

Analysis of Fracture Porosity of Coalbed with NMR Experiments and Resistivity Logging Data

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Abstract—Coal bed methane (CBM) exists in the pore of coal, and the fracture of the coal seam also provides the seepage path for mining. The correct evaluation of the pore is the key to the exploration and development of coalbed methane, which is also a difficult point. In this paper, we use NMR experiments to accurately evaluate the pore structure of coal seams, and got the fracture porosity of coal seam. Because the method of NMR experiment to obtain porosity is one-sided, and its cost is also very expensive. Therefore, this paper puts forward using resistivity logging data to calculate the fracture porosity of coal seam, and then use the NMR data to correct the porosity of the resistivity calculation. Finally, we obtained the method to effectively evaluate the fracture porosity of coal seam by electrical resistivity method. At the same time, we also evaluated that whether the Archie is applicable in the coal seam. The results showed that the T_2 chart of the area clearly showed two peaks, and the matrix pores accounted for more than 85% of the total porosity. And the porosity calculated by Archie method largely reflects the fracture porosity of coalbed.

Keywords- coal bed ; porosity; NMR experiment; resistivity

I. INTRODUCTION

Coal seam is a kind of typical dual pore structure of rock composed by pore and fracture, its porosity is the adsorption space of coal-bed methane (CBM), the fracture plays an important role in CBM migration and mining^[1]. As an important reservoir parameter of coal reservoir, the effective evaluation of porosity is significant to coal mining, coal mine safety production and coal chemical industry and the correct identify of the physical parameters such as pore structure is also important to the development and exploration of CBM^[2].

The current methods to get porosity of coal seam is mainly measured by experiments, including helium^[3], liquid nitrogen, true relative density, weighing by saturated water, mercury injection^[4], NMR experiment^[5] and X-CT technology^[6,7]. The weighing by saturated water method and true visual density has relatively larger error. The mercury injection and liquid nitrogen will damage the original structure of coal sample in measuring porosity, cause measurement error. X-CT technology can not distinguish pore diameter distribution scope of coal samples. As a kind of new technology, nuclear magnetic resonance (NMR) can provide accurate physical parameters, including total porosity, effective porosity, permeability and irreducible water saturation, etc. It can also

be used to analyze the pore structure and the pore throat of reservoir and pore diameter distribution. Meanwhile, NMR experiment will not destroy the original structure, so the measured physical parameters are more accurate^[8]. Because of the fragility of coal, the measured porosity in experiment always has the problems of coring difficulty and measurement inaccuracy, and it can only get the porosity parameter of fixed coal sample at a single depth point. So, it needs a method that can directly make use of logging data to evaluate porosity in the exploration and development of coal bed methane.

Logging method can effectively and conveniently evaluate the porosity of reservoir in sand-mudstone reservoir. However, due to the complex composition and structure of coal reservoir, the common logging such as CNL, AC and DEN have large error in calculating the porosity. And these methods can only obtain the total porosity but not to get porosity of fracture. Resistivity data can effectively evaluate the porosity of sandstone^[9,10]. We always use Archie formula to obtain the total porosity of reservoir and the deep-shallow resistivity method to evaluate fracture porosity of reservoir accurately. So this paper begins with a foundation of the nuclear magnetic resonance (NMR) technology that analyzes coal seam pore structure. Then we analyze the applicability of Archie formula on coal seam evaluation. Finally, we get the fracture porosity of coal seam effectively using the log resistivity reading, which is corrected by the nuclear magnetic data.

II. USE NUCLEAR MAGNETIC RESONANCE (NMR) COAL RESERVOIR POROSITY ANALYSIS

First, NMR experiment adopts low magnetic field intensity, which not only shield nuclear magnetic signal of ¹³C nucleus and H nucleus of coal body skeleton, but only reflects H nuclear signal of water in the pore. And due to H nuclear of water in the pore transverse relaxation time (T_2) is proportional to the rock pore diameter—the larger of the pores, the longer the T_2 and the smaller of pore diameter, the shorter of the T_2 ^[11,12].

