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Analysis and Research on Influencing Factors of Coal Reservoir Permeability

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ANALYSIS AND RESEARCH ON INFLUENCING FACTORS OF COAL RESERVOIR PERMEABILITY

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ABSTRACT: The permeability of coal is an important parameter in the theory of coal reservoir gas flow. Experiments have demonstrated that after the coal matrix adsorbs gas, adsorption swelling deformation will occur and when gas desorbs from coal matrix, it undergoes a shrinkage deformation. A new formula for estimating permeability is developed. By considering the adsorption swelling and desorption shrinkage deformation in this formula for permeability, the effect of coal matrix swelling and shrinkage on coal reservoir permeability is studied. The study shows that, as gas in the coal reservoir desorbs, gas pressure decreases and the coal matrix shrinks, so as to make swelling deformation smaller and increase the permeability of the coal reservoir. In addition, the influence of effective stress, Klinkenberg effects, burial depth and natural fracture on coal reservoir permeability is analyzed. The analysis and research is of significance to coal mine gas disaster prevention and coal bed methane gas resource development.

INTRODUCTION

The permeability of coal is an important parameter in the theory of coal reservoir gas flow. Many gas dynamic phenomena, such as coal and gas outburst, emission etc, are dependent coal reservoir permeability during exploitation. In this paper the effect of coal matrix swelling and shrinkage on coal reservoir permeability is studied by considering adsorption swelling and desorption shrinkage deformation in a new formula for estimating permeability. The influence of effective stress, Klinkenberg effects, burial depth and natural fracture on coal reservoir permeability is also analysed.

FACTORS INFLUENCING COAL RESERVOIR PERMEABILITY

Shrinkage effects of coal matrix

Many experiments have demonstrated that after the coal matrix adsorbs gas, adsorption swelling deformation will occur and when gas desorbs from the coal matrix, it undergoes a shrinkage deformation (Reucroft P J,Patel H, 1986; Seidle J P, Huitt L G, 1995; Levine J R, 1996). In the process of coal production the equilibrium of the original stress field and the original gas pressure field is disturbed, which lead to a stress redistribution near the mining space and results in gas flow. When the gas pressure falls below the critical desorption pressure, gas starts to desorp. With the decrease of pore pressure, gas desorption and micro-porous surface free energy increase, which results in the coal matrix shrinking and enhanced permeability of coal reservoir.

The increase of coal porosity will lead to the change of the permeability of coal and this affects gas seepage in the coal reservoir. According to the Kozeny-Carman equation, the change of permeability with porosity, φ, can be expressed as (Lu Ping et al., 2002)

$$k = \frac{\varphi}{k_z S_p^2} = \frac{\varphi^3}{k_z S_V{}^2} \tag{1}$$

where k_z is a dimensionless constant, S_V is the pore surface area in a unit volume of porous media, S_p is pore surface area in a unit pore volume of porous media.

In equation (1) the relation between porosity and adsorption swelling deformation can be expressed as (Li Xiangchun et al., 2005)

$$\varphi = \frac{\varphi_0 + \varepsilon_V - \varepsilon_P}{1 + \varepsilon_V} \tag{2}$$

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where φ_0 is original porosity in the coal reservoir, ε_V is the volumetric strain due to stress change , ε_P is the volumetric strain due to adsorption swelling, which can be expressed as (He Xueqiu et al., 1996)

$$\varepsilon_p = \frac{ak_c RT}{V_0}\ln(1+bp) \tag{3}$$

where k_c is a proportion constant, V_0 is the volume of the mole of gas at STP, R is the gas constant, a , b are adsorption constants, T is the absolute temperature, p is the gas pressure in the coal reservoir.

Because adsorption of coal particles and molecular scale pore volume is not changed by the total stress, in the process of the change of the coal stress and strain it can be regarded that pore surface area of unit pore volume of porous media is constant (Lu Ping et al., 2002). It can be known from equation (1) that the change of coal permeability is mainly caused by the change of porosity. Substituting equation (2) into equation (1), the relation between permeability and adsorption swelling deformation can be expressed as

$$k = \frac{k_0}{1+\varepsilon_V}\left(1+\frac{\varepsilon_V-\varepsilon_P}{\varphi_0}\right)^3 \tag{4}$$

where k_0 is original permeability in the coal reservoir.

