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Theoretical analysis of influencing factors on resistance in the process of gas migration in coal seams

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ABSTRACT

Inspired by previous resistance models for porous media, a resistance expression of gas migration within coal seams based on the ideal matchstick geometry, combined with the Darcy equation and the modified Poiseuille equation is proposed. The resistance to gas migration is generally dynamic because of the variations in adsorption swelling and matrix shrinkage. Due to the limitations of experimental conditions, only a theoretical expression of resistance to gas migration in coal is deduced, and the impacts of tortuosity, effective stress and pore pressure on the resistance are then considered. To validate the proposed expression, previous data from other researchers are adopted for the history matching exercise, and the agreement between the two is good.

1. Introduction

Coal is characterized as a typical porous medium in which pores and fractures exist simultaneously. Gas is generated and occurs in coal; thus, the analysis of the resistance in the process of gas migration in coal seams has great engineering significance on gas extraction and coalbed methane exploitation. Zhou [1] put forward in 1985 that gas migration in coal seams conforms to Darcy's law primarily; based on this, it is easy to understand that the emphasis of research should be on permeability when we analyze gas migration resistance. Many studies on factors influencing permeability have been performed; Olson et al. [2] confirmed the effect of the cleat and fracture system on coal permeability, while Somerton et al. [3], Palmer et al. [4], and Sasaki et al. [5] researched the effect of stress, porosity, gas pressure and adsorption swelling on permeability based on experiments. Zheng et al. [6] studied the influence law of effective stress, pore pressure, gas type and temperature on coal permeability. Harpalani et al. [7] described the result of the Klinkenberg effect and gas desorption on permeability. According to previous research findings, there are many factors influencing permeability; those factors are always investigated through experimental analysis and verification, and cannot be analyzed through an expression intuitively and comprehensively. Schneebeli [8], Shenoy [9], Wu et al. [10], and Tang et al. [11] proposed many resistance models for the migration of a single-phase fluid within porous media under the hypothesis that pores and fractures in packed porous media can be modeled as several capillaries. From the proposed models, we gain some enlightenment and conclude that the analysis of resistance to gas migration in coal seams can be carried out by viewing permeability as a bridge. Take the resistance model for flow through porous media put forward by Ergun [12] in 1952 as an example. The Ergun equation is: $\frac{\Delta P}{L}=\frac{150\mu(1-\phi)^2V_S}{D_P^2\phi^3}+1.75\frac{1-\phi}{\phi^3}\frac{\rho V_S^2}{D_P}$, where ΔP is the differential pressure between the inlet and outlet of porous media; L is the apparent length of the porous media; μ is the viscosity of the fluid; ϕ is the porosity of the porous media; ρ is the density of the fluid; V_S is the apparent velocity at the end of the porous media; and D_P is the average diameter of particles packed in the porous medium (the porous medium consist of particles with the number n). The resistance model consists of two parts; the first-term on the right-hand side of the equation is called the Blake-Kozeny equation, which describes the viscous energy loss primarily in a laminar flow state under a low Reynolds number. The second-term on the right-hand side of the equation is called the Burke-Plummer equation, which represents the kinetic energy loss primarily in a turbulent flow state under a high Reynolds number. The Ergun equation reflects the complicated influencing factors on fluid migration in

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porous media comprehensively. In this paper, the analysis of gas migration in coal seams considers only the viscous energy loss, and neglects the kinetic energy loss, when considering gas migration in coal seams belonging to a laminar flow with a low Reynolds number. Most resistance expressions of porous media are established based on the hypothesis that pores and fractures in packed porous media can be modeled as several capillaries, but the ideal matchstick model is accepted by most researchers. In consideration of the many resistance models for porous media, a resistance model expression of porous media is newly deduced. First, a comparison to the existing models is made in this paper, and then, the resistance expression for coal based on the matchstick model is established.

2. Resistance expression for coal

2.1. Viscous energy loss of liquid migration in porous media

In this paper, we assumed that the pores and fractures in porous media consist of tortuous capillaries. The law of fluid flow through capillary channels satisfies the modified Hagen-Poiseuille [13] equation, as follows:

$$q = \frac{\pi r^4 \Delta P}{8 \mu L_S} \tag{1}$$

where q is the fluid flow rate in a capillary; r is the radius of the capillary; ΔP is the differential pressure between the inlet and outlet of the capillary; μ is the viscosity of the fluid; and L_S is the actual length of the tortuous capillary, where, Bear [14] defined $\tau = L_S/L$, and L is the apparent length of porous media.

