Fuel 128 (2014) 53–61

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

# Improved apparent permeability models of gas flow in coal with Klinkenberg effect

Gongda Wang [a,b,1], Ting Ren [b,*], Kai Wang [a], Aitao Zhou [a]

[a] Faculty of Resources & Safety Engineering, China University of Mining and Technology, Beijing 100083, PR China
[b] School of Civil, Mining & Environmental Engineering, University of Wollongong, NSW 2500, Australia

## HIGHLIGHTS

- A critical review of gas permeability models with Klinkenberg effect.
- Discussion on the variations of Klinkenberg coefficient during CBM recovery.
- Development of two apparent permeability models.
- Validation of developed models with published data.

ARTICLE INFO

*Article history:*
Received 14 January 2014
Received in revised form 14 February 2014
Accepted 26 February 2014
Available online 14 March 2014

*Keywords:*
Klinkenberg effect
Gas reservoir permeability
Coalbed methane
Matrix shrinkage
Apparent permeability model

ABSTRACT

Klinkenberg effect is an important phenomenon for gas flow in low permeability reservoirs, and its influence increases with the reduction of gas pressure. Unlike conventional gas reservoirs, coal seam is unique with its high compressibility and sorption-induced-swelling features. During the coalbed methane (CBM) recovery process, coal cleat width varies due to the net effect of effective stress and coal matrix shrinkage, thus the Klinkenberg coefficient cannot be treated as a constant like rock reservoirs. A brief review of previous studies shows that the influence of coal seam characteristics on Klinkenberg effect was ignored by other researchers. By using the bundled matchstick conceptual model of coal, two improved models are proposed in this paper, one is under constant effective stress and the other is under reservoir condition. The former shows that the proportion of permeability change due to Klinkenberg effect is greater than the result from original model, and the Klinkenberg coefficient varies substantially albeit the influence of effective stress is eliminated. The latter links apparent permeability and coal porosity together, and the results show good agreement with field data, especially when the gas pressure is relative low. It can be concluded that apparent permeability model is crucial for explicit prediction of gas permeability changes during CBM recovery process, which may be underestimated without due consideration of Klinkenberg effect. The development of the improved apparent permeability models has significant value in the accurate prediction of CBM production as a result of permeability changes.

© 2014 Elsevier Ltd. All rights reserved.

## 1. Introduction

Convective flow, known as Darcy flow, is pressure-driven flow of gas through porous media. Darcy flow is the primary driver in micro-scale flow, even very small pressure gradients will cause larger flux than flux generated by very steep concentration gradients [1]. However, Knudsen diffusion is significant when the mean free path of gas molecules approaches the average diameter of pore throats in porous media [2]. The Knudsen number characterises the deviation from Darcy flow:

$$K_n = \frac{\bar{\lambda}}{w_{pore}} \tag{1}$$

where $K_n$ is the Knudsen number, $\lambda$ is the mean free path of gas molecules, and $w_{pore}$ is the width of pore throat in porous media. The phenomenon of Knudsen flow was first applied to petroleum engineering problems by Klinkenberg [3], known as Klinkenberg effect or gas slippage. A linear relationship between measured gas permeability and absolute permeability was proposed based on:

* Corresponding author. Address: Faculty of Engineering and Information Sciences, University of Wollongong, NSW 2500, Australia. Tel.: +61 40202 0175.
E-mail addresses: wgdcumt@gmail.com (G. Wang), tren@uow.edu.au (T. Ren).
1 Address: Room 309, Building 6, University of Wollongong, NSW 2500, Australia. Tel.: +61 46687 9391.

http://dx.doi.org/10.1016/j.fuel.2014.02.066
0016-2361/© 2014 Elsevier Ltd. All rights reserved.

$$k_a = k_0\left(1 + \frac{b}{P_m}\right) \quad (2)$$

where $k_a$ is the measured or apparent permeability, $k_0$ is the intrinsic or absolute permeability of the porous medium, $P_m$ is the mean gas pressure, and $b$ is the so-called 'Klinkenberg coefficient'. It is obvious that for a certain gas pressure, the value of $b$ is significant for the difference between apparent permeability and absolute permeability. Various correlations for Klinkenberg coefficient are available in the literature. Basically, there are three forms for the determination of $b$, one is given as [4,5].

$$b = \frac{16c\mu}{w_{pore}}\sqrt{\frac{2RT}{\pi M}} \quad (3)$$

where $c$ is a constant (typically taken as 0.9), $\mu$ is the kinetic viscosity of the fluid, $M$ is the fluid molecular weight, $R$ is the universal gas constant, and $T$ is the absolute temperature. It can be seen that $b$ is determined by both fluid properties ($\mu$, $M$) and porous media property ($w_{pore}$). Since the value of $w_{pore}$ is difficult to measured directly, the following two forms are extensively used for the investigation of gas permeability in rock, e.g. sandstone, gas sand, sedimentary rock and shale [6–11].

$$b = \alpha(k_\infty)^\beta \quad (4)$$

and

$$b = \alpha\left(\frac{k_\infty}{\phi}\right)^\beta \quad (5)$$

where $\alpha$ and $\beta$ are constants measured by experiments, $k_\infty$ is Klinkenberg's corrected permeability at a very large gas-phase pressure, and $\phi$ is fractional porosity. It should be noted that $k_\infty$ is equal to $k_0$ in these studies, and porous media properties ($w_{pore}$ and $\phi$) are considered independent of the gas properties. The value of $k_\infty$ can be calculated from the straight-line intercept on a Klinkenberg plot of apparent permeability versus the reciprocal mean gas pressure (as shown in Fig. 1).