It can be seen from equation (3) and equation (4) that as coal seam methane desorption pore pressure decreases and coal matrix shrinks, it will in turn lead to adsorption swelling deformation decrease and permeability increase. For the same coal sample and under the same conditions the more gas adsorbs, the greater the adsorption swelling deformation and the lower the coal permeability. The reason is that coal permeability is only related to the mesoporous, macroporous and fracture. When the swelling deformation of coal can not be generated along the outward direction under confined pressure the adsorption swelling deformation in micro-cracks and micro-pores will develop along the inward direction. Thus, the pore volume will decrease and gas flow is affected. In addition, adsorption gas will occupy parts of gas channel which, results in pore cross section decrease and coal permeability lower.

2.2 Klinkenberg effects

The important difference between the gas flow and the liquid flow in porous media is the phenomenon of gas slippage in solid walls. The essence of slippage is that because the gas molecular mean free path is equivalent to fluid field characteristic scale, the fluid molecules interact with the capillary wall which results in gas molecules slip along the porous surface and molecular velocity increase. For different materials the physical process is different, such as fluid surface adsorption, evaporation after gas condensates on the surface. In the seepage mechanics the interaction between the gas molecules and solid molecular is known as Klinkenberg effects (Klinkenberg L J, 1941). The permeability formula is (Joachim Gross, et al, 2003)

$$k_r = k_a\left(1+\frac{b_s}{p_m}\right) \tag{5}$$

where k_r is relative permeability, k_a is absolute permeability, p_m is gas mean pressure, b_s is a slippage factor, which can be expressed as (Joachim Gross, et al, 2003)

$$b_s = \frac{4c}{r}\lambda p_m \tag{6}$$

where c is a proportion factor, r is the mean radius of a pore, λ is the gas molecular mean free path, which can be expressed as (Joachim Gross, et al, 2003)

$$\lambda = \frac{k_b T}{\sqrt{2}\pi d^2 p_m} \tag{7}$$

where k_b is Boltzmann's gas constant, d is the molecular diameter, T is the absolute temperature.

It can be seen from equation (5) that the permeability increment caused by Klinkenberg effects is (Joachim Gross, et al, 2003)

$$k_{slippage} = k_0 b_s / p_m \tag{8}$$

Because of the existence of Klinkenberg effect, coal reservoir permeability will increase. The experiment research on aerosol permeability shows that the permeability increases with the decrease of porous fluid pressure (Joachim Gross, et al, 2003). The phenomenon of the experiment can be explained by Klinkenberg model. In general, coal seam methane flow in cleat can be described by Darcy seepage equation in which a stagnant gas layer near fracture wall is assumed. But under low pressure the gas layer will slip which result in higher actual gas production than the calculated value by equation. According to adsorption isotherm, the lower the gas pressures in coal reservoir the more coal seam methane desorption and production caused by per pressure decrease. Thus, with gas pressure in coal reservoir decreases Klinkenberg effect will have much influence on coal bed methane desorption and production.

2.3 Effective stress

The relation between the pore fluid pressure and rock skeleton deformation is based on the principle of effective stress, which was developed by Terzaghi. A simple effective stress formula can be expressed as

$$\sigma_{ij} = \sigma'_{ij} + p\delta_{ij} \tag{9}$$

where σ_{ij} is total stress, σ'_{ij} is the effective stress, p is the pore pressure, δ_{ij} is the Kronecker Delta symbol.

A simple relation formula is reflected by the above effective stress formula among the pore pressure, the total stress and the effective stress. The important significance of the simple relation formula is that the study on the complex deformation of the porous media is equivalent to the study on no pore equivalent deformation under effective stress. The increase of effective stress can lead to fracture width decrease, pore closure and the permeability drop. Somerton (1975) established the relation between permeability k and effective stress σ'_{ij} by experiment research, which can be expressed as

$$k = 1.03 \times 10^{-0.31\sigma'_{ij}} \tag{10}$$

It can be known from equations (10) that there is a power function relation between the effective stress and permeability. The permeability will decrease with effective stress increase.

Another formula is given by Mckee et al. (1987).

$$k = k_0 \cdot e^{-3C_p \Delta\sigma} \tag{11}$$

where $\Delta\sigma$ is effective stress increment, C_p is pore volume compressibility coefficient.

It can be seen from equation (9) that during gas exploitation effective stress increases as pore pressure decreases. It can be seen from equation (10) and equation (11) that with effective stress increase some cleats in the coal seam will close, which results in porosity and permeability decrease. The same conclusion was gained in experiment by Jiang Deyi et al.(1997). Figure1 shows the permeability decreases with effective stress increase.