Eq. (1) can also be transformed as:

$$q = \frac{\pi r^4 \Delta P}{8 \mu \tau L} \tag{2}$$

By assuming that the cross-sectional area of A contains n capillaries, the total fluid flow rate in porous media can be expressed as:

$$Q = n \frac{\pi r^4 \Delta P}{8 \mu \tau L} \tag{3}$$

Krishna et al. [15] consider that Darcy's law applies for the law of fluid migration with a Reynolds number less than 1; therefore, the law of low Reynolds number fluid flow through capillaries in porous media can be expressed as:

$$Q = \frac{K A \Delta P}{\mu L} \tag{4}$$

where Q is the fluid flow rate in porous media; K is the permeability of the porous media; ΔP is the differential pressure between the inlet and outlet of the porous media; A is the cross-sectional area; μ is the viscosity of the fluid; and L is the apparent length of the porous media.

By using Eqs. (3) and (4), the following relationship can be obtained:

$$\frac{K A \Delta P}{\mu L} = n \frac{\pi r^4 \Delta P}{8 \mu \tau L} \tag{5}$$

According to the definition of porosity, the porosity of porous media can be represented by:

$$\phi = \frac{n \pi r^2}{A} \tag{6}$$

Substituting Eq. (6) into Eq. (5) yields:

$$K = \frac{\phi r^2}{8 \tau} \tag{7}$$

Bird et al. [16] introduced the average hydraulic radius R ($2R = r$), which is expressed as: $R = \frac{\phi}{a}$, where $a = \frac{6(1-\phi)}{D_P}$, and D_P is the average diameter of particles packed in porous media. Substituting r into Eq. (7) yields:

$$K = \frac{D_P^2 \phi^3}{72 \tau (1-\phi)^2} \tag{8}$$

Substituting Eq. (8) into Eq. (4) produces:

$$\frac{\Delta P}{L} = \frac{72 \tau \mu (1-\phi)^2 V_S}{D_P^2 \phi^3} \tag{9}$$

Eq. (9) agrees with the deduced result of Wu et al. [10], but the path of derivation in this paper is different from that of Wu. If we adopt the tortuosity $\tau = 25/12$, an empirical value from Christopher et al. [17], then Eq. (9) can be transformed into the Blake-Kozeny equation, which confirms the correctness of the deduced method and the above process simultaneously.

2.2. Analysis of resistance in the process of gas migration in coal seams

Coal belongs to the category of porous media, and the matchstick model (Fig. 1) is the most popular research model for studying gas seepage in coal seams. The studies by Seidle et al. [18], Gu et al. [19] and Ma et al. [20] are the representative research on the matchstick model. The deduction process in this paper is based on the following hypotheses: (1) gas migration in coal seams belongs to laminar flow under a low Reynolds number, with the flow law obeying Darcy's law; (2) the flow of gas in coal seams is unidirectional, and countercurrent phenomena do not occur; (3) the coal seam is homogeneous and isotropic; and (4) the heterogeneity of adsorption swelling and matrix shrinkage in different parts of the coal seam can be neglected in the process of gas migration.

Fig. 2 presents the schematic diagram of a fracture, where b, l, and L are the width, height and length of a fracture, respectively. According to Reiss [21], the gas flow law obeys the modified Poiseuille equation, and can be expressed as:

$$q = \frac{b^3 l \Delta P}{12 \mu L_S} = \frac{b^3 l \Delta P}{12 \mu \tau L} \tag{10}$$

where q is the gas flow rate in the fracture; ΔP is the differential pressure; μ is the viscosity of the gas; τ is the tortuosity of the fracture in the coal sample; and $\tau = L_S/L$, where L is the apparent length of the coal sample and L_S is the actual length of the fracture.

Assuming that the cross-sectional area of A contains n fractures, the total gas flow rate in the coal sample can be expressed as:

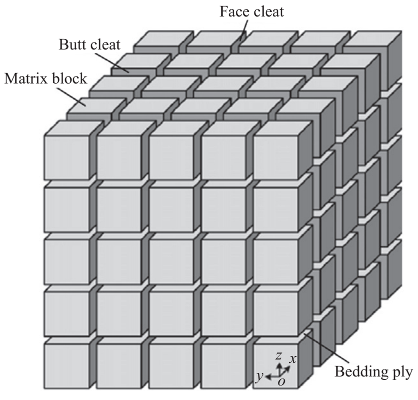

Fig. 1. Matchstick model.