CSCanada
Advances in Petroleum Exploration and Development
Vol. 7, No. 1, 2014, pp. 7-12
DOI:10.3968/j.aped.1925543820140701.1516

ISSN 1925-542X [Print]
ISSN 1925-5438 [Online]
www.cscanada.net
www.cscanada.org

The Relationship of Ultra-Low Permeability Sandstone Aspect Ratio With Porosity, Permeability

WEI Haoguang[a],*; MA Kun[b]; YUE Xiang'an[c]; WANG Xinxin[d]

[a]SINOPEC Research Institute of Petroleum Engineering, Beijing, China.
[b]China National Software & Service Co., Ltd., Beijing, China.
[c]MOE Key Laboratory of Petroleum Engineering in China University of Petroleum, Beijing, China.
[d]Engineering Technology Bureau, Jilin Oilfield Company, Songyuan Jilin, China.
*Corresponding author.

Received 6 September 2013; accepted 28 January 2014

Abstract

The ultra-low permeability sandstone reservoir has large aspect ratio which significantly influences the multi-phase percolation characteristic. The ratio could be accurately measured by rate-controlled mercury porosimetry, but the testing technology is expensive, time-consuming and core-contaminating. There is not a simple effective method to describe the aspect ratio. The pores of the ultra-low permeability sandstone are mainly connected by the very long narrow throats, which could be advantageously simulated by the compound capillary bundles model. The analytical expressions of porosity and permeability about major pore structure parameters are established based on the model for the tight porous media. After solving the two expressions, the relationship between aspect ratio and parameter combination of porosity, permeability is obtained for the ultra-low permeable sandstone. Then the relation is fitted in this article using many previous published rate-controlled mercury data on compact sandstone and the relevance is strong, which proves that aspect ratio of tight rock is able to be calculated with its porosity and permeability.

Key words: Ultra-low permeability sandstone; Aspect ratio; Pore; Throat; Porosity; Permeability

Wei, H. G., Ma, K., Yue, X. A., & Wang, X. X. (2014). The relationship of ultra-low permeability sandstone aspect ratio with porosity, permeability. *Advances in Petroleum Exploration and Development*, *7*(1), 7-12. Available from: URL: http://www.cscanada.net/index.php/aped/article/view/j.aped.1925543820140701.1516
DOI: http://dx.doi.org/10.3968/j.aped.1925543820140701.1516

INTRODUCTION

The porosity system distributed as an interconnected network is made up of pores and throats in all sedimentary rocks. Pores are relatively large nodes mutually connected by throats in the network. A throat is the constriction of minimal cross sectional area of a conduit connecting one pore to another[1,2]. With continued growth in the exploration and development of the ultra-low permeability (10^{-3} μm ^{2}) sandstone hydrocarbon reservoir, petroleum geoscientists and engineers are increasingly concerned with microscopic physical property and multi-phase fluid flow. The low-quality reservoir sand-rocks generally have micro throats, and aspect ratio defined as the ratio of the pore size to the throat size becomes very large. Yang *et al.*[3] have reported that well production in Daqing's peripheral oilfields is much lower than that in Changqing oilfields even though their permeabilities are approximated, and the much larger aspect ratio is one of the dominating causes.

Aspect ratio influences multi-phase fluid distribution and flow in porous media. Snap-off occurs when the acceleration of the non-wetting phase, as it passes from throat to pore, is sufficient to break the thread of non-wetting phase near the pore/throat interface. Then the phase is isolated and can only engage in flow if reconnected[4,5]. With network model simulations and microcosmic experiments, snap-off is the most pronounced mechanism of entrapping residual oil in water-wet rocks of large aspect ratio[6-8]. Lower aspect ratios suppress snap-off and capillary pressure which results in a more efficient displacement with higher relative permeabilities and lower residual saturations[9,10].

