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PORE-SCALE SIMULATIONS OF RAREFIED GAS FLOWS IN POROUS MEDIA

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KEY WORDS

tight porous media, shale gas, permeability correction

SHORT SUMMARY

Although the unconventional gas has accounted for 40% of the recoverable resource of natural gas, its production contributed only 14% of nature gas supply in 2010. This share of unconventional gas in nature gas provision is expected to rise to 21% and 32% in 2020 and 2035, respectively [1]. To predict the gas permeability through ultra-tight porous media, gas rarefaction effect which enhances permeability should be taken into account. In this work, gas flows through samples of porous media are directly simulated by solving the BGK kinetic equation [2] using Discrete Velocity Method (DVM) and lattice Boltzmann method (LBM) for a wide range of the Knudsen number. While the LBM cannot capture rarefaction effect, the results indicate that the resolution of the velocity grid has little influence on the DVM results for complex geometry, even in the free molecular flow regime.

EXTENDED ABSTRACT

Gas rarefaction effects, which are significant when the number of molecule-surface collisions is comparable to that of molecule-molecule collisions, may alter the gas transport mechanism in micro/nano-pores of porous media. The rarefaction level can be indicated by the Knudsen number Kn, defined as the ratio of the molecular mean free path λ to the characteristic flow length L.

$$Kn = \frac{\lambda}{L}, \qquad \lambda = \frac{\mu(\hat{T}_0)}{\bar{p}}\sqrt{\frac{\pi R \hat{T}_0}{2}}, \tag{1}$$

where R, $\bar{p}$ and $\mu(\hat{T}_0)$ are the gas constant, mean gas pressure and dynamic viscosity of the gas at a reference temperature $\hat{T}_0$, respectively. In this work, rarefied gas flows through 2 dimensional (2D)

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porous media are simulated directly by solving the Bhatnagar-Gross-Krook (BGK) kinetic equation [2] using Discrete Velocity Method (DVM) and lattice Boltzmann method (LBM) with the diffuse boundary condition. The numerical data will be compared with the Darcy-type models in terms of permeability correction.

In order to appropriately compare the pore-scale rarefaction effects in different porous samples of various sizes, the effective Knudsen number Kn_l is defined as

$$Kn_l = \frac{\lambda}{L^*} = \frac{Kn}{L^*/L}, \tag{2}$$

where the average pore size L^* is defined as

$$L^*/L = \sqrt{\frac{12k_\infty}{\epsilon}}. \tag{3}$$

The intrinsic permeability k_∞ (at the hydrodynamic limit $Kn \to 0$) is obtained by extrapolating from the apparent permeability k_a resulted from the LBM D2Q9 with the bounce-back reflection on solid surfaces near the hydrodynamic flow regime. The porosity ϵ of a porous model in Eq. (3) is determined by the ratio of the number of fluid points to the total number of points. Following the work of Beskok and Karniadakis on the second-order correlation for a straight tube [4], Civan proposed a second-order correction for tight porous media [5]

$$\frac{k_a}{k_\infty} = [1 + \alpha Kn_l]\left[1 + \frac{4Kn_l}{1 + Kn_l}\right], \tag{4}$$

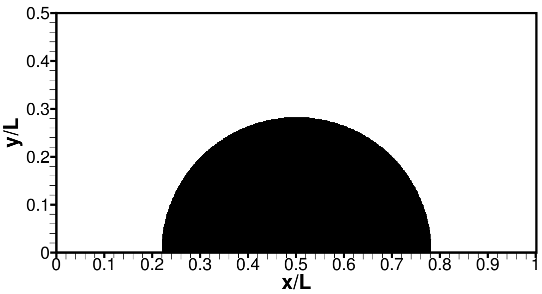
where the empirical coefficient α is correlated with numerical data as follows

