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Gas and water relative permeability in different coals: Model match and new insights

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ABSTRACT

A recently derived relative permeability model for coal reservoirs has been applied to fit the published gas–water relative permeability data for different coals from Europe, China, Australia and the U.S., which exhibit a myriad of shapes and curvatures. The two-parameter model is shown to be capable of describing a total of 32 sets of data, including those history-matched from field production and laboratory core flooding tests as well as laboratory-measured ones. The fitted values of the two model parameters, namely cleat tortuosity parameter (η) and cleat size distribution index (λ), fall in the range between 0 and 2, and 0.3 and 8.8, respectively. For the European and Chinese coals whose rank information is available, there is tentative evidence that a U shape correlation between λ and coal rank exists, whereas no discernible trend is observed for η. This U shape dependency on coal rank has also been reported for some other coal properties such as total porosity.

1. Introduction

Coal seams are naturally fractured reservoirs consisting of matrix blocks, where most gas is adsorbed on coal surfaces, and a network of cleats, which provide the main flow paths for gas and water flow in coal seams. The cleats are usually saturated with water at the in-situ state, so water is produced first (dewatering) from the coal seams in commercial coalbed methane (CBM) production through pressure depletion. This is followed by a two phase flow regime where water and gas production is primarily governed by the characteristics of gas–water relative permeability of the cleats. Knowledge of relative permeability of coals is important for simulation studies of two phase flow behaviour in coal (Clarkson et al., 2011; Ham and Kantzas, 2008).

Coal is evolved from peat, which is formed after organic material is buried, compressed, and dewatered. As peat is buried more deeply over geological time, heat and pressure progressively drive off more and more water and volatiles. This process is referred to as coalification, whereby the carbon content of the coal is gradually increased through develoatilization. During coalification the rank of coal increases accordingly from lignite to sub-bituminous, bituminous, and anthracite. The rank of a coal is defined by its physical and chemical properties such as vitrinite reflectance, fixed carbon content, volatile matter content, moisture content (ASTM standards: http://www.astm.org/), which change progressively with coalification.

It has been reported that a number of coal properties, such as pore surface area (Williams et al., 2001), gas sorption capacity (Ahsan, 2006; Levine, 1996; Yao et al., 2011; Yee et al., 1993; Zhang et al., 2011) and total porosity (Mares et al., 2009; Rodrigues and Lemos de Sousa, 2002), are closely related to its rank in the form of a U shape curve (Fig. 1). This U-shape trend was first reported by King and Wilkins (1944). There is also evidence that cleat spacing in coal is rank-dependent (Law, 1993). Recently Yao et al. (2009) investigated the correlation between fractal dimension and coal rank for a number of Chinese coals with rank from sub-bituminous right up to anthracite (vitrinite reflectance between 0.4 and 4.2).

Since 1970s a number of relative permeability experiments have been conducted on coal samples (Dabbous et al., 1974; Gash, 1991; Gash et al., 1993; Meaney and Paterson, 1996; Paterson et al., 1992; Puri et al., 1991; Reznik et al., 1974). However, very few attempts have been made to relate the measured relative permeability curves of coals to their ranks. This is partly due to the lack of coal rank data in the publications. Ahsan (2006) measured gas (helium) and water relative permeability for several European coals of various ranks (from high vol. bituminous B to anthracite). Shen et al. (2011) investigated the influence of coal properties such as coal rank and maceral composition on the relative permeabilities of gas and water for different rank coals selected from South Qinshui Basin, China.

In this study the relative permeability equations derived specifically for coal by one of the authors (Chen et al., 2013) are used to fit the experimental data for both Chinese and European coals covering a wide

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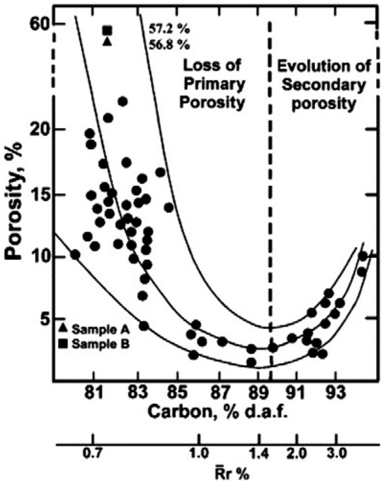

Fig. 1. Relationship between coal porosity and rank (after Rodrigues and Lemos de Sousa, 2002).

range of ranks. An attempt has been made to correlate the two parameters defining the characteristics of relative permeability to coal rank. In addition, published relative permeability data for Australian and the U.S. coals, whose rank information is unknown, has also been fitted with the same relative permeability model to obtain the range of the parameters, and towards building a database of laboratory measured relative permeability data together with fitted parameters.