Mercury injection is the quantitative measurement method to determine the aspect ratio, and there are two experimental modes of data acquisition in mercury porosimetry. The first one, pressure-controlled mercury porosimetry gives information on throat sizes rather than on the pores behind the throats[11-13]. The aspect ratio is not capable of being measured accurately. The second, rate-controlled mercury porosimetry is based on a technique that injects mercury into a core sample at extremely low rates. Mercury successively enters into single throat and pore, and the experiment process is quasi-static. Monitoring fluctuations in mercury injection pressure can identify throat and pore[14]. However, the highest pressure of injecting mercury is just 6.2055 MPa, and the corresponding throat radius is 0.12 μm, then throats smaller than 0.12μm and pores controlled by them are not able to be measured[15]. Additionally, the two testing technologies of mercury porosimetry are expensive, time-consuming and core-contaminating. There is not a simple effective method to describe the aspect ratio.

Forecast of the aspect ratio requires the choice of (1) a simple method of measurement, (2) an effective model for converting the measurement to the ratio. Pores account for pore volume and represent capacity. Throats control permeability [2,16]. Porosity and permeability respectively reflect pore scale and throat scale, and there exist intrinsic functions between them. In comparison to directly measuring the aspect ratio with mercury porosimetry, porosity and permeability, as macro physical property, can be tested easily. Besides, petroleum geologists are accustomed to characterizing reservoir rocks with porosity and permeability instead of microscopic property parameters. So the purpose of this paper is that the mathematical relationship between aspect ratio and the macro physical property would be established with an abstract pore-throat model to describe the aspect ratio.

1. PORES AND THROATS IN ULTRA-LOW PERMEABILITY SANDSTONES

1.1 Scales of Porosity System in Ultra-Low Permeability Sandstones

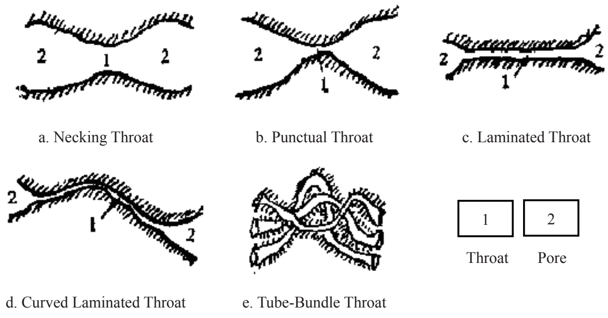
Measurement results of rate-controlled mercury porosimetry in the literatures are applied in this paper, amounting to forty-four ultra-low permeability rocks of various geologic ages and from various Chinese oilfields[17-21]. Cores depths range from 1000 to 3000 m. Permeability covers $0.1\text{-}5.46\times10^{-3}$ μm ^{2}, and porosity is 9.2%-20.1%. The average pore radius range is from 103.7 μm to 180.3 μm, and the mean throat radius range is from 0.31 μm to 2.81 μm.

These data have provided further evidence that ultra-low permeability caused by fierce diageneses powerfully decreases throat size with small pore size variation for sand-rock reservoir, which leads to higher aspect ratio. Aspect ratio extent of the compact cores is from 47.4 to 334.5.

1.2 Porosity System Feature of Ultra-Low Permeability Sandstones

Porosity system feature of sandstones is mainly subject to contact type and cementation type of the grain. There are four common throat types as follows [22]:

- Necking Throat: Compaction is very weak and cement is few. The throat is the reduced part of the pore, and both are difficult to be distinguished. Rock has great porosity and huge permeability. The aspect ratio is close to one.
- Punctual Throat: The grains are point-contact due to compaction. Throats are constricted enormously though the bodies of pores retained are still large. The rock has high porosity, low permeability and large aspect ratio.
- (Curved) Laminated Throat: When compact effect is stronger and pressure solution makes crystals regrow, the pores formed by the regrowth sides become small and keep tetrahedral or polyhedral shape. The throats connecting pores are intercrystalline clearances which are laminated or curved laminated due to the grain shape. The opening degree of laminated throats is extremely narrow and approximate to 1 μm. Laminated throat sandstones have extra-low permeability, moderate or low porosity and large aspect ratio. The contact pattern of grains contains line contact, concave-convex contact.
- Tube-bundle Throat: When the rock has enough matrix and cement, the primary intergranular pores may be completely clogged up. A large amount of micropores, as many capillary tubes, are uniformly distributed in the matrix and cement The micropores whose sizes are usually lower than 0.5 μm are not only pores but also connecting channels with suture contact and basal cement. Porosity is very low and permeability is smaller than 0.1×10^{-3} μm ^{2}. Because the pore is throat in itself, aspect ratio is 1.