$$\alpha = \frac{1.358}{1 + 0.178Kn_l^{-0.4348}}. \tag{5}$$

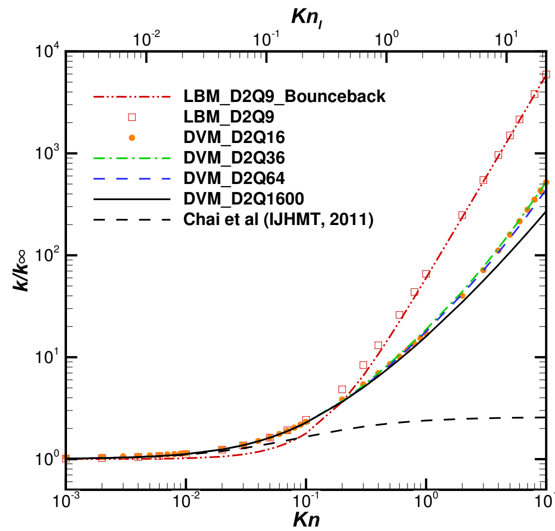
However, this model, referred to as Beskok-Karniadakis-Civan (BKC) model, was originally derived for 3D porous media. In order to adapt it to 2D porous media, α should be correlated by channel flows instead of by pipe flows [4]. In addition, the coefficient 4 in the last term of Eq. (4) is replaced by 6 for 2D porous media.

Figure 1 demonstrates the consistency of the permeability correction k_a/k_∞ obtained by all examined approaches in the continuum limit ($Kn_l \lesssim 0.005$). However, in the slip regime, the effect of boundary condition on the LBM simulations can be observed: the LBM data with the bounce-back and diffuse boundary conditions start to deviate from that of the DVM at $Kn_l \approx 0.01$ and $Kn_l \approx 0.2$, respectively. By comparing with the DVM data, the analytical slip solution derived from the Stokes approximation with the Maxwell's slip boundary condition [6] is valid when $Kn_l \lesssim 0.05$. The effect of resolution of the molecular velocity grid of DVM is pronounced when $Kn_l \gtrsim 3$ and the largest relative discrepancy between $D2Q16$ and $D2Q1600$ models is about 192% at $Kn_l \approx 20$.

The 2D micromodel of Berea sandstone [7], see Fig. 2(a), represents a complex porous structure that leads to highly tortuous flow path. Figure 2(b) indicates that the resolution of velocity grid in the DVM simulations plays an insignificant role in all the flow regimes for this tight porous sample. The maximum disagreement in permeability correction between $D2Q16$ and $D2Q1600$ models diminishes to approximately 11% at $Kn_l \approx 4000$. Figure 2(c) compares the permeability correction for micromodel of Berea sandstone obtained by the direct simulation with the BKC model Eq. (4). The BKC model with the empirical parameter $\alpha = 0$, i.e. first-order correction, underestimates the permeability correction in transitional and free-molecular regimes. However, the BKC model with $\alpha = 2.2$, i.e. second-order correction for 2D channel of length-to-height ratio of 20, overestimates the numerical prediction in the slip regime. It is found that the BKC with $\alpha = 0.5$ is in good agreement with $D2Q1600$.



(a) Square array of circular cylinder



(b) Permeability correction

Figure 1: Square array of circular cylinder: (a) the white and black regions represent the matrix and void. The image resolution $N_x = 400 \times 800$ and porosity = 0.75 ; (b) permeability correction obtained by the LBM and DVM simulations are compared with the slip analytical solution [6].

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References

[1] International Energy Agency, Golden rules for a golden age of gas, special report on unconventional gas, Tech. rep., International Energy Administration, OECD, Paris (2012).

[2] P. Bhatnagar, E. Gross, M. Krook, A model for collision processes in gases. I. Small amplitude processes in charged and neutral one-component systems, Physical Review 94 (3) (1954) 511–525.

