Contents lists available at ScienceDirect



Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol



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



Juntai Shi<sup>a,\*</sup>, Xiangfang Li<sup>a</sup>, Qian Li<sup>b</sup>, Fanliao Wang<sup>a</sup>, Kamy Sepehrnoori<sup>c</sup>

<sup>a</sup> MOE Key Laboratory of Petroleum Engineering, China University of Petroleum at Beijing, Beijing 102249, PR China

<sup>b</sup> Exploration and Development Research Institute, Petrochina Southwest Oil and Gasfield Company, Chengdu 610041, PR China

<sup>c</sup> The University of Texas at Austin, Austin, TX 78712, USA

#### ARTICLE INFO

Article history: Received 20 April 2013 Accepted 29 April 2014 Available online 15 May 2014

Keywords: permeability measurement gas permeability model rock deformation gas slippage water saturation low permeability rocks

#### 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  $T/p-k_{\sigma}$  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 waterbearing rocks, modeling well performance, and gas production forecasting.

© 2014 Elsevier B.V. All rights reserved.

#### 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

http://dx.doi.org/10.1016/j.petrol.2014.04.019 0920-4105/© 2014 Elsevier B.V. All rights reserved. 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

<sup>\*</sup> Corresponding author. Tel.: +86 10 8973 4330; fax: +86 10 8973 4951. *E-mail address:* juntai.shi@gmail.com (J. Shi).