a. Necking Throat b. Punctual Throat c. Laminated Throat

d. Curved Laminated Throat e. Tube-Bundle Throat

Figure 1
Throat Type[22]

Evidently punctual throat rock, laminated throat rock and tube-bundle throat rock all have bad permeability, and the three have vast difference in the storage capacity. The ultra-low permeable sandstones in section 2.1 have porosity-permeability characteristic of laminated throat rocks.

The pores of rocks may be qualitative described by means of observing the thin section, but the probability of the plane of section intercepting a throat is almost nil[2]. The pore structure of a sandstone sample (0.51×10^{-3} μm^{2}, 11.8%) is analyzed by SEM. Pores are underdeveloped, and facial porosity is small (Figure 2). It could be speculated that the pores are connected by long narrow laminated throats in the ultra-low permeable sand rocks.

Compact sandstones with lamellar throats have poor pore interconnection and very large aspect ratio.

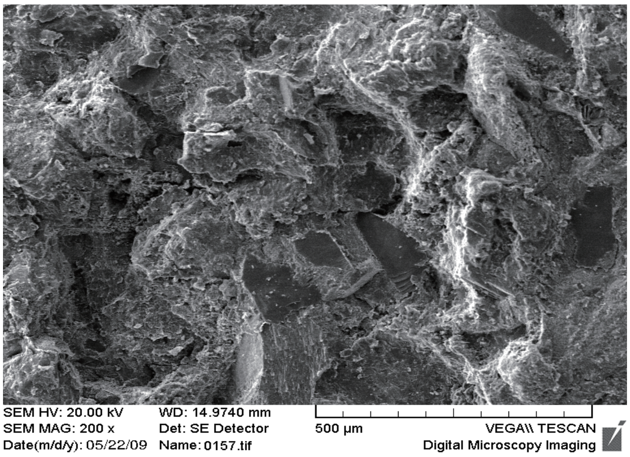


Figure 2
SEM Image of the Sandstone Sample (0.51×10^{-3} μm^2, 11.8%)

1.3 Hypothetical Rock Model

Successfully building the analytical formulas between micro structure and macro property crucially lies in choosing a reasonable hypothetical rock model, which not only simulates validly the porosity system feature of ultra-low permeability rocks but also is able to be used in analytic computation.

The shape of porosity system is very complex. To research the physical property of reservoir rocks, several kinds of hypothetical rock model have been established. Expressions of porosity, permeability could be derived on the basis of these models[23,24], such as: network model, truncated cone model, capillary bundle model, compound capillary bundle model and so on.

The fluid seepage characteristics in porous media are simulated by computer technology and with network model which has been greatly developed since 1956[25]. Compared to numerical simulation, application of analytic calculation method is much fewer. Based on the remaining three, solving analytic equations about the rock property is feasible. Truncated cone model is very analogous to the necking throat and punctual throat. Capillary bundle model possesses simple composition. The model is very analogous to the necking throat and tube-bundle throat because aspect ratio is 1. Compound capillary bundle model is comprised of unequal size capillaries in series. The model is used in this paper because the porosity system that pores are connected by the narrow long throats in the compact rock is able to be simulated advantageously, even though the real pore space differs from the tube.

2. THEORETICAL ANALYSIS

The main factors are average pore size and average throat size which are directly bound up to aspect ratio during the theoretical analysis. Many groups of rate-controlled mercury porosimetry results are used to validate the equations derived in this paper.

