig. 1: Sorts of pore throats

3. Analyses of Capillary Pressure Curves Measured by MIP

To reveal quantitative correlation between pores' microstructure and the macro fluid flow, mercury intrusion experiments were carried out on several cores from Fuyang reservoir of Songliao basin by a Porosimeter WS2000. The petrophysical parameters of such cores see Table 1. Fig. 2 and Fig. 3 shows the mercury intrusion-withdrawal capillary pressure curves of core #11 and #15.

The pores of low or ultra-low permeability reservoir are characteristical of small pores, micro throats and high pore-throat ratio. Such pore structure characteristics will have strong effect on the inside multi-phase fluid distribution and its flowing mechanism which is reflected in mercury experiments by poor withdrawal efficiency due to a great proportion of small pores. The low withdrawal efficiency indicates that a great proportion of crude oil is difficult to recover of while the small portion always begins withdrawal when the pressure has reduced to a low level at a great pressure gradient, often with no or a little withdrawn mercury at the starting stage. This manifests high fluid flow resistance and existence of trigger pressure at low permeability reservoir.

Table1: Parameter of pore structure calculated from MIP

No.	Kg($10^{-3}\mu m^2$)	Rr(μm)	WE(%)	Rd(μm)
10	0.7005	0.7035	27.80	5.775
12	0.7692	0.7135	31.80	5.552
11	0.9913	0.7490	37.25	5.775
16	1.2886	0.8645	29.22	6.258
18	2.4340	0.8465	33.55	5.775
15	6.3432	1.0480	23.56	13.652

To analyze the effect of pore structure on the oil & water distribution and their fluid flowing process, mercury intrusion capillary pressure curves obtained from above experiments were used to calculate the proportions of different sizes of pores to the total value, see Table 2.

Table 2: The proportions of different pore volume to total pore volume

No.	K($\times 10^{-3}\mu\ m^2$)	Pore Proportion （%）		
		<1μ m	<0.75μ m	<0.5μ m
10	0.7005	82	74	62
12	0.7692	76	69	53
11	0.9913	78	67	46
16	1.2886	74	66	52
18	2.4340	71	63	53

The mercury intrusion experiment on sandstone samples from Fuyang reservoir demonstrates the sandstone with its effective porosity bigger than 10% will have certain of oil storage capability if its pore space of size is larger than 0.1μm with movable fluid more than 50% of total pore space; herein the oil occurs in the way of oil sands and flecks primarily. The sandstone with its effective porosity less than 10% will have poor oil storage capability if its pore space with movable fluid takes less than 30% of total pore space; herein the oil occurs in the way of oil immersion and flecks primarily, sometimes as dry sands. This indicates inside reservoir the disconnected oil phase and low initial oil saturation. Within the oil bearing area of Fuyang, the reservoir petrophysical properties change rapidly. As for this type of ultra-low permeability reservoir, the sandstone pore structure not only affects its oil storage capability but also control the fluid flow to some extent in the process of oil production.

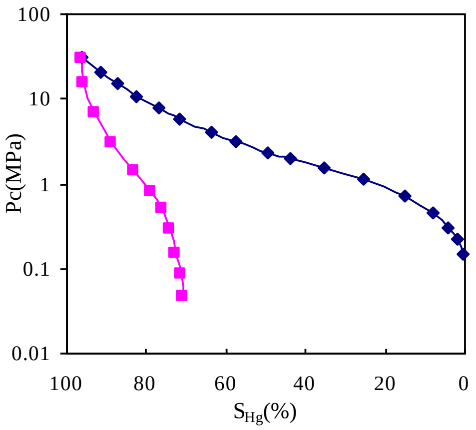


Fig. 2: Capillary pressure-saturation of core #11

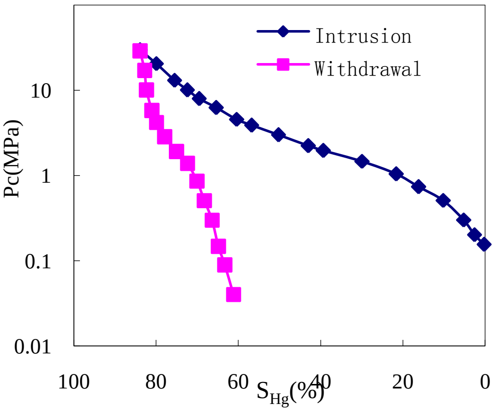


Fig. 3: Capillary pressure-saturation of core #15

4. Coupling Analysis between Fractal Pore structure and inside non-linear fluid flowing mechanism

The log-log curves of $S_{Hg}\sim P_c$, pore distribution and cumulative pore distribution of Core #11 see Fig. 4. Here the two-section linear fitting method is used to estimate the two fractal dimensions for the linear segments with different slopes [7]. Regarding that several fractal dimensions could be obtained from respective linear parts of log-log curves of $S_{Hg}\sim P_c$, we define a multi-fractal dimension spectrum for a group of such dimension values obtained from a capillary curve [12]. Such results could be obtained as follows:

(1) The two-section linear fitting method can match the log-log curves of $S_{Hg}\sim P_c$ better; The fractal dimensions of the big pores and micro pores are respectively 3.11 and 2.22, of which their variance seems obviously large; This indicates the distinguished difference of pore distribution between the two section pores of Core #11.

