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Scaling law for slip flow of gases in nanoporous media from nanofluidics, rocks, and pore-scale simulations

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ABSTRACT

In unconventional reservoirs, as the effective pore size becomes close to the mean free path of gas molecules, gas transport in porous media begins to deviate from Darcy's law. The objective of this study is to explore the similarities of gas flows in nanochannels and core samples as well as those simulated by direct simulation BGK (DSBGK), a particle-based method that solves the Bhatnagar-Gross-Krook (BGK) equation.

Due to difficulties in fabrication and experimentation, previous study on gas flow experiments in nanochannels is very limited. In this work, steady-state gas flow was measured in reactive-ion etched nanochannels with a controlled channel size on a sillicon wafer. A core-based permeability measurement apparatus was used to perform steady-state gas flow measurements on carbonate and shale samples. Klinkenberg permeability was obtained under varying pore pressures but constant temperature and effective stress. Methane was used in nanofluidic and rock experiments, making them directly comparable. Results from both experiments were then compared to gas flow simulations by DSBGK method carried out on several independently constructed geometry models. DSBGK uses hundreds of millions of simulated molecules to approximate gas flow inside the pore space. The intermolecular collisions are handled by directly integrating the BGK equation along each molecules trajectory, rather than through a sampling scheme like that in the direct simulation Monte-Carlo (DSMC) method. Consequently, the stochastic noise is significantly reduced, and simulation of nano-scale gas flows in complex geometries becomes computationally affordable.

The slippage factors obtained from these independent studies varied across three orders of magnitude, yet they all appear to collapse on a single scaling relation where the slippage factor in the slip flow regime is inversely proportional to the square root of intrinsic permeability over porosity. Our correlation could also fit the data in the literature, which were often obtained using nitrogen, after correcting for temperature and gas properties. This study contributes to rock characterization, well testing analysis as well as the understanding of rarefied gas transport in porous media.

1. Introduction

Even with the significant progress made in producing oil and gas from unconventional reservoirs with multistage fractured horizontal wells in the past decades, the recovery factor of hydrocarbons from these reservoirs remains very low. For gas reservoirs, the estimated recovery factor varies in the range of 5–30% while for oil reservoirs it is often <10% [1]. Compared with conventional reservoirs, the significant amount of residual hydrocarbons and substantial initial investments in drilling and stimulation make it pressing to develop practical tools to improve recovery factors and maximize the net present value. Gas slippage in the matrix has a significant impact on production performance of unconventional gas wells as well as modeling of unconventional gas reservoirs [2,3]. Moreover, it could also affect unconventional oil reservoirs as gas injection has become the top choice for EOR pilot tests in unconventional reservoirs [4]. Hence understanding the physics of gas flow in nanoporous rocks becomes crucial.

1.1. Empirical correlations for Klinkenberg coefficient

In the tight matrix of unconventional reservoirs, Klinkenberg effect would govern gas transport when the mean free path of gas molecules approaches the pore size in the nanoscale. According to Klinkenberg (1941) [5], the apparent permeability of gas k_g increases with decreasing average pressure and apparent gas permeability is given as,

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Table 1
Klinkenberg coefficient b as a power-law function of k_∞.

References	α	β	Gas
Heid et al. 1950 [6]	0.1106	−0.39	Air
Jones, 1972 [7]	0.1885	−0.36	N_2
Jones and Owens, 1980 [8]	0.9735	−0.33	N_2
Tanikawa and Shimamoto, 2009 [9]	0.1500	−0.37	N_2

$$k_g = k_\infty\left(1 + \frac{b}{\overline{p}}\right) \tag{1}$$

where b is the Klinkenberg coefficient (or slippage factor). In reservoir simulators, Klinkenberg effect can be modelled with different choices of Klinkenberg coefficient b. Characterization of Klinkenberg coefficient is hence of great value. Klinkenberg (1941) [5] proposed to relate b to the ratio between the mean free path λ and the characteristic dimension (radius) of pores r,

$$b = \frac{4c\lambda\overline{p}}{r} \tag{2}$$

However, since r is usually not directly measured for rocks, b is often empirically expressed as a power-law function of the intrinsic permeability of rock k_∞ for practical reservoir engineering purpose, i.e., $b = \alpha k_\infty^\beta$ as shown in Table 1.

By assuming that flow through porous media can be modelled by a bundle of capillary tubes, some researchers proposed that b should be a power-law function of k_∞/ϕ, i.e., $b = \alpha(k_\infty/\phi)^\beta$ as shown in Table 2. Most correlations in Table 2 have β as −0.5, which comes from replacing r in Eq. (2) by $(k_\infty/\phi)^{-0.5}$.

However, most current studies of gas slippage in cores often lacks the characterization of porosity let alone pore sizes. The effects of changing temperature, effective stress, and gas species on the slippage factor b are seldom systematically measured on the same rock. In order to better understand the above effects, the physics that leads to Klinkenberg effect needs to be reviewed.