2.1 Relation Between Porosity and Pore Radius

In the compound capillary bundle model, a pore is joined by λ equal-length throats, which consists of a nonobjective pore-throat model. Then the volume V in the single pore-throat model is:

$$V = \pi\left(r_p^2 l_p + \lambda r_t^2 l_t\right) \tag{1}$$

Here, λ is coordination number, r_P is pore radius, r_t is throat radius, r_{Pt} is aspect ratio, l_P is pore length, and l_t is throat length. The ratio of pore length to throat length is l_{Pt}. Laminated throat is abstracted as a simple capillary tube, and volume of the hypothetical throat is equivalent to that of real throat. Then throat length in the model is much longer than its real value. Length ratio might be less than one, which will be demonstrated detailedly in section 3.4.

Then, the porosity of hypothetical rock is given by:

$$\phi = \frac{nA\pi\left(r_p^2 l_p + \lambda r_t^2 l_t\right)}{A\left(l_p + l_t\right)} = \frac{\pi n r_p^2\left(l_{pt} + \dfrac{\lambda}{r_{pt}^2}\right)}{(l_{pt}+1)} \tag{2}$$

In which A is cross area, n is area density of pore-throat. For example, to have a porosity of 20%, the density (n) of pores with 100 microns in radius has to be about of 6 million pores per square meter. Coordination number of compact sandstones is small. Equation 2 indicates that pore radius, throat radius, area density and the length ratio are related to the porosity of ultra-low permeable sandstones. To study the aspect ratio, this paper pays close attention to the radii of pore and throat. It can be found that large scale pores provide predominantly storage space (Figure 3). The minor throats have little volume in tight rocks, which means that there is little relativity between the throat dimension and the porosity (Figure 4).

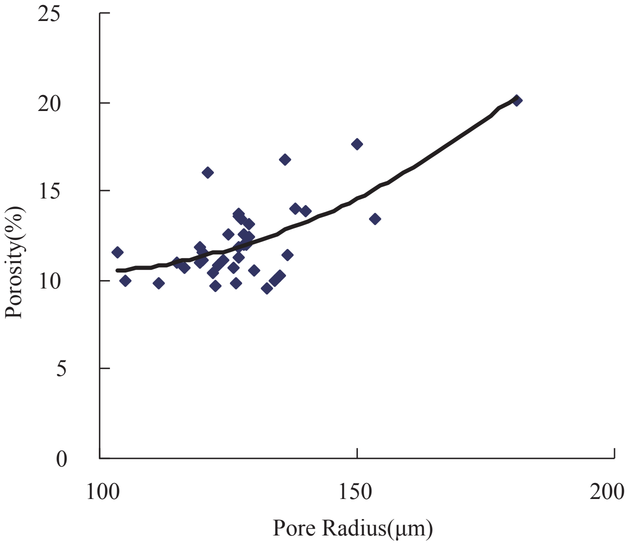


Figure 3
Porosity Versus Pore Radius

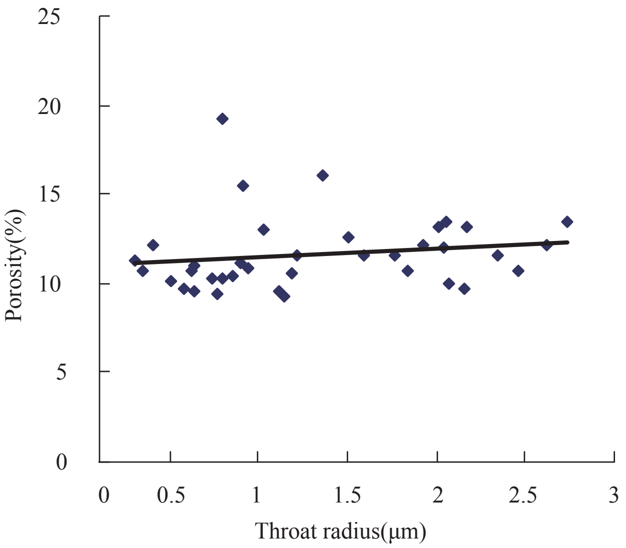


Figure 4
Porosity Versus Throat Radius

2.2 Relation Between Permeability and Throat Radius

Now apply the Poiseuille law to seek the quantity of flow (q) in a pore-throat model:

$$q = \lambda \frac{\pi r_t^4 \Delta p_t}{8\mu l_t} = \frac{\pi r_p^4 \Delta p_p}{8\mu l_p} \tag{3}$$

In which, ΔP_p, ΔP_t and ΔPsymbolize apiece the pressure differences in pore, throat and model. Viscosity is μ.The pressure relation is:

$$\Delta p_t + \Delta p_p = \Delta p \tag{4}$$

Substituting Equation 4 into Equation 3 yields:

$$q = \lambda \frac{\pi r_t^4}{8\mu l_t} \frac{r_p^4}{\left(r_p^4 + \lambda l_{pt} r_t^4\right)} \Delta p \tag{5}$$

The flow of hypothetical rock Q is obtained:

$$Q = nAq = nA\lambda \frac{\pi r_t^4}{8\mu l_t} \frac{r_p^4}{\left(r_p^4 + \lambda l_{pt} r_t^4\right)} \Delta p \tag{6}$$

While Darcy's law fluid flow in a porous media is:

$$Q = \frac{KA\Delta p}{\mu\left(l_p + l_t\right)} \tag{7}$$

Equating Equations 6 and 7, and rearranging yields the permeability formula:

$$K = \frac{\pi n \lambda r_t^4 \left(l_{pt} + 1\right)}{8\tau^2} \frac{r_p^4}{\left(r_p^4 + \lambda l_{pt} r_t^4\right)} \tag{8}$$

Where τ is defined as tortuosity factor. Data from literatures demonstrate radii of throats are two to three orders of magnitude difference to that of pores in tight porous media. The term $\lambda l_{Pt} r_t^4$ is negligible compared to the term r_P^4. Therefore, permeability of ultra-low permeable sandstone is unconcerned with the pore radius, and the factors that decide the penetration of fluids are throat traits including size, length, area density, coordinate number and tortuosity where the flow field characteristic size is crucial. Factors related to aspect ratio are investigated. Figures 5 and 6 also illustrate that throat scale rather than pore scale dominates the fluid flow ability in the compact porous media.

