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Evaluation of the reservoir permeability of anthracite coals by geophysical logging data

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ABSTRACT

Permeability is one of the most significant reservoir parameters. It is commonly obtained by experiment, history simulation, injection/falloff well test and geophysical logging. Among these, geophysical logging remains as the most economic and efficient technique in evaluating coal permeability in the vicinity of an open-hole. In this paper, geophysical logging data are used to evaluate the coal reservoir permeability for the No. 3 coal seam in the southern Qinshui Basin (Fanzhuang and Zhengzhuang coal zones). Ideally coal reservoirs consist of coal matrix and fracture networks that can be represented by a model called *a collection of sheets*. Based on the model, coal reservoir permeability can be quantitatively calculated using the theoretical formula of $k_f = 8.50 \times 10^{-4}\, w^2 \varphi_f$, in which fracture width (w) and fracture porosity (φ_f) were obtained by dual laterolog and density logging data, respectively. Calculative results show that coal reservoir permeability ranged from 0.017 mD to 0.617 mD for the Fanzhuang coal zone and from 0.047 mD to 1.337 mD for the Zhengzhuang coal zone. The permeability decreases with coal burial depth, reflecting variations in penetration capability of coal reservoirs at varying depths. Comparing results with those from injection/falloff well tests, however, shows that the model-calculated permeability is slightly higher. This is expected because the model did not include the influence from coal anisotropy.

1. Introduction

As an alternative energy source, coalbed methane (CBM) serves as a significant supplement for conventional resources such as coal, petroleum and natural gas. In recent years, CBM exploration and development has been intensively studied globally. Some investigations have focused on the physical properties of coal reservoirs for the purpose of targeting favorable CBM development districts (Liu et al., 2009; Yao et al., 2008, 2009). Other researchers emphasized the controlling factors of CBM production and evolution (Arrey, 2004; Karacan et al., 2008; Pashin and Groshong, 1998). Evidence has shown that CBM production is affected by coal reservoir parameters such as coalbed gas content, coal reservoir permeability, coal seam thickness, critical desorption pressure, coal reservoir pressure, etc., among which the permeability is crucial to the migration and flow of CBM in coal reservoir and thus controls CBM production.

Coal reservoir permeability is obtained mainly from (a) measurements of core samples; (b) history simulation using production data; and (c) injection/falloff well test. The permeability obtained from measurements is inaccurate because it cannot represent the nature of in-place reservoir. The history-matching permeability can be acquired only at the middle or late CBM development stages, which is nearly unfeasible for coal reservoirs in China. Although the injection/falloff permeability is commonly analyzed and used in exploration, it is inconvenient to be used in CBM development wells. Moreover, the injection/falloff permeability has uncertainties when analyzing low permeable coal reservoirs, which is very common in anthracite coals. Different from the three methods mentioned above, the geophysical logging method is more economic and convenient. It can measure the coal permeability in arbitrary sites of a coal reservoir around the borehole, but it requires a reliable permeability estimation model that efficiently and accurately uses the geophysical logging data.

Geophysical logging measures the changes in the properties of coals near the borehole using electrical, magnetic, nuclear and acoustic methods (Fu et al., 2009a,b; Scholes, 1993). Many properties of coals such as natural potential, conductivity, density, radioactivity and acoustic time can be measured directly (Hou, 2000). Geophysical logging data can be used to predict coalbed gas content, estimate mechanical properties of coal, and even evaluate physical properties and petrophysical characteristics of coals such as porosity, permeability, coal moisture, ash, fixed carbon and volatile contents, etc. (Charbucinski and Nichols, 2003; Fu et al., 2009a,b; Hawkins et al., 1992; Karacan, 2009a,b; Olszewski et al., 1993; Oyler et al., 2010). Commonly, they are carried out by analyzing the correlation between the data from measurements and corresponding log responses and then establishing a relationship between them. Utilizing the relationship, the values of coal property studied can be predicted or estimated. For example, coalbed gas content shown in Fu et al.

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(2009a) used coal burial depth, resistivity and acoustic time. Most investigations focused on the qualitative estimation of coal properties. In this paper, we provide a new method that quantitatively calculates the permeability of coal reservoirs by using the logging data and a coal reservoir model called *a collection of sheets*.

2. Methodology and procedures

2.1. Coal permeability models

Coal is a heterogeneous medium with dual pore systems including the matrix pores and natural fractures. It can be divided into two parts: coal matrix and natural fracture network. In coal matrix, well-developed micro-pores provide an adsorptive space for coalbed gasses. The natural fracture network is the dominant pathway of free fluids, consisting of exogenous (mainly caused by tectonic stress) and endogenous (including face and butt cleats formed by coalification) fractures and some interconnected macro-pores. The fracture network in coals, in most cases, is saturated with formation water that cannot penetrate the coal matrix.

