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7

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rate will be relatively high in a period of time after reaching the peak gas rate; the gas production is more sensitive to sorption time constant for the low-permeability tectonically deformed coal seam than for the high-permeability one.

Key words: coal bed methane; high rank coal seam; diffusion; gas rate; coal texture.

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，，．，、 3 ．，、、，（Duong, 1998；，1998；，2014）；、，（Saghafi *et al*., 2007；，2013）；、，、，，（，2012；Cai *et al*., 2012；Meng and Li, 2013；，2014；，2014），（，2015）．、（）（Karniadakis *et al*., 2005）．、（Smith and Williams, 1984; Li and Saghafi, 2014）．，（Saghafi *et al*., 2007）（，2009；，2011），．、（，2009；，2011；Liu *et al*., 2015）．（2014）5，、、、．（2013），．（2014），，．（2012）CO_2，CO_2．（2015），、，．Pillalamarry *et al*.(2011)，3.5 MPa

．Guo *et al*.(2016)，．(2016)，，．Drazer *et al*.(1999)，，．Letham and Bustin (2015)，．Hu *et al*.(2017)，160 ℃，，，，．，．，、．、，，，．

1

1.1 气体在多孔介质中的运移模式

Kn，4：、、（1）(Karniadakis *et al*., 2005)．Kn：

$$Kn=\frac{\lambda}{d}\,, \tag{1}$$

，λ，m；d

表 1 气体在多孔介质中的运移模式

Table 1 Flow regimes of gas through porous media

Kn	<0.001	0.001～0.1	0.1～10	>10

, , m.

λ :

$$\lambda=\frac{K_B T}{\sqrt{2}\pi d_0^2 p}\ , \qquad (2)$$

, K_B , 1.38×10^{-23} J/K; T , K; d_0 , nm; p , MPa.

,

, ,

(Klinkenberg, 1941; Zhang *et al*., 2012; , 2016).

:

$$k_g=k_\infty\left(1+\frac{b}{p_m}\right)\ , \qquad (3)$$

$$p_m=\frac{p_o+p_i}{2}\ , \qquad (4)$$

$$b=\frac{4C\lambda p_m}{r_H}\ , \qquad (5)$$

, k_g , m^2; k_∞ , m^2; b , Pa; p_m , Pa; p_i, p_o , Pa; C , 1; r_H , m.

(1) (3)～(5),

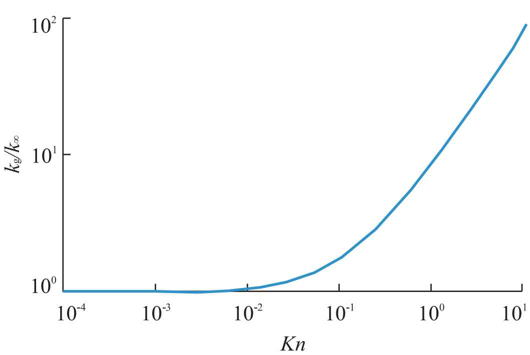
:

$$\frac{k_g}{k_\infty}=1+4CKn$$ [redacted]

[redacted] , , (1).

1.2 气体在多孔介质中的扩散模式

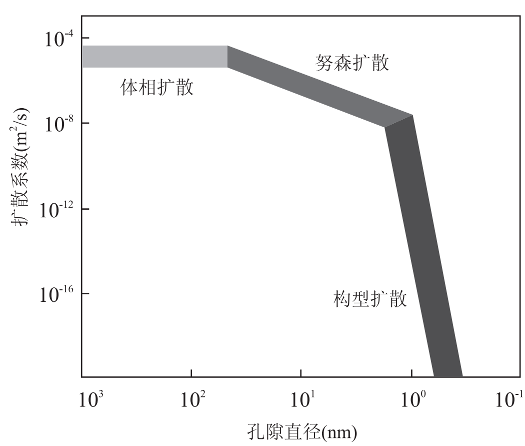
, . ( ), .



1

Fig.1 Variation coefficient of gas permeability at different Knudsen numbers

, . , (Drazer *et al*., 1999; Schuring, [redacted]



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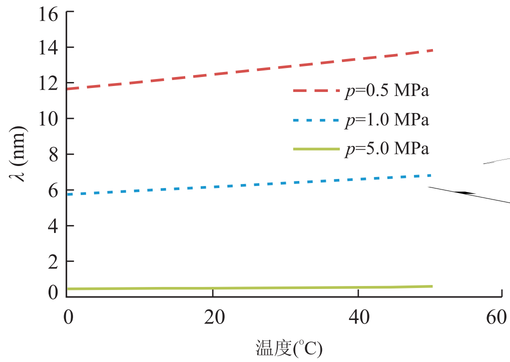
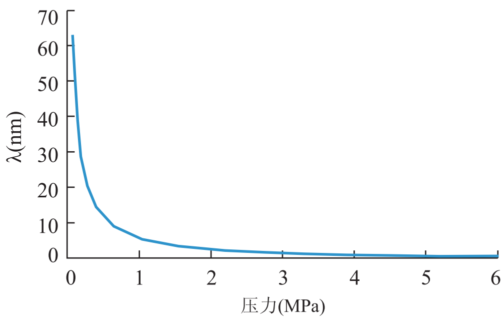


3

Fig.3 Variation of mean free path of methane over temperature



4 20 ℃

Fig.4 Variation of mean free path of methane over pressure at 20 ℃

20 ℃ , 63 nm(4).