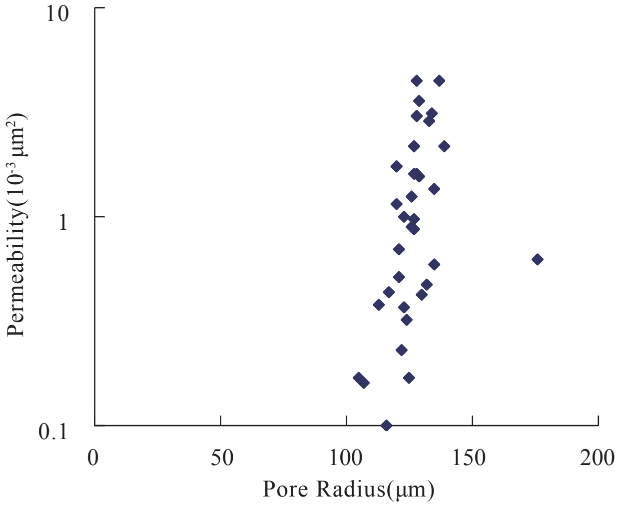


Figure 5
Permeability Versus Pore Radius

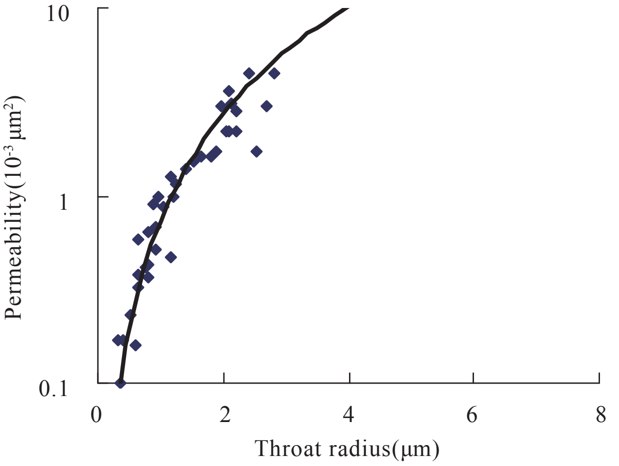


Figure 6
Permeability Versus Throat Radius

2.3 The Relationship Between Aspect Ratio and Porosity, Permeability for Ultra-Low Permeable Sandstones

Lessening the scales of pore and throat, compaction and cementation generally diminish reservoir quality.

With a combined analysis of Equations 2 and 8, elimination of the item r_t^4 yields:

$$K = \frac{\lambda}{8\pi n\tau^2} \frac{\phi^2 (l_{pt}+1)^3}{\left(r_{pt}^4 + \lambda l_{pt}\right)\left(l_{pt} + \frac{\lambda}{r_{pt}^2}\right)^2} \tag{9}$$

Rearranging Equation 9 yields:

$$\left(l_{pt} r_{pt}^2 + \lambda\right)^2 + \lambda l_{pt}\left(l_{pt} + \frac{\lambda}{r_{pt}^2}\right)^2 = \frac{\lambda (l_{pt}+1)^3}{8n\pi\tau^2} \frac{\phi^2}{K} \tag{10}$$

The aspect ratio of ultra-low permeability sandstone $\lambda l_{pt}\left(l_{pt} + \frac{\lambda}{r_{pt}^2}\right)^2$ is so large that the second item is negligible compared to the first item $\left(l_{pt} r_{pt}^2 + \lambda\right)^2$. Extraction of root gives:

$$l_{pt} r_{pt}^2 + \lambda = \frac{\lambda^{0.5}(l_{pt}+1)^{1.5}}{2\sqrt{2n\pi\tau}} \frac{\phi}{K^{0.5}} \tag{11}$$

Extracting Equation 11 and rearranging yields:

$$\frac{\phi^{0.5}}{K^{0.25}} = \sqrt{B r_{pt}^2 + C} \tag{12}$$

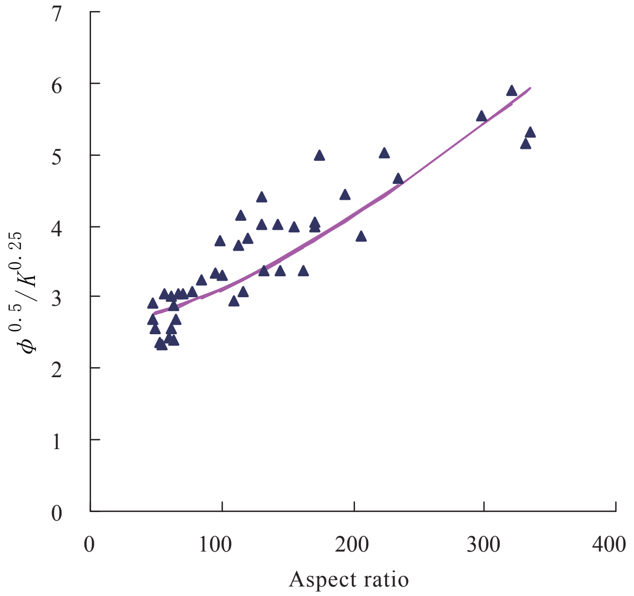


Figure 7
Aspect Ratio Versus Permeability, Porosity

Where $B = \frac{2\sqrt{2n\pi}\tau l_{pt}}{\lambda^{0.5}(l_{pt}+1)^{1.5}}$, $C = \frac{2\sqrt{2n\pi}\tau\lambda}{\lambda^{0.5}(l_{pt}+1)^{1.5}}$.