2. Relative permeability model for coals

Most conventional relative permeability models are derived based on the bundle of capillary tubes model representation of porous media (Fig. 2a). Recognising that the cleat network in coals is better represented by a matchstick model (Fig. 2b), Chen et al. (2013) recently derived the following equations to describe the gas and water relative permeability in coal:

$$k_{rw} = k^*_{rw}\left(S^*_w\right)^{\eta+1+2/\lambda} \tag{1}$$

$$k_{rnw} = k^*_{rnw}\left(1-S^*_w\right)^{\eta}\left[1-\left(S^*_w\right)^{1+2/\lambda}\right] \tag{2}$$

where k^*_{rw} is the end-point relative permeability of the wetting phase, η is the cleat tortuosity parameter, λ is the cleat size distribution index analogous to the pore size distribution index used for porous media, k^*_{rnw} is the end-point relative permeability of the nonwetting phase, and S^*_w is the normalized wetting phase saturation given by:

$$S^*_w = \frac{S_w - S_{wr}}{1-S_{wr}-S_{nwr}} \tag{3}$$

where S_w is the wetting phase saturation, S_{wr} is the residual wetting phase saturation, and S_{nwr} is the residual nonwetting phase saturation. In this study, coal is assumed as water wet and thus the gas is the nonwetting phase.

It can be seen that the general shape of relative permeability in coals is determined by two parameters, namely cleat tortuosity parameter (η) and cleat size distribution index (λ). Note that Eqs. (1) and (2) have very similar forms as Brooks and Corey (1966) equations. Indeed, they reduce to the latter when η equals to 2. If η is set to 0, then Eqs. (1) and (2) reduce to the Purcell (1949) equations.

The cleat tortuosity parameter (η) is introduced to account for the fact that actual cleat structure in coal (Fig. 3a) is often much more complex than the simple matchstick model. Its value reflects the degree of tortuosity of the flow path formed by the connecting cleats. The value of η obtained from fitting the experimental data in the current study falls in the range between 0 and 2 (see Section 3). For comparison, isotropic and granular porous media usually have a tortuosity of 2 (Carman, 1937).

It might be expected that an increase in tortuosity would lead to a reduction in both gas and water relative permeability. This is clearly illustrated in Fig. 4, which compares the computed relative permeabilities for different tortuosity parameter values between 0 (Purcell model) and 2 (Brooks and Corey model) for two representative values of λ. It is noted that the curvature of the relative permeability to gas undergoes a transition from being convex to concave as η is increased from 0 to 2. Both shapes have been observed in the relative permeability of coals measured in the laboratory. It shall be seen that this flexibility of the model allows it to match relative permeability curves of different shapes and curvatures. It is further noted that the impact appears to be more pronounced for gas than water phase, especially when the gas saturation is low. The asymmetric impact of tortuosity on the non-

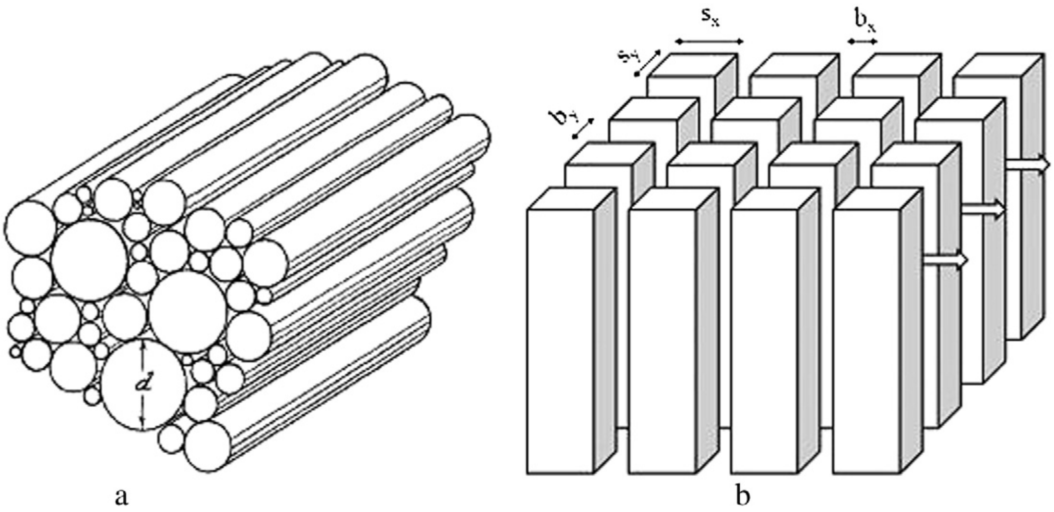

Fig. 2. (a) bundle of capillary tubes model (after Gates and Leitz, 1950); (b) Matchstick model (after Seidle et al., 1992).