(2) The micro pores take 50% of the total pore space while the big size pores takes only 40% of the total value. So the fractal pores take more than 90% of the total pore volume.

The log-log curves of $S_{Hg}\sim P_c$, pore distribution and cumulative pore distribution of Core #15 see Fig. 5. Similar recognitions could be obtained as Core #11, while the difference is as follows:

(1) For Core #15, the fractal dimensions of two segments of pores are 2.89 and 2.15, respectively. Their variance is less than that of Core #11. This indicates its poorer heterogeneity of pore distribution than Core #11.

(2) The micro pores take 40% of the total pore space while the big size pores takes only 55% of the total value. So the fractal pores take more than 90% of the total pore volume.

(3) In comparison with Core #15, Core #11 has some higher scale of micro pore. This might be the primary reason for its poorer physical properties like permeability. At the same time, the focus of pores on the micro-pores makes the mercury withdrawal efficiency higher than Core #15.

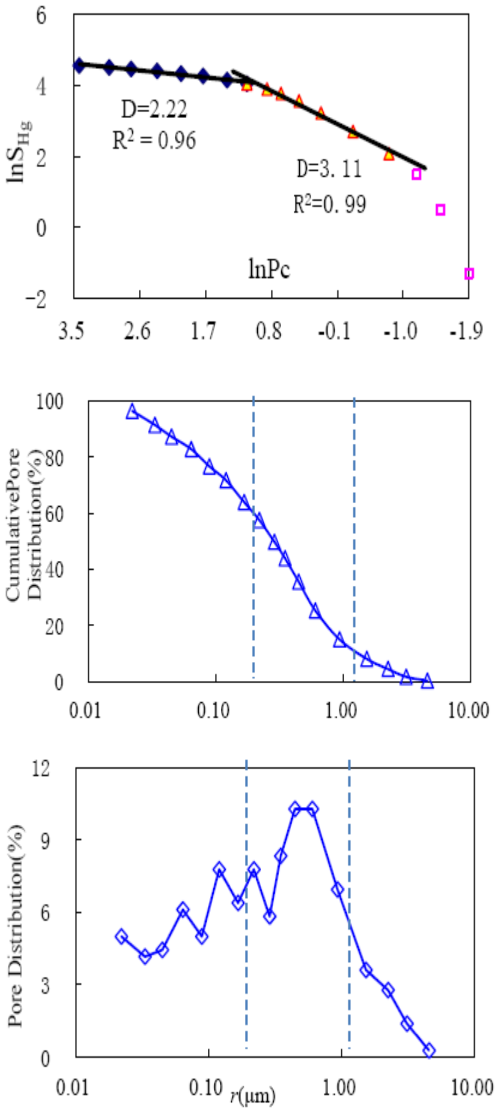


Fig. 4: Comprehensive analyses of the pore structure of Core 11

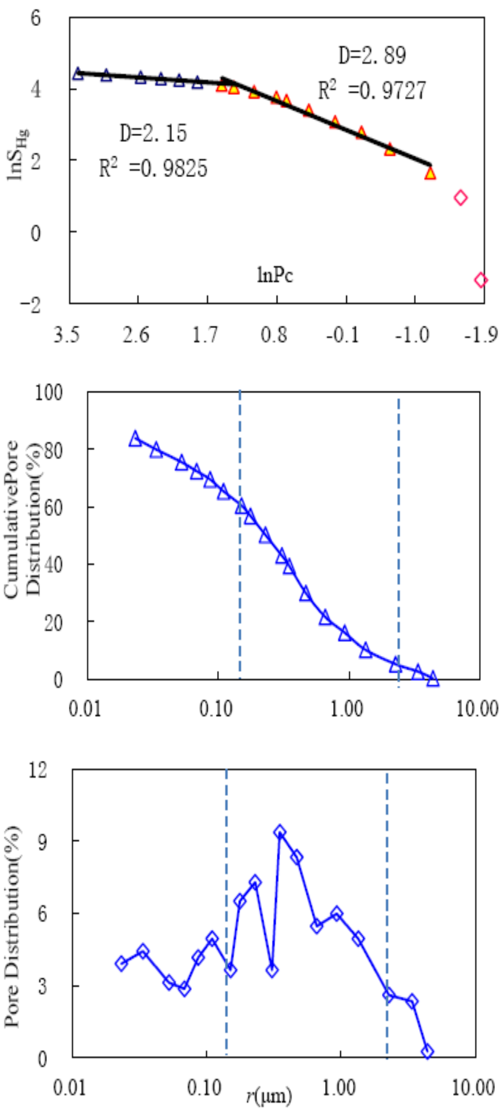


Fig. 5: Comprehensive analyses of the pore structure of Core 15

Based on the above analyses for Fig. 4 and Fig. 5, by comparison with cores of medium or high permeability cores, the following results could be achieved:

