Non-Darcy properties of gas flow in different metamorphic grade coals

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Abstract

Under different confining pressure, gas seepage tests are carried out in different metamorphic grade coals, which tests is used to discuss gas penetration mechanism in coal. The tested and theoretical results show that under different confining pressure, gas seepage laws are consistent in different metamorphic grade coals, but under the same confining pressure and the same gas pressure at the entrance, the metamorphism grade of coal is higher, the gas seepage flow is bigger. In the higher gas pressure section, the percolation curve of Q and Δ^2p/L meets the linear relationship, but the gas pressure is lower, the percolation curve of Q and Δ^2p/L deviates linear relationship of Darcy's law. The critical point lies from nonlinear to linear segment of gas flow in coal, and it is a gradual process from Non-Darcy flow to Darcy flow. At high Reynolds number, gas percolation obeys Darcy's law, but at low Reynolds number, the gas seepage in different metamorphic grade coals is non-Darcy flow. The collision of gas molecules and coal wall is the physical mechanism of gas non-Darcy flow phenomenon, which is determined by the mean free path of gas molecules and pore structure of coal, and the theoretical calculation well reveals the mechanism of gas non-Darcy seepage in coal.

Keywords: gas, coal, non-Darcy seepage, metamorphic grade

1 Introduction

When the fluid flow occurs in low permeability porous medium, large specific surface and thin pore properties lead the inner fluid near the surface of solid to change, thus emerging the non-Darcy seepage situation, this change is more apparent with the increase of permeability[1-2]. In the development of oil and gas reservoir, the thorough research has been conducted by many scholars for its percolation law deviates from Darcy's law problem, and has made gratifying achievements [3-11]. In the development of coal seam gas, Song Hong-qing [12], Wang Xin-hai [13], Zhang Dong-li[14], Zhang Xiao-dong [15], Sun Ping [16] through theory and experiment show that, even the fluid physical conditions are good, non-Darcy phenomenon in the gas flow in low permeability in coal is still obvious, that is existing the starting pressure gradient. However, the characteristics of non-Darcy percolation of coal gas in the low velocity still need further research.

In the coal sector, the microporosity whose aperture belongs to micron accounted for a non-negligible proportion in the pore volume. In the low pore pressure, the velocity of gas molecules in the pores of the migration is low, but the free path of its [*]movement is large, so in micropores the probability of gas molecule in low speed effect of seepage collision between pore walls is large, the influence on the percolation law and macroeconomic performance can not be ignored, which will cause the deviation of Darcy linear seepage law, non-Darcy phenomenon in coal gas flow at low velocity will occur [17].This paper selects the coal gas-fat coal, lean coal and anthracite coal in different metamorphic degree, through the theoretical analysis on seepage experiment and Reynolds correlation curve, study the non-Darcy characteristic in different metamorphic degree of coal gas in low speed seepage.

2 Low speed seepage experiment in coal

2.1 COAL SAMPLES COLLECTED AND RELATER BASIC PARAMETERS

Experiment coal samples select from Pan North gas-fat coal, (gas & fat coal) XinYuan lean coal (lean coal), Jiaozuo JiuLisan anthracite (anthracite), according to GB/T212-2008 "coal industry analysis method", coal industrial analysis results as shown in Table 1.

TABLE 1 The Testing Results of Industrial Analysis

Coal sample	**industrial analysis**		
	M_{ad} (%)	A_{ad} (%)	V_{daf} (%)
gas & fat coal	1.01	11.01	36.04
lean coal	1.53	7.14	11.84
anthracite	2.24	8.68	8.47

According to GB/T217-2008 "coal on the determination of density" and "GB/T6949-1998" method for determination of relative density of coal, true relative density and apparent relative density as shown in Table 2.