From the nuclear magnetic resonance (NMR) experiment about 17 wells of saturated water coal sample of FZ area in QS basin, china, it can be found that the selected coal samples are similar in T_2 spectrum shape. As shown in Figure I, different point represents the porosity of different pore diameter of T_2 value. The sum of all porosity components of T_2 values is the

total porosity. The T_2 spectrum shows obvious bimodal pattern. Left forward is most development, which mainly reflects the adsorption porosity, and the T_2 value of its peak is mainly distributed between 1~3 ms; right peak is significantly smaller than left peak, mainly reflects the development of the fracture, and its T_2 value of peak is mainly distributed between 30~70 ms; It can be seen that the coal adsorption porosity of this area accounts for the most part of total porosity, about 85% and above, while the fracture pore is smaller, accounting for less than 15% basically. Meanwhile, there is obvious discontinuous between the peak of this two kinds of pore, which indicates the connectivity between the two types of pore is poor.

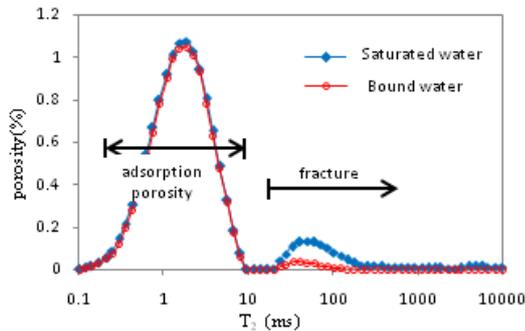


FIGURE I. A TYPICAL T_2 SPECTRUM AND PORE DISTRIBUTION OF THE REGION

The NMR T_2 spectrum still showed a bimodal structure after centrifugal experiment. The change of left peak of T_2 spectrum is smaller in the centrifugal experiment, which shows that the connectivity of the adsorption pore is poor. And the right peak of T_2 spectrum decreased significantly. It shows that the connectivity of large holes is good, which is good for the migration of fluids, but there still exist litter bound water.

By analyzing the T_2 spectrum, in the area, the adsorption porosity of coal is very large, CBM has sufficient adsorption space. Fracture provides seepage channels for migration and production of CBM, and the porosity directly affect the capacity of the CBM development. Therefore, the correct evaluation of fracture is very important.

III. RESISTIVITY ANALYSIS OF FRACTURE POROSITY OF COALBED

A. Archie Method

Archie formula is the classic formula to evaluate the relation of sandstone reservoir formation resistivity, porosity and water saturation^[13]. Porosity can be calculated by Archie formula as,

$$\Phi_a = (a * R_w / R_0)^{1/m} \quad (1)$$

Because the CBM is in adsorption state, the pore of coal seam is filled with water. We can assume that water saturation of flushed zone is 100% and use resistivity of flushed zone to calculate porosity, therefore, Eq.(1) can be turned as,

$$\Phi_a = (a * R_\theta / R_{rxo})^{1/m} \quad (2)$$

$$\frac{1}{R_\theta} = \frac{V_w}{R_w} + \frac{V_{mf}}{R_{mf}} \quad (3)$$

where R_{rxo} represents resistivity of flushed zone; V_w and V_{mf} represent the relative volume of stratum water and mud filtrate in receptivity; R_θ represents the relative resistivity of coal seam contained both stratum water and mud filtrate; R_w, R_{mf} represent the resistivity of stratum water and mud filtrate respectively.

In order to accurately get the electrical parameters, we carry on rock resistivity experiments of coal samples of this area. In the experiments, water temperature for soaking coal sample is constant at 20 °C, its degree of mineralization is 5000mg/L, and the resistivity is 1.177Ω.m. Through litho-electric experiment, we obtain the cross-plot of coal seam Formation resistivity factor (F) and porosity (Φ), as shown in Figure II.