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1 μm ,

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1.3 扩散性能的定量表征

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Chapman-Enskog ,

(Duong, 1998; Karniadakis *et al*., 2005):

$$D=\frac{1.86\times10^{-3}\varphi T^{3/2}(1/M_1+1/M_2)^{1/2}}{\xi p\sigma_{12}^2\Omega},\quad(7)$$

, D , cm^2/s; φ ,

; ξ , ; M_1、M_2

, g/mol; $\sigma_{12}=\frac{1}{2}(\sigma_1+\sigma_2)$,

, 0 σ_1、σ_2 , 10^{-10} m; $\Omega=$

$f(\frac{K_B T}{\varepsilon_{12}})$,

(,1999), ,

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.Simed

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Simed , S-D ,

(, 2014; Li and Saghafi, 2014).

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, , 400～700 m,

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4 000 m^3/d; 、 ,

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(,2014), ,

2.5 m/d, 150 kPa.

表 2 煤层气藏数值模拟输入参数

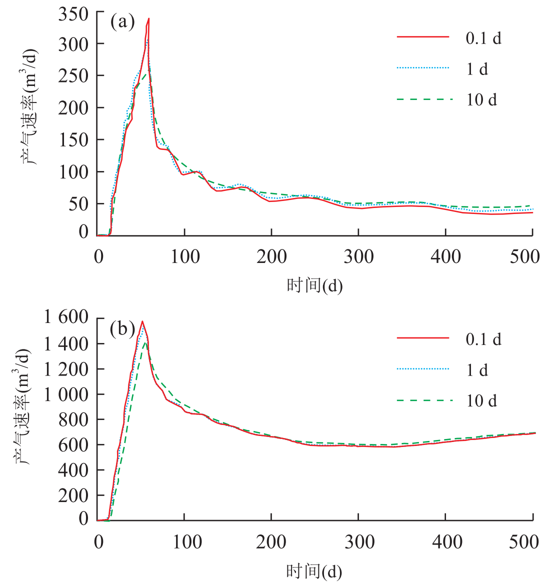
Table 2 Parameters used in numeric simulation of coal bed methane reservoirs

(m)	500
(m)	5
(10^{-15} m^2)	5^A、0.2^B
	1 : 2 : 2
(kPa)	13.8
(1/MPa)	0.25
	0.012
(m^3/t)	40
(kPa)	1 500
(m^3/t)	18
(d)	10、1、0.1
(m)	50^A、30^B
(μm^2 · m)	2
(m×m)	300×200

: A、B .

3

5 3 :(1)



5

Fig.5 Gas rate of a CBM well at different sorption time constants

a. 0.2×10^{-15} m^2; b. 5×10^{-15} m^2

表 3 模拟结果统计

Table 3 Results of numerical simulation

(10^{-15} m^2)	(d)	(m^3/d)	(m^3)
	10	257.89	131 086.6
0.2	1	306.99	131 428.5
	0.1	335.31	131 575.7
	10	1 403.12	1 871 920.4
5	1	1 543.16	1 882 621.3
	0.1	1 579.93	1 882 613.9

k 0.2×10^{-15} m^2 ,

10、1 0.1 d ,

100.00:119.04:130.02,

100. 00: 100. 26: 100. 37; (2)

5×10^{-15} m^2 , 10、1

0.1 d , 100.00:

109.98:112.60, 100.00:100.

57:100.57.

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4.1 数值模拟假设条件的讨论

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， Darcy

， . Klinkenberg

(1941) ，

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2.36×10^{-15} m^2， 2.1 kPa

27.4. ，

1×10^{-15} m^2， 0.01×10^{-15} m^2. ，

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4.2 吸附浓度对扩散性能的影响

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（ (7) (8)）

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， (Schuring，2002)：

$$J=-L\frac{\partial\mu}{\partial x}\text{，}\tag{13}$$

，J ，mol/(m^2·s)；L Onsager ，mol/(J·m·s)；x ，m；μ ，J/mol. ：

$$\mu=\mu^0+RT\ln\frac{p}{p_0}\text{，}\tag{14}$$

，μ^0 ，J/mol；R ，J/(mol·K)；T ，K；p ，Pa；p_0 ，Pa.

(13) (14)， ，

：

$$D_t=RTL\frac{\mathrm{dln}\dfrac{p}{p_0}}{\mathrm{d}C}=D_0\Gamma(p,c)\text{，}\tag{15}$$

，C ，mol/m^3，D_t ，m^2/s；D_0 ，m^2/s；$\Gamma(p,c)$ ， ， .

(15) ， ，

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4.3 混合气体之间相互作用对扩散性能的影响

，N_2、CO_2

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(3) 、
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