Equation 12 manifests that aspect ratio of ultra-low permeable porous media is a function of porosity, permeability. The parameters of *B* and C are constants associated with rock structure on statistical averages, and they can be determined by the experimental fitting. In this article, forty-four groups of speed-controlled mercury porosimetry data are fitted (see the red curve in Figure 7) and the fitted values of *B* and *C* are respectively 0.00025, 7.1. Then the aspect ratio of ultra-low permeability is able to be described with the following equation:

$$r_{pt} = 63.24\sqrt{\frac{\phi}{K^{0.5}} - 7.1} \tag{13}$$

Equation 13 is just used to forecast the aspect ratio for the sandstone whose permeability covers 0.1-5.46×10^{-3} μm^2, because measurement results of rate-controlled mercury porosimetry used in this paper the permeability lies in the extent. The throats of mid-high permeability rocks are big so that small aspect ratio makes item $\lambda l_{pt}\left(l_{pt} + \frac{\lambda}{r_{pt}^2}\right)^2$ is not negligible compared to item $\left(l_{pt} r_{pt}^2 + \lambda\right)^2$ in Equation 11. The two aspect ratios of mid-permeable rocks do not accord with Equation 12.

Now *B* divides by *C* to analyze the length ratio l_{Pt}.

$$\frac{B}{C} = \frac{l_{pt}}{\lambda} \tag{14}$$

Coordination number of compact sandstones is small, so the length ratio of pore to throat is much less than one. There are two typical reasons accounting for the l_{Pt} value. The throats in the compact sandstones are very long to connect the pores which are less than those in conventional rocks. Then the hypothetical pore-throat model makes throat longer, although the model describes precisely the throat radius. The real throat shape is laminated rather than tubular, which means that the length of tubular throat is lengthened to keep the throat volume invariant. However, the l_{Pt} value has nothing to do with the aspect ratio, which does not influence the derived result in this paper.

CONCLUSIONS

a. Ultra-low permeability caused by fierce diageneses decreases throat size much more than pore-body size, which leads to higher aspect ratio and moderate or low porosity. Analysis on the compact sand-rock by SEM indicates that pores underdevelop with small facial porosity and the pores just can be connected by long narrow throats.

b. Compound capillary bundle model advantageously simulates the throat feature of compact rock, even though the real pore space differs from the tube. The analytical expressions of porosity and permeability about major pore structure parameters are established. The radii of pore, throat respectively control porosity and permeability of tight rock in terms of the expressions. After solution, the relation between aspect ratio and porosity, permeability is obtained. So the aspect ratio is able to be predetermined with the relation.

REFERENCES

[1] Dullien, F. A. L. (1979). *Porous media-fluid transport and pore structure*. San Diego, California: Academic Press.

[2] Edward, L. E., David, S. B., Robert, E., *et al*. (1988). Relations between pores, throats and permeability: A petrographic/physical analysis of some carbonate grainstones and packstones. *Carbonates and Evaporites*, *3*(1), 17-32.

[3] Yang, Z. M., Zhang, Y. Z., Hao, M. Q., *et al*. (2006). Comprehensive evaluation of reservoir in low-permeability oilfields. *Acta Petroiei Sinica*, *27*(2), 64-67.

[4] Chatzis, I., Morrow, N. R., & Lim, H. T. (1983). Magnitude and detailed structure of residual oil saturation, *SPE J*, *23*(2), 311-326.

[5] Li, Y., & Wardlaw, N.C. (1986). The influence of wettability and critical pore-throat size ratio on snap-off. *Journal of Colloid and Interface Science*, *109*(2), 461-472.

[6] Mogensen, K., & Stenby, E. H. (1998). A dynamic two-phase pore-scale model of imbibition. *Transport in Porous Media*, *32*(3), 299-327.