 $C_1''$ 

### Nomenclatures

$k_g$ absolute permeability, $\mu m^2$ $c_2$ the second permeability coefficient of rock deformation tion, dimensionless $k_{\infty0}$ initial absolute permeability, $\mu m^2$ $c_3$ the second permeability coefficient of rock deformation $\mu m^2 Pa^{-c_4}$ $k_{\infty0}$ mean free path of gas molecules, $\mu m$ $c_4$ the second porosity coefficient of rock deformation dimensionless $c_4$ the second porosity coefficient of rock deformation, dimensionless $m^2 Pa^{-c_4}$ $c_4$ the second porosity coefficient of rock deformation, dimensionless $m^2 Pa^{-(1-b)} K^{-1}$ $c_4$ the porosity coefficient of rock deformation, unity, dimensionless $m^2 Pa^{(1-b)} K^{-1}$ $c_4$ the porosity coefficient of rock deformation, unity, dimensionless $m^2 Pa^{(1-b)} K^{-1}$ $r$ the porosity of low permeability sandstones, dimensionless $a'$ $r$ the tortuosity of low permeability sandstones, dimensionless $a'$ $r$ the boltzmann constant, which is equal to $1.38 \times 10^{-23} J/K = 1.38 \times 10^{-5} \mu m^3 Pa/K$ $B'$ $T$ temperature, K diameter of gas molecules, $\mu m$ $B'$ $p_{ave}$ average pore pressure, i.e., pore pressure, atm or Pa $p_{ave}$ $B'$ $p_{ave}$ average pore pressure, i.e., pore property of core sample, dimensionless $B'$ $m$ the first permeability coefficient of rock deformation, $m^2 Pa^{-c_2}$ $B'_{averase}$ $f_1$ the first permeability coefficient of rock deformation $m^2 Pa^{-c_2}$ $B'_{averase}$ $f_1$ the first permeability coefficient of rock deformation			•	when the net stress is kept the same. D or mD
	k <sub>a</sub>	apparent gas permeability, $\mu m^2$	C <sub>2</sub>	the second permeability coefficient of rock deforma-
$k_{co}$ initial absolute permeability, $\mu m^2$ $c_3$ the first porosity coefficient of rock deformation, $\mu m^2 Pa^{-c_4}$ $b$ Klinkenberg slip factor, Pa $c_4$ the second porosity coefficient of rock deformation, dimensionless $D_c$ pore diameter of low permeability sandstones, $\mu m$ $b_1$ the exponent of rock deformation, $\mu m^2 Pa^{-(1-b)} K^{-1}$ $c_1$ the proportionality factor, which is a constant near unity, dimensionless $b_1$ the exponent of rock deformation, $\mu m^2 Pa^{-(1-b)} K^{-1}$ $k_i$ apparent permeability measured by fluid i, $\mu m^2$ $a'$ the coefficient of rock deformation, $\mu m^2 Pa^{-(1-b)} K^{-1}$ $k_i$ apparent permeability sandstones, dimensionless $a'$ the coefficient of rock deformation, $D Pa K^{-1}$ or m $D Pa K^{-1}$ $\kappa$ the boltzmann constant, which is equal to $1.38 \times 10^{-5} \mu^3 Pa^{-K}$ $B'$ slope of straight line in the plot of $k_g$ versus $T/p$ $D Pa or mD Pa K^{-1}$ $p_{ave}$ average pore pressure, atm or Pa $Pa_{ave}$ $k_{rw}$ water effective permeability, f $Pa_{ave}$ $p_{ave}$ average pore pressure, atm or Pa $Pa_{av}$ $k_{rw}$ water effective permeability, f $Pa_{av}$ $p_{ave}$ average pore property of core sample, dimensionless $k_{rw}$ water effective permeability, f $Pa_{av}$ $p_{ave}$ for property of core sample, dimensionless $k_{rw}$ water effective permeability, f $Pa_{av}$ $p_{ave}$ for permeability coefficient of rock deformation, $pa_{av}$ $k_{rw}$ water effective permeability, f $Pa_{av}$ $f_{a$	k_	absolute permeability of rock without considering	_	tion, dimensionless
$k_{so0}$ initial absolute permeability, $\mu m^2$ $\mu m^2 Pa^{-c_4}$ bKlinkenberg slip factor, Pa $c_4$ $\lambda_g$ mean free path of gas molecules, $\mu m$ the second porosity coefficient of rock deformation, dimensionlesscthe proportionality factor, which is a constant near unity, dimensionless $b_1$ cthe proportionality factor, which is a constant near unity, dimensionless $b_1$ kiapparent permeability measured by fluid i, $\mu m^2$ $a''$ $\lambda_i$ mean free path of molecules of fluid i, $\mu m^2$ $a''$ $\lambda_i$ mean free path of molecules of fluid i, $\mu m^2$ $a''$ $\tau$ the torosity of low permeability sandstones, dimensionless $a''$ $\tau$ the tortuosity of low permeability sandstones, dimensionless $m D Pa K^{-1}$ $\tau$ the boltzmann constant, which is equal to $1.38 \times 10^{-23}$ J/K= $1.38 \times 10^{-5} \mu m^3 Pa/K$ $B''$ $T$ temperature, K $k_w$ water relative permeability, f slope