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A Unified Viscous-Diffusion Layered Model of Non-ideal Rarefied Gas Flow in Micro- and Nanoscale Porous Media

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OBJECTIVES/SCOPE:
Existing rarefied gas flow models cannot accurately unify various flow mechanisms by empirical methods and overlook the van der Waals effect. In this paper, a model for non-ideal rarefied gas flow in nano- and micro-porous media is developed based on the well-recognized Bravo's conceptual layered model with the rigorous interpretation. The gas transport behavior in nanopores can be simulated by the developed model which can be integrated with hydraulic fracturing models to optimize the production performance of shale gas reservoirs.

METHODS, PROCEDURES, PROCESS:
The cross-section of a nano-capillary can be divided into two zones based on Bravo's model, i.e., an inner circular zone where the viscous flow behavior mainly exists due to the dominant intermolecular collision and an outer annular zone where non-equilibrium phenomenon exists and the classic constitutive relation breaks down due to a lack of intermolecular collisions. We proposed a virtual boundary between two zones which is determined by Kennard's collision model, where the radius of inner zone is correlated with the fraction of intermolecular collisions. The convective and diffusive fluxes are rigorously integrated based on the virtual boundary. The mass flux, contributed by different transport mechanisms, thus could be analyzed by varying the Knudsen number. Subsequently, non-ideality property of rarefied gas is characterized by incorporating a compressibility correlation and real gas viscosity function. Physical and numerical experiments show the support of the new formulation and provide approaches to obtain apparent permeability and a generalized Klinkenberg's parameter which is a function of Knudsen's number.

RESULTS, OBSERVATIONS, CONCLUSIONS:
The newly proposed model allows for determination of the pressure dependence of the Klinkenberg parameter across the transition flow regime and yields the most accurate prediction compared with five existing models. The apparent permeability does not change obviously when pressure is over 10 MPa and pore size is larger than 100 nm. Although the surface roughness can significantly reduce the apparent permeability, its impact is minor when the pressure is higher than 10 MPa. The molar gas flux declines significantly by incorporating the real gas effect into the model, leading to a decreasing apparent permeability. Sensitivity analysis shows the apparent permeability is found to be strongly dependent on pore size and weakly dependent on roughness. Finally, it is found that Knudsen diffusion dominates the flow performance with a proportion larger than 60% in small pores (e.g., ≤ 50 nm) at the low pressures (e.g., ≤ 0.2 MPa).

NOVELTY:
Instead of the empirical coefficients commonly used in most existing models, the weight coefficient of viscous flow and Knudsen diffusion in the proposed layered model is analytically derived based on Bravo's layered model. This work also provides approaches to obtain a generalized Klinkenberg's parameter. In addition, a multi-objective optimization method is adopted to enhance the conveniences of searching local optimal fitting parameters in empirical correlations.

References

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