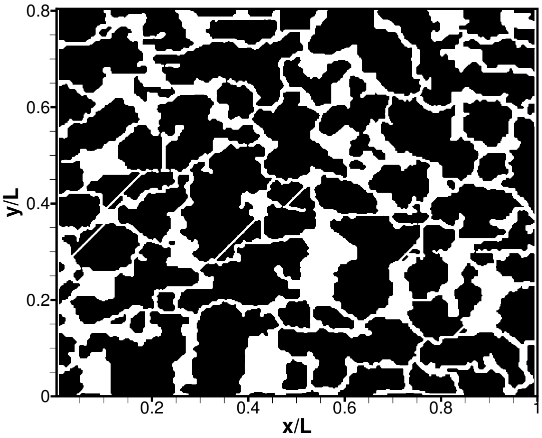
[3] L. Klinkenberg, The permeability of porous media to liquids and gases, Drilling Production Practice (1941) 200–213.

[4] A. Beskok, G. E. Karniadakis, Report: A model for flows in channels, pipes and ducts at micro and nano scales, Microscale Thermophysical Engineering 3 (1) (1999) 43–77.

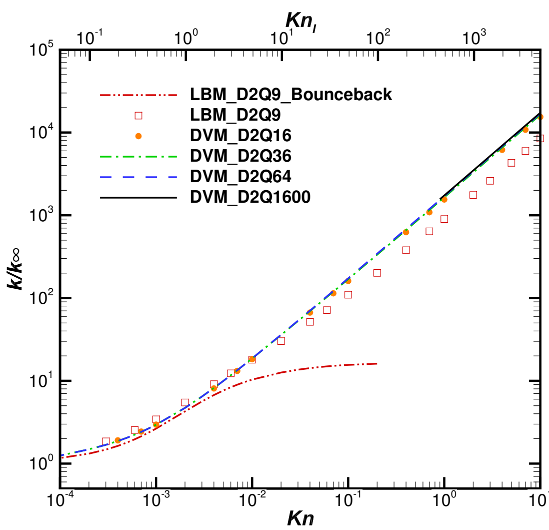
[5] F. Civan, Effective correlation of apparent gas permeability in tight porous media, Transport in Porous Media 82 (2) (2010) 375–384.

[6] Z. Chai, J. Lu, B. Shi, Z. Guo, Gas slippage effect on the permeability of circular cylinders in a square array, International Journal of Heat and Mass Transfer 54 (13-14) (2011) 3009–3014.

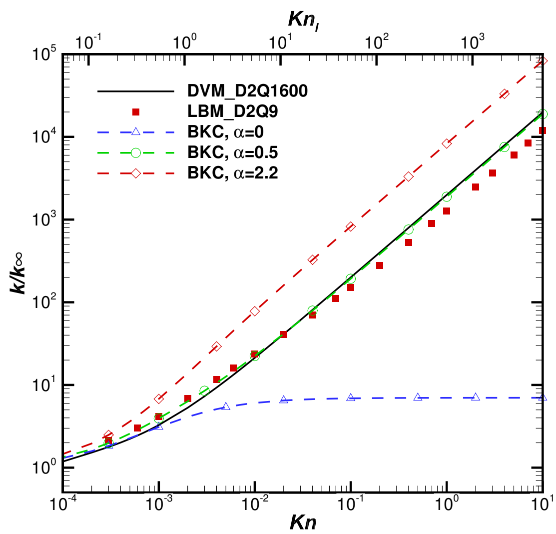
[7] E. S. Boek, M. Venturoli, Lattice-Boltzmann studies of fluid flow in porous media with realistic rock geometries, Computers & Mathematics with Applications 59 (7) (2010) 2305–2314.



(a) Berea sandstone



(b) Permeability correction



(c) BKC model

Figure 2: Micro model of Berea sandstone: (a) the white and black regions represent the matrix and void. The image resolution $N_x = 1597 \times 1282$ and porosity = 0.32; (b) permeability correction obtained by the LBM and DVM simulations with different velocity grid; (c) BKC model.