of straight line in the plot of $k_g$ versus and $1/p$ . $p$ gas average pressure, i.e., pore pressure, atm or Pa $h_{row}$ $k_{row}$ water relative permeability, f $h_{row}$ $p_{obb}$ confining pressure, psi or Pa $n$ $A_s$ cross sectional area, $\mu m^2$ $n$ the first exponent of gas saturation, dimensionless $x$ $h_{o}$ cross sectional area, $\mu m^2$ $r$ the coefficient of pore property of core sample, dimensionless $h_{o}$ initial diameter of capillary tubes, $\mu m$ $r$ the first permeability coefficient of rock deformation $\mu$		rock deformation. $\mu m^2$	C3	the first porosity coefficient of rock deformation,
bKlinkenberg slip factor, PaC4the second porosity coefficient of rock deformation, dimensionless $\lambda_g$ mean free path of molecules of fluid i, µmb1 the exponent of rock deformation, µm² Pa <sup>(1-b)</sup> K <sup>-1</sup> the coefficient of rock deformation, µm² Pa <sup>(1-b)</sup> K <sup>-1</sup> the coefficient of rock deformation, D Pa K <sup>-1</sup> or mD Pa K <sup>-1</sup> the coefficient of rock deformation, D Pa K <sup>-1</sup> or D Pa K <sup>-1</sup> the porosity of low permeability sandstones, dimensionlessa"the second porosity coefficient of rock deformation, dimensionless the coefficient of rock deformation, D Pa K <sup>-1</sup> or mD Pa K <sup>-1</sup> $\chi$ immean free path of molecules of fluid i, µm $\psi$ the tortuosity of low permeability sandstones, dimensionlessa"the coefficient of rock deformation, D Pa K <sup>-1</sup> or mD Pa K <sup>-1</sup> $\chi$ immean free path of molecules of pressure, k dimensionlessthe ortuosity of low permeability sandstones, dimensionlessa"the coefficient of rock deformation, D Pa K <sup>-1</sup> or mD Pa K <sup>-1</sup> $\chi$ immean free path of molecules, µma"the coefficient of rock deformation, D Pa K <sup>-1</sup> or mD Pa K <sup>-1</sup> .b $\chi$ immeanter of gas molecules, µmb"b"slope of straight line in the plot of $k_g$ versus and $1/p$ D Pa or mD Pa K <sup>-1</sup> $\chi$ pob confining pressure, i.e., pore pressure, atm or Pa m the first exponent of gas saturation, dimensionless x the coefficient of pore property of core sample, dimensionlesskw w water relative permeability, f A_s cross sectional area, µm² the first permeability coefficient of rock deformation, µm² Pa <sup>-C2</sup> $\Delta p$ r r rnet stress, Pa cri the first permeability coefficient of rock deformation, µ	$k_{\infty 0}$	initial absolute permeability. $\mu m^2$		$\mu m^2 \operatorname{Pa}^{-c_4}$
$ \begin{array}{llllllllllllllllllllllllllllllllllll$	b	Klinkenberg slip factor, Pa	<i>C</i> <sub>4</sub>	the second porosity coefficient of rock deformation,
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	λσ	mean free path of gas molecules, µm		dimensionless
cthe proportionality factor, which is a constant near unity, dimensionlessathe coefficient of rock deformation, $\mu m^2 Pa^{(1-b)} K^{-1}$ the coefficient of rock deformation when the water saturation is kept the same, $\mu m^2 Pa^{(1-b)} K^{-1}$ the coefficient of rock deformation, $\mu m^2 Pa^{(1-b)} K^{-1}$ the torusity of low permeability sandstones, dimensionlessa $\tau$ the torusity of low permeability sandstones, dimensionless $A$ intercept of the straight line in the plot of $k_g$ versus $T/p$ $D Pa K^{-1}$ or mD Pa $K^{-1}$ slope of straight line in the plot of $k_g$ versus $m^2/p^2$ $D Pa rom D MPa$ $K$ the Boltzmann constant, which is equal to $1.38 \times 10^{-23} J/K = 1.38 \times 10^{-5} \mu m^3 Pa/K$ $B'$ slope of straight line in the plot of $k_g$ versus $T/p$ $D Pa rom D MPa$ $f$ temperature, K d d d diameter of gas nolecules, $\mu m$ $k_w$ water effective permeability, f $r_g$ sa ross sectional area, $\mu m^2$ $p_{ove}$ average pore pressure, atm or Pa m the first per	D <sub>c</sub>	pore diameter of low permeability sandstones, µm	$b_1$	the exponent of rock deformation, dimensionless