(1) The low permeability reservoirs have a more complicated pore structure than that with medium or high permeability. The two-section line fitting method can achieve satisfactory results for log-log curves of $S_{Hg} \sim P_c$. The variance of the acquired fractal dimensions is larger than that of medium or high permeability cores.

(2) The cumulative fractal pores of both #11 and #15 take more than 90% of the total pore space, so it is obviously higher than that of the medium or high permeability cores. This indicates the feasibility of fractal theory to describe the complicated pore structure of low permeability reservoirs.

The low permeability reservoir is typical of the fluid flow characteristics as Fig. 6 [13]. When the pressure gradient reaches the value at point “a” the fluid begins flowing; However only after the pressure gradient reaches the highest value at point “b” the Darcy flow appears; the fluid flowing represented by arc “ad” has non-linear characteristics; the point “d” as a critical value from non-linear stage to linear stage defines two different flow regimes which reflect two laws of fluid flowing through porous media.

Hence, for core #11 and #15 the fractal characteristics of the one loop of capillary pressure curves can be explained in the way that there is small movable fluid saturation and the fluid membrane on inside wall of pores have significant effect on the flowing process where the trigger pressure gradient exists, see Fig. 6. In the non-linear flowing area within arc “ad”, along with the continual incremental pressure gradient the fluid membrane on inside walls of pores is becoming thinner while more pores, especially more micro pores are accessible to flowing fluid; this process is corresponding to the linear segment of log-log curve of $S_{Hg} \sim P_c$ which present the big size of pores; hence the fractal dimension of the linear segment of log-log curve of $S_{Hg} \sim P_c$ could also be an indication of the complexity of such non-linear flowing characteristics. According to the log-log correlations of $S_{Hg} \sim P_c$, the fractal dimension of linear segment after the first segment tends to become less. Thus the variance of fractal dimensions not only represents the heterogeneous distribution of pores but also the non-linear fluid flowing extent through porous media.

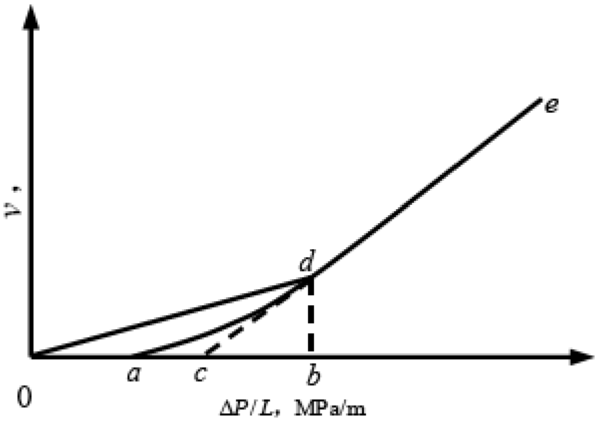


Fig. 6: Non-linear fluid flowing characteristic curve in the low permeability reservoir

5. Conclusions

The capillary pressure curves measured by MIP and the casting thin sections images scanned by SEM were combined to analyze the correlation between fractal dimension spectrum of pores distribution and reservoir physical properties & inside non-linear fluid flowing features for low permeability reservoirs. The summary is listed as follows:

(1) The reservoir of Fuyang are typical of small pores, micro throats, high ratio of pore-throat and small coordination number of pores, which manifests in the mercury intrusion experiments the low mercury withdrawal efficiency always with no or little mercury withdrawn during the initial stage; such type of pore structure tends to have low initial oil saturation and cause great resistance to fluid flowing.

(2) The two linear sections fitting method can match the log-log correlation of $S_{Hg} \sim P_c$ to a satisfactory degree for low permeability reservoirs where there is a bigger variance of fractal dimensions between two

portions of pores with different sizes than mediate or high permeability reservoirs; the larger difference of the fractal dimensions between the two portions of pores, the greater heterogeneous distribution and then the poorer reservoir physical properties.

(3) The low permeability reservoir is represented by high complexity of pore structures while the fractal pores take the majority, which indicates its adaptability to quantitative lineation of these reservoirs.

(4) The low permeability cores present non-linear characteristics of v～△p/L while its fractal dimension is bigger than that of the linear flowing part; thus the fractal dimension shall be a significant measure of the non-linear fluid flowing.

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