Fractured coal reservoirs are represented mainly by three ideal models (Reiss, 1980) including *a collection of sheets* (I), *a bundle of matchsticks* (II) and *a collection of cubes* (III). The models (II) and (III) are suitable for coal reservoirs that have a highly symmetric fracture network. However, the fracture network of coals is not always homogeneous. Endogenous fractures and face cleat are much more continuous than butt cleat and are commonly the dominant passageway of fluids. In addition, the horizontal stratifications developed in coal seams, especially in anthracite coals, may be closed by the compressive stress from overlying strata, making coal beds less conductive to fluids (Harpalani and Chen, 1997). For these reasons, the model I (Fig. 1) is appropriate for representing high-rank coals, including anthracitic coals. The formula of calculating fracture permeability for the model I is given (Hou, 2000) as:

$$k_f = 8.50 \times 10^{-4} w^2 \varphi_f \tag{1}$$

where k_f is fracture permeability (mD), i.e. coal reservoir permeability; w is fracture width (μm); and φ_f is fracture porosity.

The model I was chosen to estimate permeability in this paper.

2.2. Fracture porosity estimation by logging data

The natural fracture network porosity (referred to as fracture porosity in the paper) is defined as the ratio of fracture network volume to total bulk volume of coal. Combined with the aforementioned coal reservoir models, the effective porosity of coal is approximately equal to its fracture porosity, where the effective porosity indicates the ratio of interconnected pores-fracture volume to total bulk volume of coal. The value of effective porosity can be obtained by density logging techniques. It is performed in the vicinity of the borehole by measuring the density fluctuations of coal reservoir.

Commonly, the total bulk density of coal is a combination of coal skeleton density and fluids (including saturated water and hydrocarbon). The influence of fluids on total density is related to the coal porosity. Total density will decrease with the increase of porosity because the density of fluids is less than that of the skeleton. Thus, the porosity of coal can be recorded by the density log response. The formula calculating effective porosity can be given as:

$$\varphi_f = \frac{(\rho_b - \rho_{ma}) \times \left(\rho_{ma} - \rho_{mf}\right)}{\left(\rho_f - \rho_{ma}\right) \times \left[\left(\rho_{ma} - \rho_{mf}\right) + s_h \times \left(\rho_{mf} - \rho_h\right)\right]} \tag{2}$$

where φ_f is effective porosity (or fracture porosity); ρ_b is the density obtained directly from density log response, cm^3/g; ρ_{ma} is the density of coal skeleton, cm^3/g; ρ_{mf} indicates the density of drilling fluid, cm^3/g; S_h is residual hydrocarbon saturation in coal; ρ_h is the density of residual hydrocarbon, cm^3/g; and ρ_f stands for the total density of fluids, cm^3/g.

2.3. Fracture width estimation by logging data

A research (Sibbit and Faivre, 1985) presented methods of calculating the width of the vertical fracture in ideal coal reservoir model I by combining dual laterolog data with Archie's law (Archie, 1942). In this paper, the methods were further modified. Assuming that the radius of an open-hole CBM well is r_w (in m), the fracture width is w (in μm), and the investigation depths (in m) of deep and shallow laterolog are given as d_2 and d_1, respectively. There are several significant equations as shown in the following paragraphs.

The fracture porosity obtained from deep laterolog response is written as:

$$\varphi_{fd} = \frac{(d_2 - r_w)w}{d_2^2\pi - r_w^2\pi} = \frac{w}{\pi(d_2 + r_w)}. \tag{3}$$

The fracture porosity obtained from shallow laterolog response is written as:

$$\varphi_{fs} = \frac{(d_1 - r_w)w}{d_1^2\pi - r_w^2\pi} = \frac{w}{\pi(d_1 + r_w)}. \tag{4}$$

The characteristics of electroconductivity in detection zone of deep laterolog are expressed as:

$$\frac{1}{R_{LLD}} = \frac{\varphi_{fd}^{m_f} S_{wfd}^{n_f}}{R_{zd}}. \tag{5}$$

The characteristics of electroconductivity in detection zone of shallow laterolog are expressed as:

$$\frac{1}{R_{LLS}} = \frac{\varphi_{fs}^{m_f} S_{wfs}^{n_f}}{R_{zs}} \tag{6}$$

According to the model I, the fracture network of coal around the borehole was intruded by and filled with drilling fluid during well drilling, while the coal matrix cannot be intruded by drilling fluid. Hence, there will be some theoretical relationships of $S_{wfs} = S_{wfd} = 1$, $R_{zd} = R_w$ and $R_{zs} = R_{mf}$.

From the Eqs. (5) and (6), we can obtain:

$$\frac{1}{R_{LLS}} - \frac{1}{R_{LLD}} = \frac{\phi_{fs}^{m_f}}{R_{mf}} - \frac{\phi_{fd}^{m_f}}{R_w}. \tag{7}$$

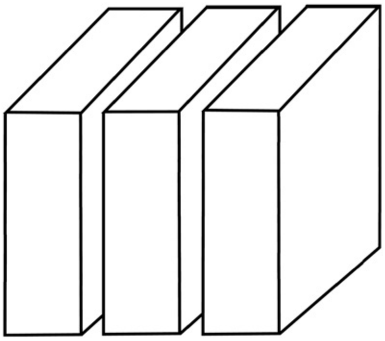

Fig. 1. Model evaluating coal reservoir permeability.