unity, dimensionlessathe coefficient of rock deformation when the water saturation is kept the same, $\mu m^2 Pa^{(1-b)} K^{-1}$ $\lambda_i$ mean free path of molecules of fluid i, $\mu m^2$ athe coefficient of rock deformation, D Pa K^{-1} $\lambda_i$ mean free path of molecules of fluid i, $\mu m^2$ athe coefficient of rock deformation, D Pa K^{-1} $\lambda_i$ mean free path of molecules of fluid i, $\mu m^2$ athe coefficient of rock deformation, D Pa K^{-1} $\phi$ the porosity of low permeability sandstones, dimensionlessintercept of the straight line in the plot of $k_g$ versus $T$ . $p^{-1}$ , D or mD $\tau$ the boltzmann constant, which is equal to $1.38 \times 10^{-23}$ J/K = $1.38 \times 10^{-5}$ $\mu m^3$ Pa/KB'slope of straight line in the plot of $k_g$ versus and $1/p_i$ D Pa K^{-1} or mD Pa K^{-1} $T$ temperature, KB'slope of straight line in the plot of $k_g$ versus and $1/p_i$ D Pa or mD MPa $q$ vareage pore pressure, atm or Pa Pave $k_{rg}$ gas relative permeability, $\mu^2$ water relative permeability, f $p_{obc}$ confining pressure, psi or Pa n $A_s$ cross sectional area, $\mu m^2$ $n$ the first exponent of gas saturation, dimensionless $x$ $L$ length of the core, m $m$ the scond exponent of pace saturation, dimensionless $x$ $S_w$ water saturation, f $\rho_1$ the first permeability coefficient of rock deformation, $\mu m^2$ Pa^{-c_2} $W_0$ initial length of slits, $\mu m$ $c_1'$ the first permeability coefficient of rock deformation, $\mu m^2$ Pa^{-c_2} $W_0$ initial length of slits, $\mu m$ </td <td>С</td> <td>the proportionality factor, which is a constant near</td> <td>а</td> <td>the coefficient of rock deformation, <math>\mu m^2 Pa^{(1-b)} K^{-1}</math></td>	С	the proportionality factor, which is a constant near	а	the coefficient of rock deformation, $\mu m^2 Pa^{(1-b)} K^{-1}$
$k_i$ apparent permeability measured by fluid i, $\mu m^2$ saturation is kept the same, $\mu m^2 Pa^{(1-b)} K^{-1}$ $\lambda_i$ mean free path of molecules of fluid i, $\mu m$ $a''$ the coefficient of rock deformation, DPa K^{-1} or $\phi$ the porosity of low permeability sandstones, dimensionless $a''$ the coefficient of rock deformation, DPa K^{-1} or $\tau$ the tortuosity of low permeability sandstones, dimensionless $A$ intercept of the straight line in the plot of $k_g$ versus $\tau$ the tortuosity of low permeability sandstones, dimensionless $B$ slope of straight line in the plot of $k_g$ versus $T/p$ . $\kappa$ the Boltzmann constant, which is equal to $1.38 \times 10^{-23}$ J/K= $1.38 \times 10^{-5} \mu m^3$ Pa/K $B'$ slope of straight line in the plot of $k_g$ versus and $1/p$ . $T$ temperature, K $B'$ slope of straight line in the plot of $k_g$ versus and $1/p$ . $q$ average pore pressure, i.e., pore pressure, atm or Pa $k_{rg}$ gas average pressure, pi or Pa $A_s$ cross sectional area, $\mu m^2$ $n$ the first exponent of gas saturation, dimensionless $L$ length of the core, mlength of the core, dimensionless $\kappa$ the coefficient of pore property of core sample, dimensionless $D_{co}$ initial diameter of capillary tubes, $\mu m$ $\alpha''$ the first permeability coefficient of rock deformation, $\mu m^2$ Pa <sup>-C2</sup> $B''$ initial length of slits, $\mu m$ $\kappa_1$ the first permeability coefficient of rock deformation, $\mu m^2$ Pa <sup>-C2</sup> $B''$ initial length of slits, $\mu m$ $\alpha'$ the first permeability coefficient of rock defor		unity, dimensionless	a'	the coefficient of rock deformation when the water
λ₁mean free path of molecules of fluid i, μma"the coefficient of rock deformation, D Pa K^{-1} or mD Pa K^{-1}φthe porosity of low permeability sandstones, dimensionlessa"the coefficient of rock deformation, D Pa K^{-1} or mD Pa K^{-1}τthe tortuosity of low permeability sandstones, dimensionlessaslope of straight line in the plot of kg versus T/p. D Pa K^{-1} or mD Pa K^{-1}κthe Boltzmann constant, which is equal to 1.38 × 10^{-23} J/K=1.38 × 10^{-5} µm <sup>3</sup> Pa/KB'slope of straight line in the plot of kg versus and 1/p. D Pa or mD MPaddiameter of gas molecules, µm p gas average pore pressure, i.e., pore pressure, atm or Pa mkw water effective permeability, µm <sup>2</sup> gas relative permeability, fpobconfining pressure, psi or Pa dimensionlessAs cons sectional area, µm <sup>2</sup> πthe second exponent of gas saturation, dimensionless xthe coefficient of pore property of core sample, dimensionlessBo mΔpnet stress, Pa c1Bo the first permeability coefficient of rock deformation, when the water saturation is kept the same, µm <sup>2</sup> Pa^{-C2}Bo the first, µm $C_1'$ the first permeability coefficient of rock deformation when the water saturation is kept the same, µm <sup>2</sup> Pa^{-C2}Bo the same, wlength of slits, µm	$k_{\rm i}$	apparent permeability measured by fluid i, $\mu m^2$		saturation is kept the same, $\mu m^2 \operatorname{Pa}^{(1-b)} \mathrm{K}^{-1}$