[7] Cerepi, A., Durand, C., & Brosse, E. (2002). Pore microgeometry analysis in low-resistivity sandstone reservoirs. *Journal of Petroleum Science and Engineering*, *35*(3), 205-232.

[8] Li, Z. Q., Hou, J., Cao, X. L., *et al*. (2005). Microscopic simulation for influence of microscopic reservoir parameters on remaining oil distribution. *Acta Petroiei Sinica*, *26*(6), 69-73.

[9] Mahmud, W. M., & Nguyen, V. H. (2006). Effects of snap-off in imbibition in porous media with different spatial correlations. *Transport in Porous Media*, *64*(3), 279–300.

[10] Gao, H. M., Jiang, H. Q., & Chen, M. F. (2007). Simulation study on the effect of the microscopic parameters of reservoir pore structure on oil-water relative permeability. *Journal of Xi'an Shivou University: Nature Science Edition*, *22*(2), 56-59.

[11] León y León, C. A. (1998). New perspectives in mercury porosimetry. *Adcances in Colloid and Interface Science*, *76*, 341-372.

[12] Aguilera, R. (2002). Incorporating capillary pressure, pore throat aperture radii, height above free-water table, and winland r_{35} values on Pickett plots. *AAPG Bulletin*, *86*(4), 605-624.

[13] Teige, G. M. G., Hermanrud, C., Thomas, W. L. H., *et al*. (2005). Capillary resistance and trapping of hydrocarbons: A laboratory experiment. *Petroleum Geoscience*, *11*(2), 125-129.

[14] Yuan, H. H., & Swanson, B. F. (1989). Resolving pore-space statistics and capillary by rate controlled porosimetry. *Society of Petroleum Engineers Formation Evaluation*, *4*(1), 17-24.

[15] Wang, R. F., Shen, P. P., Song, Z. Q., *et al*. (2009). Characteristics of micro-pore throat in ultra-low permeability sandstone reservoir. *Acta Petroiei Sinica*, *30*(4), 560-563, 569.

[16] Nelson, P. H. (2009). Pore-throat sizes in sandstones, tight sandstones, and shales. *AAPG Bulletin*, *93*(3), 329-340.

[17] Wang, R. F. (2007). *Research on microcosmic characteristics and quality evolution in low permeability sandstone reservoir* (Doctoral dissertation). Northwest University, China.

[18] Xie, W. (2008). *A study on micro-pore structure and infiltrating mechanism of Chang-8 reservoir in Qingyang area Xifeng oilfield* (Doctoral dissertation). Northwest University, China.

[19] Mao, C. L. (2006). *Evaluation on characteristics of deltaic front sand bodies of Gao-Tai-Zi Reservoir in Changling depression, southen Songliao basin* (Doctoral dissertation). China University of Geosciences, China.

[20] Gao, H. (2009). *Research on micro-pore structure and micro-flow mechanism of ultra-low permeability sandstone reservoir* (Doctoral dissertation). Northwest University, China.

[21] Guo, Q. (2008). *A study on micro-pore structure and infiltrating mechanism in Niuquanhu area of Santanghu oilfield as an example to Qigu group and Toutunhe group* (Doctoral dissertation). Northwest University, China.

[22] Luo, Z. T., & Wang, Y. C. (1986). *Pore structure of hydrocarbon reservoir*. Beijing: Science Press.

[23] Fatt, I. (1956). The network model of porous media I. Capillary pressure characteristics *Petroleum Transactions. AIME*, *207*(7), 144-177.

[24] Yang, Y. L., & Aplin, A. C. (1998). Influence of lithology and compaction on the pore size distribution and modelled permeability of some mudstones from the Norwegian margin. *Marine and Petroleum Geology*, *15*(2), 163-175.

[25] Chen, S., & Doolen, G. D. (1998). Lattice Boltzmann method for fluid flows. *Annual Review of Fluid Mechanics*, *30*(1), 329-364.