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Gas permeability model considering rock deformation and slippage in low permeability water-bearing gas reservoirs

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ABSTRACT

Permeability measurement is necessary in oil and gas fields. During the measurement, slippage, rock deformation, and water saturation affect apparent permeability of low permeability sandstones measured by different fluids. It is well known that gas slippage effect is very obvious and crucial in apparent permeability of low permeability sandstones measured for gas. Klinkenberg correlation was proposed to calculate gas permeability and absolute permeability for low permeability sandstones without considering rock deformation and water saturation. Most previous researchers modified the slippage factor b as a function of absolute permeability, porosity, and water saturation. However, few models were proposed for gas permeability calculation, simultaneously considering effects of rock deformation, gas slippage, and water saturation. In this work, Klinkenberg correlation was extended for permeability calculations measured by liquid and gases. The difference between apparent liquid permeability and apparent gas permeability was that gas slippage, which was much more evident from liquid slippage. An apparent gas permeability model was proposed for gas permeability and absolute permeability calculation simultaneously considering rock deformation, gas slippage, and water saturation in low permeability sandstones. The apparent gas permeability is proportional to the term T/p. Both the interception and the slope of the straight line in the T/p–k_g plot with Cartesian coordinate were power law functions of net stress and gas saturation. Some experimental data from literature were applied to validate the proposed model. Good agreements between experimental data and those evaluated by the proposed model were obtained. The apparent gas permeability model proposed in this work will be useful to professionals involved in laboratory measurement of low permeability water-bearing rocks, modeling well performance, and gas production forecasting.

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1. Introduction

Permeability measurement is important in the development of oil and gas reservoirs. In order to determine the rock permeability, four methods are mainly applied: (1) measuring the permeability of core samples through experiments in the lab, (2) interpreting the permeability through well logging, (3) interpreting the permeability from dynamic testing, such as Pressure Transient Analysis (PTA), Diagnostic Fluid Injection Tests (DFIT), Rate Transient Analysis (RTA), etc., (4) calculating the permeability by established permeability models, based on both theory and experiments. The first method is direct, common, and worthwhile, but it is not feasible to measure the permeability of the whole reservoir formation. Furthermore, results are believable only if the experimental condition accords with real formation condition. Permeability interpreted by the second and third method is more accurate, because of its compliance with formation condition, but the uncertainty during inversion may result in incorrect understanding of the permeability. The forth method is most convenient and useful; just a few groups of experiments will be used to determine coefficients of models. In reality, four methods should be integrated to obtain reliable estimate. Many investigators have done a lot of experiments on permeability measurement for gas, water, and/or oil in the lab, but only few authors have formulated corresponding permeability models considering fluid types, temperature, rock deformation, gas slippage, and water saturation at the same time.

Rock permeability can be measured by liquid or gases. It is found that the apparent permeability measured by gas is higher than that measured by liquid, especially for the low permeability

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Nomenclatures

k_g	apparent gas permeability, μm^2
k_∞	absolute permeability of rock without considering rock deformation, μm^2
$k_{\infty 0}$	initial absolute permeability, μm^2
b	Klinkenberg slip factor, Pa
λ_g	mean free path of gas molecules, μm
D_c	pore diameter of low permeability sandstones, μm
c	the proportionality factor, which is a constant near unity, dimensionless
k_i	apparent permeability measured by fluid i, μm^2
λ_i	mean free path of molecules of fluid i, μm
ϕ	the porosity of low permeability sandstones, dimensionless
τ	the tortuosity of low permeability sandstones, dimensionless
κ	the Boltzmann constant, which is equal to 1.38×10^{-23} J/K$=1.38\times10^{-5}$ μm^3 Pa/K
T	temperature, K
d	diameter of gas molecules, μm
p	gas average pressure, i.e., pore pressure, atm or Pa
p_{ave}	average pore pressure, atm or Pa
p_{ob}	confining pressure, psi or Pa
n	the first exponent of gas saturation, dimensionless
m	the second exponent of gas saturation, dimensionless
x	the coefficient of pore property of core sample, dimensionless
Δp	net stress, Pa
c_1	the first permeability coefficient of rock deformation, μm^2 Pa$^{-c_2}$
c_1'	the first permeability coefficient of rock deformation when the water saturation is kept the same, μm^2 Pa$^{-c_2}$
c_1''	the first permeability coefficient of rock deformation when the net stress is kept the same, D or mD
c_2	the second permeability coefficient of rock deformation, dimensionless
c_3	the first porosity coefficient of rock deformation, μm^2 Pa$^{-c_4}$
c_4	the second porosity coefficient of rock deformation, dimensionless
b_1	the exponent of rock deformation, dimensionless
a	the coefficient of rock deformation, μm^2 Pa$^{(1-b)}$ K^{-1}
a'	the coefficient of rock deformation when the water saturation is kept the same, μm^2 Pa$^{(1-b)}$ K^{-1}
a''	the coefficient of rock deformation, D Pa K^{-1} or mD Pa K^{-1}
A	intercept of the straight line in the plot of k_g versus $T\cdot p^{-1}$, D or mD
B	slope of straight line in the plot of k_g versus T/p, D Pa K^{-1} or mD Pa K^{-1}
B'	slope of straight line in the plot of k_g versus and $1/p$, D Pa or mD MPa
k_w	water effective permeability, μm^2
k_{rg}	gas relative permeability, f
k_{rw}	water relative permeability, f
A_s	cross sectional area, μm^2
L	length of the core, m
ϕ_0	initial porosity of the core, dimensionless
D_{c0}	initial diameter of capillary tubes, μm
S_w	water saturation, f
B_{f0}	initial width of slits, μm
B_f	width of slits, μm
W_0	initial length of slits, μm
W	length of slits, μm