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 × 10-5 μm3 Pa/K  d diameter of gas molecules, μm  p gas average pressure, i.e., pore pressure, atm or Pa  h the first exponent of gas saturation, dimensionless  x the coefficient of pore property of core sample, d dimensionless  x the coefficient of pore property of core sample, d dimensionless  x the coefficient of pore property of core sample, d dimensionless  x the coefficient of pore property of core sample, d dimensionless  x the coefficient of pore property of core sample, d dimensionless  x the coefficient of pore property of core sample, d dimensionless  x the coefficient of pore property of core sample, d dimensionless  x the coefficient of pore property of core sample, d dimensionless  x the coefficient of pore property of core sample, d dimensionless  x the coefficient of pore property of core sample, d dimensionless  x the coefficient of pore property of core sample, d dimensionless  x the coefficient of pore property of core sample, d dimensionless  x the coefficient of pore property of core sample, d dimensionless  x the coefficient of pore property of core sample, d dimensionless  x the coefficient of prock deformation, μm2 Pa-C2  W0 initial length of slits, μm when the water saturation is kept the same, μm2 Pa-C2	$\lambda_{i}$	mean free path of molecules of fluid i, $\mu m$	a″	the coefficient of rock deformation, D Pa $K^{-1}$ or
dimensionlessAintercept of the straight line in the plot of $k_g$ versus $\tau$ the tortuosity of low permeability sandstones, dimensionlessBslope of straight line in the plot of $k_g$ versus $T/p$ . D Pa $K^{-1}$ or mD Pa $K^{-1}$ $\kappa$ the Boltzmann constant, which is equal to $1.38 \times 10^{-23}$ J/K = $1.38 \times 10^{-5}$ µm <sup>3</sup> Pa/KB'slope of straight line in the plot of $k_g$ versus and $1/p$ . D Pa $K^{-1}$ or mD Pa $K^{-1}$ Ttemperature, KB'slope of straight line in the plot of $k_g$ versus and $1/p$ . D Pa or mD MPaddiameter of gas molecules, µm $k_w$ water effective permeability, $f$ $p$ gas average pressure, i.e., pore pressure, atm or Pa $k_{rg}$ gas relative permeability, f $p_{ave}$ average pore pressure, atm or Pa $k_{rw}$ water relative permeability, f $p_{ob}$ confining pressure, psi or Pa $A_s$ cross sectional area, µm <sup>2</sup> $n$ the first exponent of gas saturation, dimensionless $L$ length of the core, dimensionless $x$ the coefficient of pore property of core sample, dimensionless $D_{c0}$ initial diameter of capillary tubes, µm $\Delta p$ net stress, Pa $B_{r0}$ initial width of slits, µm $c_1'$ the first permeability coefficient of rock deformation when the water saturation is kept the same, $\mu^{m^2} Pa^{-c_2}$ $W_0$ initial length of slits, µm	$\phi$	the porosity of low permeability sandstones,		mD Pa $K^{-1}$
τthe tortuosity of low permeability sandstones, dimensionlessT · p^{-1}, D or mDκthe Boltzmann constant, which is equal to $1.38 \times 10^{-23}$ J/K=1.38 × $10^{-5}$ μm³ Pa/KBslope of straight line in the plot of $k_g$ versus and $1/p$ . D Pa K <sup>-1</sup> or mD Pa K <sup>-1</sup> Ttemperature, KB'slope of straight line in the plot of $k_g$ versus and $1/p$ . D Pa or mD MPaddiameter of gas molecules, μmkwwater effective permeability, μm²pgas average pressure, i.e., pore pressure, atm or Pakrwwater relative permeability, fp_{ave}average pore pressure, psi or PaA_scross sectional area, μm²nthe first exponent of gas saturation, dimensionlessLlength of the core, mmthe second exponent of gas saturation, dimensionless $D_{co}$ xthe coefficient of pore property of core sample, dimensionless $D_{co}$ $\Delta p$ net stress, Pa $B_{fo}$ initial width of slits, µm $c_1$ the first permeability coefficient of rock deformation, when the water saturation is kept the same, $\mu^{m^2} Pa^{-c_2}$ Wo		dimensionless	Α	intercept of the straight line in the plot of $k_{\rm g}$ versus