1.2. Theoretical slippage factors

It is recognized that Klinkenberg effect can be all or partly attributed to gas rarefaction that can further be classified into four categories based on the Knudsen number [13] which is defined as,

$$\mathrm{Kn} = \frac{\lambda}{L} \tag{3}$$

where λ is the mean free path of gas molecules and L is a characteristic length. When $\mathrm{Kn} < 10^{-3}$, effect of gas rarefaction can be neglected, and the flow can be accurately modeled by the compressible Naiver-Stokes (N-S) equations with classical no-slip boundary conditions. When $10^{-3} < \mathrm{Kn} < 10^{-1}$, the flow is in the slip flow regime and the N-S equations remain applicable, provided that a velocity slip is applied to the wall. The slip velocity can be correlated to the velocity gradient normal to the wall through, for instance, a first-order slip model [14]. When $10^{-1} < \mathrm{Kn} < 10$, the flow regime is termed transitional, and the continuum approach of the N-S equations is no longer valid. When $\mathrm{Kn} > 10$, the flow enters the free molecular flow regime and the occurrence of intermolecular collisions is negligible compared with the collisions between the gas molecules and the walls. DSMC is a powerful tool for flows in these two regimes. DSBGK as an alternate simulation method achieves higher efficiency with the same level of accuracy as DSMC [39]. DSBGK agrees very well with experimental data [40] and the DSMC method over a wide range of Kn [15], even if $\mathrm{Kn} < 10^{-1}$ due to high pressure, because its molecular reflection boundary condition and governing equation are generally valid for any Kn. In this work, the DSBGK method was applied to simulate flow in a wide range of Kn but only data within the Kn range of (0.01, 0.1) were selected to extract the intrinsic permeability and slippage factor b to study the scaling law for the slip flow regime.

Table 2
Klinkenberg coefficient b as a power-law function of k_∞/ϕ.

References	α	β	Gas
Sampath and Keighim, 1982 [10]	0.0011	−0.53	N_2
Florence et al. 2007 [11]	0.0094	−0.5	N_2
Florence et al. 2007 [11]	0.0096	−0.5	Air
Civan, 2010 [12]	0.0094	−0.5	N_2

The above classification of gas flow regimes based on Kn is qualitative as different choices of characteristic lengths would lead to different limits. For flow in microchannels, L is generally chosen to be the hydraulic diameter or the depth of the channel. In porous rocks, pore diameter should be used as the characteristic length. For complex geometries [16], it could be preferable to calculate L from local gradients (for example of the density ρ: $L = \rho/|\nabla\rho|$). Klinkenberg coefficients for slip flows through simple geometries, such as those between parallel plates or within capillary tubes, can be obtained by solving the N-S equation with the first-order slip boundary condition,

$$u_{\mathrm{slip}} = -\frac{2-\sigma}{\sigma}\lambda\left(\frac{\partial u}{\partial n}\right)_{\mathrm{wall}} \tag{4}$$

where σ is the tangential momentum accommodation coefficient (TMAC). For gas flows between two parallel plates [17],

$$\frac{k_g}{k_\infty} = 1 + \frac{6(2-\sigma)}{\sigma}\frac{\lambda}{h} \tag{5}$$

The characteristic length is the distance between the two plates, i.e., $L = h$, provided that h is much smaller than the size of the plate. The expression for b is therefore,

$$b = 6p\mathrm{Kn}\frac{2-\sigma}{\sigma} \tag{6}$$

Similarly, for flows within a cylindrical tube,

$$\frac{k_g}{k_\infty} = 1 + \frac{4(2-\sigma)}{\sigma}\frac{\lambda}{r} \tag{7}$$

By defining the characteristic length as the hydraulic diameter, i.e., $L = 2r$, the expression for b is therefore,

$$b = 8p\mathrm{Kn}\frac{2-\sigma}{\sigma} \tag{8}$$

The above expressions for b motivated a general correlation for the gas slippage factor,

$$b = k_1 p\mathrm{Kn}\frac{2-\sigma}{\sigma} \tag{9}$$

Here, k_1 is a factor based on the geometry, e.g., cross-section shape. Kn can be calculated once the mean free path is calculated using the gas kinetic theory. For classic collision models, based on an inverse-power-law (IPL) interaction scheme, the expression of mean free path can be written as [16],

$$\lambda = \frac{k_2\mu}{\rho}\sqrt{\frac{M_w}{RT}} \tag{10}$$

where M_w is molecular weight in kg/mol; R is the universal gas constant in J/(K·mol), and Z is the compressibility factor; and k_2 is a constant from the viscosity model and is directly related to viscosity index given by [18]. For real gases,

$$\lambda = \frac{k_2\mu Z}{p}\sqrt{\frac{RT}{M_w}} \tag{11}$$

The pore radius r is often scaled to the square root of permeability k over porosity ϕ as $r \sim \sqrt{k/\phi}$. Now a general expression for the slippage