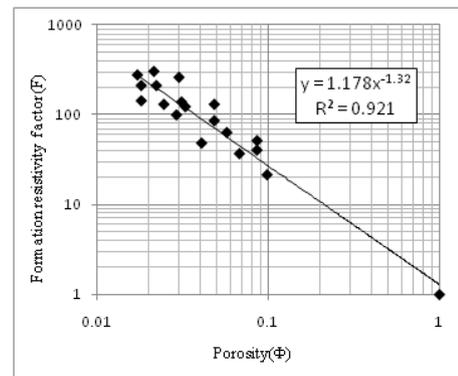


FIGURE II. THE RELATION OF STRATUM FACTORS AND POROSITY

It can be obtained from the litho-electric experiment analysis, Cementation factor (m) of coal seam in this area is low, around 1.32. Tortuosity factor (a) is around 1.178.

Taking cementation factor which obtained by litho-electric experiment into Archie formula to calculate porosity of coal seam. The porosity calculated by Archie formula is much smaller than the total porosity obtained by nuclear magnetic experiment, and they have a certain correlation. In resistivity logging, current is transmitted mainly through fracture, In addition, there may be some adsorption pore which are not connected with fracture, and their contributions to conductive process is very small, so it can be considered that the main contribution factor to conduction is the moisture in fracture, and cause the porosity calculated by Archie method which smaller than the total porosity. However, when compared the porosity calculated by Archie method with the fracture porosity obtained by NMR experiment, the correlation of both is found to be better. And the porosity calculated by Archie method is larger than the porosity of fracture, which is likely be related to the influence hole enlargement and adsorption pore connected with fracture. This is correspondent to actual situations. Therefore, when using Archie formula to analyze

the porosity, the calculated porosity is mainly related to the fracture porosity. itself is not applicable when using Archie formula to calculate the total porosity directly. But we can use the corrected Archie formula to calculate fracture porosity value.

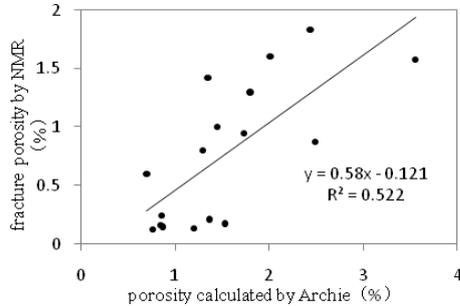


FIGURE III. COMPARISON OF POROSITY OBTAINED BY ARCHIE METHOD WITH NMR EXPERIMENT

B. Deep-Shallow Resistivity Method

In deep-shallow resistivity logging, the measured resistivity may be regarded as the result of the three parts in parallel, including skeleton, the adsorption porosity and fracture porosity.

CBM is in adsorption state in the native state. The pore can be thought to be filled with water, and water saturation is assumed to be 100%. Therefore, the resistivity of porosity part can be equivalent to resistivity of formation water in deep resistivity logging. Mud filtrate displaces the original formation water of fracture porosity in the flushed zone. Therefore, fracture porosity in the flushed zone should be equivalent to the mud filtrate resistivity. And according to Archie formula, we can get the equation as,

$$\frac{1}{R_s} = \frac{V_{ma}}{R_{ma}} + \frac{V_b}{R_w} + \frac{\Phi_f^{fm}}{R_{mf}} \quad (4)$$

$$\frac{1}{R_t} = \frac{V_{ma}}{R_{ma}} + \frac{V_b}{R_w} + \frac{\Phi_f^{fm}}{R_w} \quad (5)$$

where R_s and R_t represent shallow and deep resistivity, V_{ma} represents the relative volume of skeleton, V_b represents the relative volume of adsorption porosity. Φ_f is the fracture porosity, R_{ma} , R_w , R_{mf} respectively represent resistivity of skeleton, stratum water and mud filtrate. 'fm' is the bond index of fracture porosity. When default the pore model, it can be calculated by iteration method.

We can get fracture porosity by Eq.(4)and Eq.(5) as,

$$\Phi_f = \left(\frac{1/R_t - 1/R_s}{1/R_w - 1/R_{mf}} \right)^{\frac{1}{fm}} \quad (6)$$

We obtain the fracture porosity calculated by dual laterolog with the actual resistivity data of QS basin, and compare with fracture porosity obtained by NMR experiments, as shown in Figure IV.