dimensionlessBslope of straight line in the plot of $k_g$ versus $T/p$ . $\kappa$ the Boltzmann constant, which is equal to $1.38 \times 10^{-23}$ J/K = $1.38 \times 10^{-5}$ $\mu$ m <sup>3</sup> Pa/KD Pa K^{-1} or mD Pa K^{-1}Ttemperature, KB'slope of straight line in the plot of $k_g$ versus and $1/p$ .ddiameter of gas molecules, $\mu$ mkwwater effective permeability, $\mu$ m <sup>2</sup> pgas average pressure, i.e., pore pressure, atm or Pakrwwater relative permeability, f $p_{ave}$ average pore pressure, atm or Pakrwwater relative permeability, f $p_{ob}$ confining pressure, psi or PaA_scross sectional area, $\mu$ m <sup>2</sup> nthe first exponent of gas saturation, dimensionlessLlength of the core, mmthe second exponent of gas saturation, dimensionless $D_{c0}$ initial diameter of capillary tubes, $\mu$ m $c_1$ the first permeability coefficient of rock deformation, when the water saturation is kept the same, $\mu$ m <sup>2</sup> Pa <sup>-C2</sup> $W_0$ initial length of slits, $\mu$ m $c_1'$ the first permeability coefficient of rock deformation when the water saturation is kept the same, $\mu$ m <sup>2</sup> Pa <sup>-C2</sup> Woinitial length of slits, $\mu$ m	τ	the tortuosity of low permeability sandstones,		$T \cdot p^{-1}$ , D or mD
$\kappa$ the Boltzmann constant, which is equal to $1.38 \times 10^{-23}$ J/K= $1.38 \times 10^{-5}$ µm³ Pa/K $D Pa K^{-1}$ or mD Pa K <sup>-1</sup> $T$ temperature, K $B'$ slope of straight line in the plot of $k_g$ versus and $1/p$ . $d$ diameter of gas molecules, µm $k_w$ water effective permeability, µm² $p$ gas average pressure, i.e., pore pressure, atm or Pa $k_{rg}$ gas relative permeability, f $p_{ave}$ average pore pressure, atm or Pa $k_{rw}$ water relative permeability, f $p_{ob}$ confining pressure, psi or Pa $A_s$ cross sectional area, µm² $n$ the first exponent of gas saturation, dimensionless $L$ length of the core, m $m$ the second exponent of gas saturation, dimensionless $p_{co}$ initial porosity of the core, dimensionless $x$ the coefficient of pore property of core sample, dimensionless $p_{co}$ initial width of slits, µm $c_1$ the first permeability coefficient of rock deformation, when the water saturation is kept the same, $\mu m^2 Pa^{-c_2}$ $W_0$ initial length of slits, µm $c_1'$ the first permeability coefficient of rock deformation when the water saturation is kept the same, $\mu m^2 Pa^{-c_2}$ $W_0$ initial length of slits, µm		dimensionless	В	slope of straight line in the plot of $k_{\rm g}$ versus $T/p$ ,
$1.38 \times 10^{-23}$ J/K= $1.38 \times 10^{-5}$ μm³ Pa/KB'slope of straight line in the plot of $k_g$ versus and $1/p$ .Ttemperature, KD Pa or mD MPaddiameter of gas molecules, μmkwwater effective permeability, µm²pgas average pressure, i.e., pore pressure, atm or Pakrggas relative permeability, fp_{ave}average pore pressure, atm or Pakrwwater relative permeability, fp_obconfining pressure, psi or PaAscross sectional area, µm²nthe first exponent of gas saturation, dimensionlessLlength of the core, mmthe second exponent of gas saturation, dimensionless $\phi_0$ initial porosity of the core, dimensionlessxthe coefficient of pore property of core sample, dimensionless $D_{c0}$ initial diameter of capillary tubes, µmc_1the first permeability coefficient of rock deformation, µm² Pa^{-C2} $W_0$ initial length of slits, µmc_1'the first permeability coefficient of rock deformation when the water saturation is kept the same, µm² Pa^{-C2} $W_0$ initial length of slits, µm	κ	the Boltzmann constant, which is equal to		D Pa $K^{-1}$ or mD Pa $K^{-1}$
