THE EFFECT OF WATER SATURATION ON GAS SLIP FACTOR BY PORE SCALE NETWORK MODELING

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ABSTRACT

A pore scale network model is presented to describe the flow of gas in tight porous media. The Adzumi's approach of dual mechanism for transport of gas through the capillary is incorporated in this model. The treatment of the microscopic flow mechanism gives an insight into the Klinkenberg effect, where the effective permeability of the tight porous media is a function of the mean pressure. From the simulation, it shows that the slip factor decreased with the increase of the permeability of the porous media and was affected by the variation of the distribution function of the capillary radius. In the process of gas flow through water-saturated porous media, the slip factor is not a constant any more; it will decrease with the increase of the water saturation.

INTRODUCTION

Gas flow in porous media differs from liquid flow because of the large gas compressibility and pressure-dependent effective permeability. The latter effect, named after Klinkenberg, may have significant impact on gas flow behavior, especially in low permeability porous media. Many laboratory and numerical studies indicates that the Klinkenberg effect cannot be ignored. According to Klinkenberg[1], effective gas permeability at finite pressure is given by

$$K_g = K_\infty (1 + \frac{b}{p}) \tag{1}$$

Where k_∞ is the absolute gas permeability under very large pressure at which condition the Klinkenberg effects are negligible; and b is the Klinkenberg factor, dependent on the pore structure of the porous medium and temperature for a given gas.

The goal of this study is to obtain a fundamental understanding of the non-Darcy flow in porous media through development of a pore scale network model. The pressure drops at several flow rates were calculated, which show the validity of the Klinkenberg equation. In the gas water flow, it shows that the slip factor is saturation dependent function rather than a constant. The slip factor decreases with the increase of the water saturation.

PORE SCALE NETWORK MODEL

It is impossible to give the exact description of the morphological features of natural rocks. The essential features have to be taken into account including the distribution of the pore sizes, the connectedness of the pore space and the converging-diverging nature of pore segments. The regular triangle lattice was adopted to represent the pore morphology with the coordination number equal to six. The pore throat and pore body radii are described using a probability distribution given by a special case of Weibull distribution,

$$f(x) = \frac{r - r_{\min}}{(r_{\max} - r_{\min})_2^2} \exp\left(\frac{(r - r_{\min})^2}{(r_{\max} - r_{\min})_2^2} \right) \tag{2}$$

Where r represents the pore throat radius, r_{min} and r_{max} define the minimum and maximum sizes respectively. In this model, we assume that the pore throat radius is uncorrelated.

The permeability was calculated by the analogous electrical circuit method[2]. As each capillary element has different radius and the pressure in capillary is not uniform, the gas flow in each capillary have different pattern. It is important to investigate the flow pattern in every capillary according to the relation between the radius and mean free path of gas molecule.

In 1937, Adzumi[3] proposed the following approach to model the slip phenomena through capillary tubes. When the mean free path of gas molecular is small compared to the capillary radius, the flow phenomenon is governed by the Poiseuille law.

$$q_p = \frac{pr^4}{8m} \frac{\Delta p}{l} \tag{3}$$

Where r is the capillary radius, l is the length of the capillary, m is the viscosity of the gas. The criterion of the mean free path being small compared with the capillary radius is met for capillary with large radius or flow at high pressure.

When the mean free path large compared to the capillary radius, the flow is governed by Knudsen equation,

$$q_s = \frac{4}{3} \sqrt{\frac{2pRT}{M}} \frac{r^3}{l} \frac{\Delta p}{\overline{p}} \tag{4}$$

Where T is the absolute temperature, M is the molecular weight of gas, R is the gas constant. The criterion of the mean free path being large compared with the capillary radius is met for capillary with small radius or flow at low rate.

Gas may flow at the different regime, according to the comparison between the mean free path of gas molecule and the capillary radius. In the transition zone, both the viscous flow and the slip flow are acted and they are superposed. Adzumi gave an expression for such phenomenon

$$q = \frac{pr^4}{8m}\frac{\Delta p}{l} + e\frac{4}{3}\sqrt{\frac{2pRT}{M}}\frac{r^3}{l}\frac{\Delta p}{\overline{p}} \tag{5}$$

Where e is the Adzumi factor, which is about 0.9 by Adzumi's experiments. In this paper, we define e as the ratio between area of the slip layer and the area of the capillary, as follow

$$e = \frac{A_{slip}}{A_{total}} \tag{6}$$

Where A_{total}, A_{slip} are the area of the slip layer and the area of the capillary respectively.

RESULTS

The simulation results of the slippage effects are presented in the following. The Klinkenberg effect is exhibited by the pore scale network modeling, which is the verification of our pore scale network model for the gas flow.

Most of our computations are conducted on a 100×100 network with coordination number equal to 6, which consist of more than 120,000 throats and 40,000 nodes. With the dual flow mechanics incorporated, the permeability became a function of the mean pressure. It shows that with the increase of the average pressure, the gas permeability decrease nonlinearly.