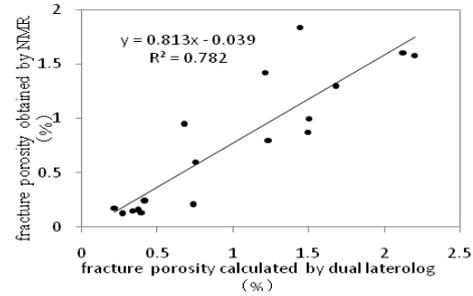


FIGURE IV. COMPARISON OF POROSITY OBTAINED BY DUAL LATEROLOG WITH NMR EXPERIMENT

The results show that fracture porosity calculated by deep-shallow resistivity has good correlation to fracture porosity of NMR experiment. But as a whole, the calculated value is larger .

C. Contrastive Analysis

Compared two methods of calculating porosity, it is found that the fracture porosity calculated by two resistivity methods has good consistency, as shown in Figure V. Both methods can effectively calculate fracture porosity.

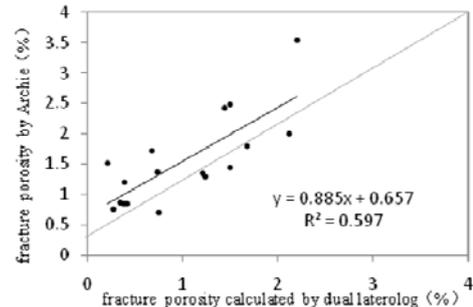


FIGURE V. COMPARISON OF CALCULATED POROSITY BY TWO KINDS OF RESISTIVITY METHOD

Fracture porosity calculated by two resistivity methods both have certain error with fracture porosity measured by NMR experiment. It may cause by the serious hole enlargement existed in the coal seam. When the hole diameter become bigger, its borehole collapse section is filled with mud. It cause smaller measured reading, and the calculated porosity is larger than the actual value. Archie method is using the resistivity of flushed zone to calculate porosity, so may be more seriously affected by hole enlargement. By contrast, the calculation result of deep-shallow resistivity is more accurate, meanwhile, the resistivity measured by instrument will be affected by surrounding bed and it has a lot of dirt bands in the coal seam, which is equivalent to thin layers, it will affect the measured resistivity readings.

Due to the certain error in the fracture porosity calculated by resistivity and NMR experiment, we can use nuclear

magnetic fracture porosity as a benchmark to further correct the fracture porosity calculated by two kinds of resistivity. The correction formula of fracture porosity calculated by resistivity method as,

$$\Phi_{fa} = \alpha_1 \Phi_a + \beta_1 \quad (7)$$

$$\Phi_{ff} = \alpha_2 \Phi_f + \beta_2 \quad (8)$$

where Φ_{fa} , Φ_f represent the corrected value of fracture porosity calculated by Archie and deep-shallow resistivity, respectively; α_1 , α_2 are the correction coefficient, and the values are different in different areas. In view of FZ area in QS basin, we determine the correction factor through calculation, and get correction formula of fracture porosity calculated by the resistivity of this area.

$$\Phi_{fa} = 0.58 * \Phi_a - 0.121 \quad (9)$$

$$\Phi_{ff} = 0.813 * \Phi_f - 0.039 \quad (10)$$

D. Applications

In order to verify the application effects of two kinds of resistivity methods in the practical logging data interpretation, this paper uses two methods to analyze and process the HG 31-2 well of FZ area in QS basin. The result is shown as in Figure VI.

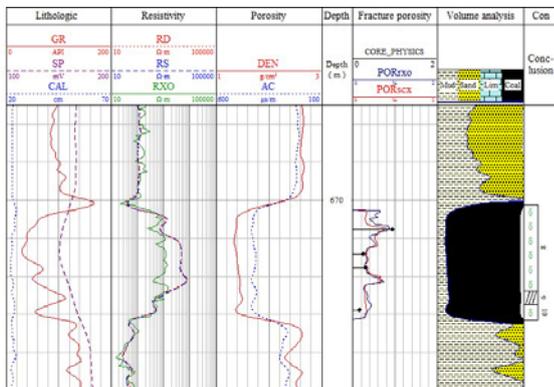


FIGURE VI. PROCESSING RESULT OF HG31-2 WELL OF FZAREA IN QS BASIN

In Figure VI, PORrxo, PORsxo respectively indicate the two fracture porosities calculated by Archie and deep-shallow resistivity methods. It can be found that the hole enlargement of this well is smaller, the curves' form of fracture porosity obtained by two kinds of resistivity methods is consistent, which is in conformity with the core data and can accurately evaluate the fracture porosity. On the top and bottom of coal seam, the curves have a certain deviation, and the possible cause may be the resistivity measured reading influenced by roof and floor board.