Ttemperature, KD Pa or mD MPaddiameter of gas molecules, $\mu$ m $k_w$ water effective permeability, $\mu$ m²pgas average pressure, i.e., pore pressure, atm or Pa $k_{rg}$ gas relative permeability, f $p_{ave}$ average pore pressure, atm or Pa $k_{rw}$ water relative permeability, f $p_{ob}$ confining pressure, psi or Pa $A_s$ cross sectional area, $\mu$ m²nthe first exponent of gas saturation, dimensionlessLlength of the core, mmthe second exponent of gas saturation, dimensionless $\phi_0$ initial porosity of the core, dimensionlessxthe coefficient of pore property of core sample, dimensionless $D_{c0}$ initial diameter of capillary tubes, $\mu$ m $S_w$ water saturation, f $\Delta p$ net stress, Pa $B_{f0}$ initial width of slits, $\mu$ m $c_1'$ the first permeability coefficient of rock deformation when the water saturation is kept the same, $\mu^{m^2} Pa^{-C_2}$ $W_0$ initial length of slits, $\mu$ m		$1.38 \times 10^{-23}$ J/K = $1.38 \times 10^{-5}$ $\mu$ m <sup>3</sup> Pa/K	B'	slope of straight line in the plot of $k_{\rm g}$ versus and $1/p$ ,
ddiameter of gas molecules, $\mu$ m $k_w$ water effective permeability, $\mu$ m²pgas average pressure, i.e., pore pressure, atm or Pa $k_{rg}$ gas relative permeability, f $p_{ave}$ average pore pressure, atm or Pa $k_{rw}$ water relative permeability, f $p_{ob}$ confining pressure, psi or Pa $A_s$ cross sectional area, $\mu$ m²nthe first exponent of gas saturation, dimensionlessLlength of the core, mmthe second exponent of gas saturation, dimensionless $\phi_0$ initial porosity of the core, dimensionlessxthe coefficient of pore property of core sample, dimensionless $D_{c0}$ initial diameter of capillary tubes, $\mu$ m $\Delta p$ net stress, Pa $B_{r0}$ initial width of slits, $\mu$ m $c_1'$ the first permeability coefficient of rock deformation when the water saturation is kept the same, $\mu m^2 Pa^{-c_2}$ $W_0$ initial length of slits, $\mu$ m	Т	temperature, K		D Pa or mD MPa
pgas average pressure, i.e., pore pressure, atm or Pa $k_{rg}$ gas relative permeability, f $p_{ave}$ average pore pressure, atm or Pa $k_{rw}$ water relative permeability, f $p_{ob}$ confining pressure, psi or Pa $A_s$ cross sectional area, $\mu m^2$ nthe first exponent of gas saturation, dimensionless $L$ length of the core, mmthe second exponent of gas saturation, dimensionless $\phi_0$ initial porosity of the core, dimensionlessxthe coefficient of pore property of core sample, dimensionless $D_{c0}$ initial diameter of capillary tubes, $\mu m$ $\Delta p$ net stress, Pa $B_{f0}$ initial width of slits, $\mu m$ $\mu m^2 Pa^{-C_2}$ $W_0$ initial length of slits, $\mu m$ c_1'the first permeability coefficient of rock deformation when the water saturation is kept the same, $\mu m^2 Pa^{-C_2}$ $W_0$ initial length of slits, $\mu m$	d	diameter of gas molecules, µm	k <sub>w</sub>	water effective permeability, µm <sup>2</sup>
$p_{ave}$ average pore pressure, atm or Pa $k_{rw}$ water relative permeability, f $p_{ob}$ confining pressure, psi or Pa $A_s$ cross sectional area, $\mu m^2$ $n$ the first exponent of gas saturation, dimensionless $L$ length of the core, m $m$ the second exponent of gas saturation, dimensionless $\phi_0$ initial porosity of the core, dimensionless $x$ the coefficient of pore property of core sample, dimensionless $D_{c0}$ initial diameter of capillary tubes, $\mu m$ $\Delta p$ net stress, Pa $B_{f0}$ initial width of slits, $\mu m$ $c_1$ the first permeability coefficient of rock deformation, when the water saturation is kept the same, $\mu m^2 Pa^{-C_2}$ Woinitial length of slits, $\mu m$ $w_{n}$ the saturation is kept the same, $\mu m^2 Pa^{-C_2}$ water saturation is kept the same, $\mu m^2 Pa^{-C_2}$ length of slits, $\mu m$	р	gas average pressure, i.e., pore pressure, atm or Pa	$k_{\rm rg}$	gas relative permeability, f
$p_{ob}$ confining pressure, psi or Pa $A_s$ cross sectional area, $\mu m^2$ $n$ the first exponent of gas saturation, dimensionless $L$ length of the core, m $m$ the second exponent of gas saturation, dimensionless $\phi_0$ initial porosity of the core, dimensionless $x$ the coefficient of pore property of core sample, dimensionless $D_{c0}$ initial diameter of capillary tubes, $\mu m$ $\Delta p$ net stress, Pa $B_{f0}$ initial width of slits, $\mu m$ $c_1$ the first permeability coefficient of rock deformation, when the water saturation is kept the same, $\mu m^2 Pa^{-c_2}$ $W_0$ initial length of slits, $\mu m$ $m^2 Pa^{-c_2}$ weater saturation is kept the same, $\mu m^2 Pa^{-c_2}$ $W_0$ initial length of slits, $\mu m$	$p_{\rm ave}$	average pore pressure, atm or Pa	k <sub>rw</sub>	water relative permeability, f