The Relationship between the Slip Factor and Permeabilities

The permeability and the slip factor are both material properties and depend on the morphology of the porous medium. Many authors have proposed general correlations between the slip factor and the gas absolute permeability. Jones and Owens [4] measured the gas permeability on more than 100 tight gas sand samples with permeabilities ranging from 0.0001 to 1.0 md and their data yield a relationship between b and k as follow

$$b = 0.86k^{-0.33} \tag{7}$$

Sampath and Keighin [5] thought that a correlation should be between b and k/f rather than between b and k. They suggested a correlation between the gas slip factor and the intrinsic gas permeabilities based on their experimental results using nitrogen:

$$b = 0.0955\left(\frac{k}{j}\right)^{-0.53} \tag{8}$$

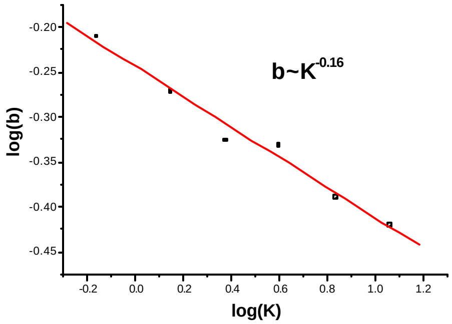

Figure 1 Relationship between gas slip factor and gas absolute permeabilities

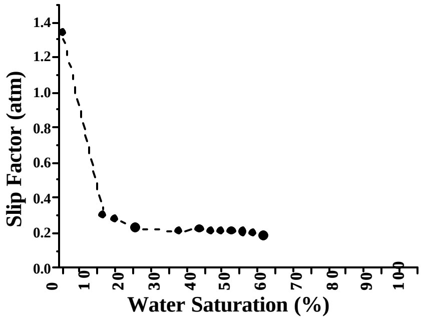

Figure 2 Simulation results for relationship between gas slip factor and water saturation

The conductance of each throat is proportional to the forth power of the throat radius, so the gas permeability decreases with the decrease in the average throat radius, as expected. While the Klinkenberg factor b decreased with the increase of the gas permeability, as showed in Figure 1. From the above observations, it is possible to derive the cross-correlation between the slip factor and the gas absolute permeability. It shows that $logb$ is linear proportional to $logk$. In our work this correlation can be specified as

$$b \propto k^{-m} \tag{9}$$

Where m is not a constant but a variable for different radius distributions. It is a similar expression with comparison to Eq.(7).

The Relationship between the Slip Factor and Water Saturation

The slip factor depends not only on the pore structure, but also on the liquid saturation. Rose [6], Fulton [7], Estes and Fulton[8] reported that the gas slip factor of the sandstone cores decreased with the increase of the water saturation. But the reason for which is not readily apparent.

Li and Horne[9] reported the slip factor increases with water saturation. They believed that: the gas slip factor is inversely proportional to the radius of the capillaries. The effective radius of the capillaries (for gas phase) in porous media must be decreased with an increase in liquid saturation. Therefore the gas slip factor should increase with the increase of the liquid saturation.

In the pore scale network model, the process of water/gas flow was modeled by invasion percolation algorithm. Then the gas slip factor at different water saturation was calculated from the model. The result was showed in Figure 2, which demonstrates the gas slip factor initially decreases with water saturation. It also shows that at water saturations above 20% the increase of slip factor is not as much as S_w less 20%.

Why are the results of these investigations on the effect of liquid saturation on slip factor dissimilar or contradictive? Li and Horne[9] believed this may be a consequence of small size of cores, the method to establish the liquid saturations, and the end effect upon the distribution of liquid saturation.

It is well known that there exist two major conceptions of the microscopic picture of two immiscible fluids flow in porous media [10]: the channel flow and the funicular flow. In channel flow concept, each phase moved through its own separate network of interconnecting channels. As the gas saturation increased there was an increase in the number of channels carrying gas and a corresponding decrease in the number of channels carrying only water. Under these conditions gas tends to occupy the larger pores and water the finer ones. This phenomenon is well modeled by the invasion percolation. In the funicular flow regime, both gas and water flow simultaneously in all capillaries, water on the outside surrounding gas, which is on the inside and occupies the centra1 portion of each capillary.

In Li *et.al.*'s experiment, the slip factors at different water saturation were calculated from a steady state method. As the water phase is mobile, the funicular flow may occur in their experiment. But in other's experiments[6,7,8], the channel flow may occur. The pore scale network model may simulate their results.

CONCLUSIONS

In this paper, we have briefly presented a conceptual framework for modeling the gas flow in the porous media. According to Adzumi's theory, the dual flow mechanism of viscous flow and gas diffusion in a capillary is incorporated into the pore scale network model. The Adzumi factor is determined from the relation between the mean free path of gas molecule and capillary radius. The conclusion can be drawn as follow:

1. From the pore scale network simulation, it shows that the slip factor decreased with the increasing of the permeability of the porous media and was affected by the variation of the distribution function of the capillary radius.

2. In the process of gas-water flow, the gas slip factor is affected by the water saturation. In the pore scale network modeling with invasion percolation, the slip factor decrease with the increase of the water saturation.

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