Klinkenberg effect is significant in fine grained, low permeability porous media [11]. Compared with conventional low permeability gas reservoirs, coal reservoirs have high compressibility, and the unique swelling/shrinkage feature due to gas adsorption/desorption in coal matrix. Primary gas production (CBM recovery) triggers the reduction of gas pressure in the fracture network (coal cleat). Consequently, the lower pressure increases effective stress, and when the gas pressure drops below desorption point, coal seam gas diffuses from coal matrix to cleat and the coal matrix shrinks. The former induces the compaction of cleat, while the latter increases the cleat width [12]. Thus, the transient intrinsic permeability of coal depends on the net influence of these two dual competing mechanisms [13–29]. However, both laboratory observations and *in situ* measurements are apparent permeability, which incorporates not only the two dual competing mechanisms, but also the influence of Klinkenberg effect. With the decrease of gas pressure in CBM extraction, Klinkenberg effect becomes more significant, however limited researches have been focused on this phenomenon.

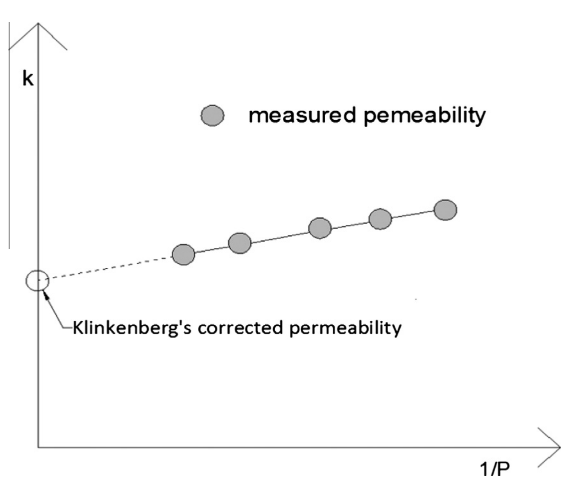


**Fig. 1.** Klinkenberg plot of measured permeability versus the reciprocal mean gas pressure.

Previous analyses illustrate the influence of Klinkenberg effect on apparent permeability of gas flow in rocks, but the basic assumption of Eqs. (4) and (5), that the porosity of porous media is independent of the gas properties is not valid for coal. Furthermore, the parameter $k_\infty$ denotes the permeability at a very large gas pressure at which Klinkenberg effect can be neglected, but the sorption-induced-swelling of coal matrix determines that the porous media properties cannot remain unchanged with the alternation of gas pressure, even if the confining stress [19,28,30–32] or effective stress [33–36] keeps constant. In other words, $k_0$ is a transient parameter for coal, and the value of Klinkenberg coefficient $b$ determined by $k_\infty$ from Eqs. (4) and (5) is not the same as that determined by $k_0$, because the cleat width differs as shown in Eq. (3). Therefore, explicit prediction of permeability changes in CBM recovery requires understanding of these complex mechanisms, include the 'coupled processes' between stress and sorptive chemist [12], as well as its influence on Klinkenberg effect, especially the change of Klinkenberg coefficient $b$.

This paper includes a brief review of the previous studies on gas permeability in coal with Klinkenberg effect. Then the apparent permeability models are developed under both constant effective stress condition and reservoir condition, respectively. The developed models incorporate a variable Klinkenberg coefficient and its influences are also discussed in this paper.

## 2. Review of previous research

Some excellent reviews of coal permeability, including not only model development but also field and laboratory permeability data, have been presented in recent years [12,37–40], however, the influence of Klinkenberg effect was rarely discussed in these reviews. Thus, a brief review and discussion of previous researches of Klinkenberg effect on coal permeability is presented in the following section.

### 2.1. Literature review

As the discrepancy between real CBM production [41,42] and simulation results was observed, Harpalani and Chen [33] proposed the first experimental investigation which involved both the Klinkenberg effect and coal matrix shrinkage. In order to single out the effect of matrix volumetric strain, the influence of effective stress was eliminated by keeping it constant. The effective stress can be defined as:

$$p_{\mathrm{eff}} = p_c - \delta p_m \quad (6)$$

where $p_c$ is the applied external stress, $p_m$ is the mean gas pressure, and $\delta$ is biot coefficient which can be determined by [43,44]:

$$\delta = 1 - K/K_s \quad (7)$$

where $K$ is bulk modulus of the bulk rock, $K_s$ is the bulk modulus of the solid grain material. The value of $\delta$ was considered as 1 in their study. Non-absorptive gas, helium, was introduced to calculate the Klinkenberg coefficient for methane by using Eq. (3):

Download English Version:

https://daneshyari.com/en/article/6637546

Download Persian Version:

https://daneshyari.com/article/6637546

Daneshyari.com