nthe first exponent of gas saturation, dimensionlessLlength of the core, mmthe second exponent of gas saturation, dimensionless $\phi_0$ initial porosity of the core, dimensionlessxthe coefficient of pore property of core sample, dimensionless $\phi_0$ initial diameter of capillary tubes, $\mu m$ $\Delta p$ net stress, Pa $B_{f0}$ initial width of slits, $\mu m$ $c_1$ the first permeability coefficient of rock deformation, $\mu m^2 Pa^{-c_2}$ $B_f$ width of slits, $\mu m$ $c_1'$ the first permeability coefficient of rock deformation when the water saturation is kept the same, $\mu m^2 Pa^{-c_2}$ $W_0$ initial length of slits, $\mu m$	$p_{\rm ob}$	confining pressure, psi or Pa	As	cross sectional area, µm <sup>2</sup>
mthe second exponent of gas saturation, dimensionless $     \phi_0 $ initial porosity of the core, dimensionlessxthe coefficient of pore property of core sample, dimensionless $     D_{c0} $ initial diameter of capillary tubes, $\mu m$ $\Delta p$ net stress, Pa $B_{f0}$ initial width of slits, $\mu m$ $c_1$ the first permeability coefficient of rock deformation $\mu m^2 Pa^{-C_2}$ $W_0$ initial length of slits, $\mu m$ $c_1'$ the first permeability coefficient of rock deformation when the water saturation is kept the same, $\mu m^2 Pa^{-C_2}$ $W_0$ initial length of slits, $\mu m$	п	the first exponent of gas saturation, dimensionless	L	length of the core, m
xthe coefficient of pore property of core sample, dimensionless $D_{c0}$ initial diameter of capillary tubes, $\mu m$ $\Delta p$ net stress, Pa $S_w$ water saturation, f $c_1$ the first permeability coefficient of rock deformation, $\mu m^2 Pa^{-c_2}$ $B_f$ width of slits, $\mu m$ $c_1'$ the first permeability coefficient of rock deformation when the water saturation is kept the same, $\mu m^2 Pa^{-c_2}$ $W_0$ initial length of slits, $\mu m$	т	the second exponent of gas saturation, dimensionless	$\phi_0$	initial porosity of the core, dimensionless
dimensionless $S_w$ Water saturation, f $\Delta p$ net stress, Pa $B_{f0}$ initial width of slits, $\mu m$ $c_1$ the first permeability coefficient of rock deformation, $\mu m^2 Pa^{-c_2}$ $W_0$ initial length of slits, $\mu m$ $c_1'$ the first permeability coefficient of rock deformation when the water saturation is kept the same, $\mu m^2 Pa^{-c_2}$ $W$ length of slits, $\mu m$	х	the coefficient of pore property of core sample,	$D_{c0}$	initial diameter of capillary tubes, $\mu m$
$\begin{array}{llllllllllllllllllllllllllllllllllll$		dimensionless	Sw	water saturation, f
$c_1$ the first permeability coefficient of rock deformation, $\mu m^2$ Pa <sup>-c2</sup> $B_f$ Width of slits, $\mu m$ $c_1'$ the first permeability coefficient of rock deformation when the water saturation is kept the same, $\mu m^2$ Pa <sup>-c2</sup> $W_0$ initial length of slits, $\mu m$	$\Delta p$	net stress, Pa	$B_{\rm f0}$	initial width of slits, $\mu m$
$\mu m^2 Pa^{-c_2}$ $W_0$ initial length of slits, $\mu m$ $c_1'$ the first permeability coefficient of rock deformation $W$ length of slits, $\mu m$ when the water saturation is kept the same, $\mu m^2 Pa^{-c_2}$	<i>c</i> <sub>1</sub>	the first permeability coefficient of rock deformation,	D <sub>f</sub>	width of slits, µlli
$c_1'$ the first permeability coefficient of rock deformation $w$ length of sits, $\mu$ m when the water saturation is kept the same, $\mu m^2 \operatorname{Pa}^{-c_2}$		$\mu m^2 Pa^{-c_2}$	VV <sub>0</sub>	linual length of slits, um
when the water saturation is kept the same, $\mu m^2 \operatorname{Pa}^{-c_2}$	$C_1'$	the first permeability coefficient of rock deformation	VV	length of sins, µm
$\mu m$ Pa *		when the water saturation is kept the same, $um^2 D = \frac{C_2}{2}$		
		µm² Pa		

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  $(k_{\infty})$  and the slope is the product of absolute permeability  $(k_{\infty})$  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.

the first permeability coefficient of rock deformation

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 Download English Version:

# https://daneshyari.com/en/article/1755031

Download Persian Version:

https://daneshyari.com/article/1755031

Daneshyari.com