rocks measured in the condition of low pore pressure, which is well known as the 'gas slippage effect' (Klinkenberg, 1941; Krutter and Day, 1941; Calhoun and Yuster, 1946). Gas slippage effect can be described as follows: when gas flows through porous media, the gas flow velocity in the immediate vicinity layer of solid surface is not zero with respect to solid surface, resulting in higher flow rate than that predicted by Poiseuille's formula.

Many factors affect the apparent gas permeability, such as absolute permeability, the nature of the gas, gas molecule diameter, pore property of core sample (dominated by pores or fractures, or averagely combined with pores and fractures), pore pressure, temperature, net stress, and water saturation.

Klinkenberg (1941) derived the apparent gas permeability model as a function of average pore pressure based on straight capillary tube model, and validated the model by experimental data. Permeability was measured by water, isooctane, nitrobenzene, air, hydrogen, and carbon dioxide. In his model, effects of the nature of gas and pore pressure were investigated; results showed that because of the difference between the mean free distance of air, hydrogen, and carbon dioxide, the apparent permeability measured by different gas is different. For a given type, the apparent gas permeability (k_g) is approximately a linear function of the reciprocal of average pore pressure ($1/p$), where the intercept is absolute permeability (k_∞) and the slope is the product of absolute permeability (k_∞) and the slippage coefficient (b). Krutter and Day (1941) modified Klinkenberg correlation; Calhoun and Yuster (1946) extended and verified the Klinkenberg correlation.

Casse and Ramey (1979), Wei et al. (1986), Gobran et al. (1987), and Rushing et al. (2003) investigated the effect of temperature on absolute permeability and apparent gas permeability. They all concluded that temperature almost did not affect the absolute permeability measured by gases, but affect the apparent gas permeability. Apparent gas permeability increased with temperature.

Casse and Ramey (1979), Jones and Owens (1979), Jennings et al. (1981), Sampath and Keighin (1981, 1982), Wei et al. (1986), Gobran et al. (1987), Rushing et al. (2003), Clarkson et al. (2012a, 2012b) investigated the effect of confining pressure on absolute permeability and apparent gas permeability. Wei et al. (1986) concluded that confining pressure was a dominant influencing factor for permeability. Gobran et al. (1987) concluded through experiments that absolute permeability linearly decreased with confining pressure increase during the first pressurization process, and thereafter nonlinearly decreased with confining pressure increase. They also pointed out that the absolute permeability could be expressed as a function of only one parameter: net confining pressure. Experiments from Sampath and Keighin (1981, 1982) demonstrated that extrapolated gas permeability of tight sandstones in the plot of gas permeability versus the reciprocal of average pore pressure (i.e. absolute permeability of rock) decreased with increasing net confining pressure, and the slope of this straight line also decreased with increasing net confining pressure. Jennings et al. (1981) proposed that the effect of confining pressure on permeability for low permeability reservoir rock could not be accurately described by capillary tube model, but by

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