IV. CONCLUSION

- Through NMR experiments we can find that the coal pore in this area is given priority to adsorption pore, and CBM has sufficient adsorption space.
- Cementation factor of coal seam is relatively lower. Meanwhile, Archie formula itself is not applicable in the evaluation of coal seam, but the calculated porosity can greatly reflect fracture porosity which can through correction to analyze.
- Compared with the Archie method, the fracture porosity calculated by deep-shallow resistivity method is more accurate.

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REFERENCES

- [1] Zhang,H., 2001.Genetical type of pores in coal reservoir and its research significance. Journal of China Coal Society, (01): 40-44.
- [2] Guo,D.Y., Li, C.J., Zhang,Y.Y.,2012. Contrast Study on Porosity and Permeability of Tectonically Deformed Coal and Indigenous Coal in Pingdingshan Mining Area, China. Editorial Committee of Earth Science-Journal of China University of Geosciences, (11): 1500-1506.
- [3] Hou,R.Y., 1996.The feature and Measurement Methods of Porosity and Relative Permeability of Coal Reservoir .Experimental Petroleum Geology ,18(3):331-335.
- [4] Qi,L.L.,Wang,Z.F.,Yang,H.M.,2012.Study on Porosity of Coal Samples Based on Low Temperature Nitrogen Adsorption Method and Mercury Porosimetry, Coal Science and Technology ,40 (8) :36-39.
- [5] Pang,Y.S., Tang,J.P.,Li,C.Q., 2008.NMRI test on two-phase transport of gas-water in coal seam. Chinese Journal of Geophysics, 51 (5) :1620-1626.
- [6] Guo, R., Kantzas, A., 2007. Coal Characterization in CBM/ECBM Processes Using X-ray CT Analysis. Annual Meeting.
- [7] Yao,Y.B., Liu,D.M., Cai,Y.D., et al.,2010.Advanced characterization of pores and fractures in coals by nuclear magnetic resonance and X-ray computed tomography. Sci China Earth Sci, 40 (11): 1598-1607.
- [8] Ge, X. M., Fan,Y.R.,Zhu,X.J.,Chen,Y.G.,Li,R.Z.,2015. Determination of NMR T₂ cutoff value based on multifractal theory-An application in sandstone with complex pore structure. Geophysics,80 (1): D11- D21.
- [9] Li, N., 1989.General Forms of The Resistivity-Porosity and Resistivity-Oil/Gas Saturation Relations, as well as The Determination of Their Optimum Approximating Function Types (I). Chinese Journal of Geophysics, 32 (5): 580-592.
- [10] Pal, P. K., Suman, P., Chatterjee, R.,2015. Estimation of In-situ Stress and Coal Bed Methane Potential of Coal Seams from Analysis of Well Logs, Ground Mapping and Laboratory Data in Central Part of Jharia Coalfield-An Overview [J]. Springer International Publishing, 143-173.
- [11] Ge, X. M., Fan, Y. R., Cao, Y. C., Xu, Y. J., Liu, X., Chen, Y. G., 2014.Reservoir Pore Structure Classification Technology of Carbonate Rock Based on NMR T₂ Spectrum Decomposition. Applied Magnetic Resonance. 45 (2):155-167.
- [12] Xie, S. B., Yao, Y. B., Chen, J. Y., et al, 2015. Research of micro-pore structure in coal reservoir using low-field NMR [J]. Journal of China Coal Society. 40 (S1): 170-176.
- [13] Archie GE., 1942. The electrical resistivity log as an aid in determining some reservoir characteristics. Trans Am Inst Mining Metallurg Eng 146: 54-61