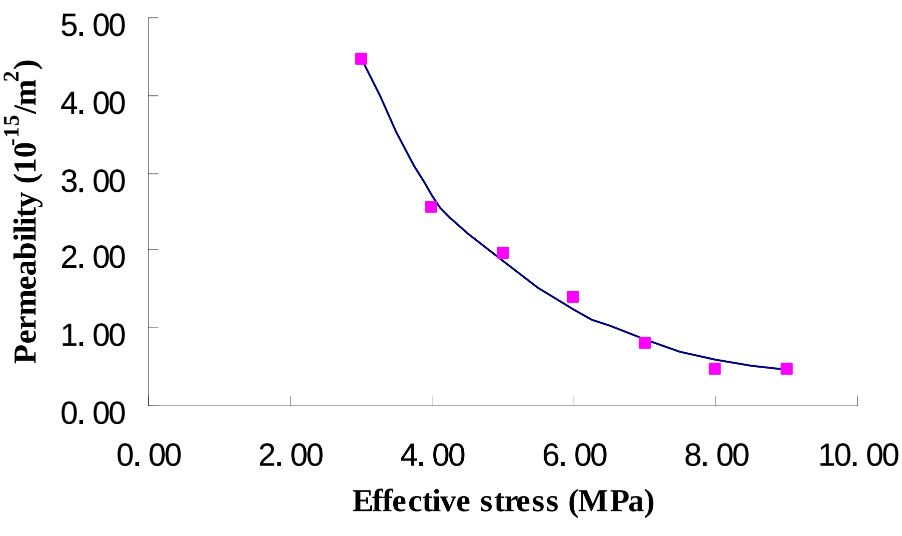

Figure1 - Relation between permeability and effective stress (Jiang Deyi et al., 1997)

2.4 Burial depth

In general, the deeper the coal reservoir is buried the smaller coal reservoir permeability becomes. The change of coal reservoir permeability with depth is a function of stress. Only when different stress environment is differentiate, the change of coal reservoir permeability with depth is analyzed. In China it is very obvious that coal reservoir permeability decreases with stress increase. The researches show that coal reservoir permeability relates to antique and contemporary stress field, structural position, coal petrography and coal rank. But the total change trend of coal reservoir permeability is that the deeper coal reservoir is buried the lower coal reservoir permeability becomes.

Ye Jianping et al. (1999) finds that the change of coal reservoir permeability with depth in different area is different. In China there are three kinds of relation between coal reservoir permeability and burial depth. First, the deeper coal reservoir is buried the smaller coal reservoir permeability becomes, such as Hongyang, Huainan, Huaibei, Qingshui, the east of Taihang hill and Hancheng. Second, the deeper coal reservoir is buried the bigger coal reservoir permeability becomes, such as Shouyang area. Third, coal reservoir permeability is not changed with the depth.

2.5 Natural fracture

Coal is a rock with porous and natural fractures, which have important influence on gas adsorption, desorption and flow. Because natural fractures are the main flow channel in coal and coal reservoir permeability is controlled by natural fractures to a large extent, in direction of fractures growth the permeability of coal reservoir is several times higher than that in the vertical direction. In theory, the growth of natural fracture of coal reservoir benefits to improve coal reservoir permeability. From 1941 to now Hydraulics is studied by fracture made by all kinds of materials by Louis, Witherspoon, Tian Kaimin, Zhang Youtian, Tao Zhenyu, et al.. In the researches the cubic law in which fractures is regarded as parallel smooth plate model is used the most frequently. The cubic law can be expressed as (Zhen Shaohe, et al., 1999)

$$q = fw^3 \qquad (12)$$

where q is seepage velocity, w is fracture width, f is coefficient.

It can be seen from equation (12) that the bigger fracture width is the easier gas flows. The permeability of coal is measured under confined pressure in laboratory. The results show that coal permeability is extremely sensitive to stress and the permeability of coal decreases sharply with confined pressure increase. When the confined pressure increases 10 times, coal permeability decreases 2-3 orders of magnitude (Zhen Shaohe, et al., 1999).

Apart from the above factors, geo-electric field, geothermal field, coal moisture content will affect the permeability of the coal reservoir also, but their effect mechanism to coal reservoir permeability is not very clear.

CONCLUSIONS

1) A new formula to estimate coal permeability was developed by considering adsorption swelling. It can be seen from analysis of this formula that as coal seam methane desorption adsorption swelling deformation decreases and coal matrix shrinks, it will in turn result in permeability increase.

2) The influence of effective stress, Klinkenberg effects, burial depth and natural fracture on coal reservoir permeability is also analyzed. The analysis and research is of significance to the prevention of gas disaster and the development of coal bed methane resource.

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