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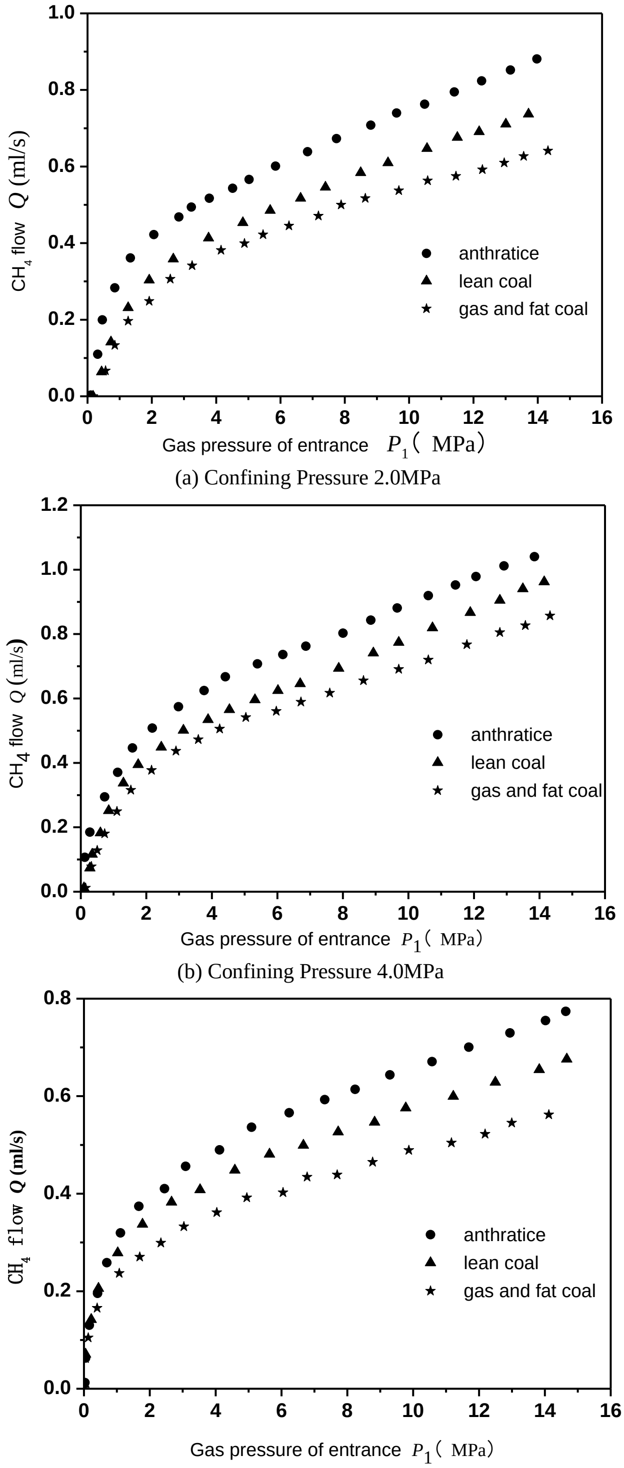
TABLE 2 The Testing Results of True Density and Apparent Relative Density of Coal Samples

Coal sample	True density (g/cm^3)	Apparent relative density (g/cm^3)	Porosity (%)
gas & fat coal	1.40	1.28	8.52
lean coal	1.43	1.28	10.35
anthracite	1.61	1.35	15.86

1.2 EXPERIMENTAL RESULTS OF GAS FLOW IN COAL SEAM

Under the three axis certain confining pressure, carry the test of seepage process in the coal. Install the sample: put raw coal sample into the heat shrinkable tube, using a hot-air gun to heat shrinkable tube, to ensure that the heat shrinkable tube can stirrup samples, and also make the heat shrinkable tube and coal side wall can tightly contact, sealing in the top and bottom of the 704 samples using silica gel, in the final coal sample will be packed in three shaft pressure chamber, connecting other system and put the whole system into the constant temperature water tank, to ensure that the CH_4 and the sample keep constant temperature. Vacuum degassing: in the guarantee of the system is properly connected, air tightness in good condition and the temperature of coal sample has reached the predetermined temperature, applied a predetermined value axial stress to coal samples, and then applying a predetermined confining pressure, in order to exclude the influence caused by the impurity gas in coal samples and system to the experimental results, use vacuum pump to degas the whole test system from the air inlet and the air outlet ends of the vacuum, until the vacuum degree in 2 hours has remained stable after the close of vacuum pump system, thus completing vacuum degassing. Seepage experiment of gas CH_4: into CH_4 of 99.999% concentration under the predetermined pressure. Permeability determination: using gradually boosting method, determine the gas pressure and flow data and make record.

As you can see from Figure 1, with the increase of inlet gas pressure, gas flow rate increases rapidly at first and then increased gradually. Under different confining pressure, different metamorphic degree of coal gas seepage law is the same, but under the same confining pressure and inlet gas pressure are the same, the higher the degree of metamorphism, the gas seepage flow is larger, it is because the higher the degree of metamorphism of coal is, the higher the porosity, permeability is larger, so the larger the amount of seepage. At the same time, it can also be seen that from Figure 1, with the increase of confining pressure, the gas seepage flow is reduced of the same coal, this is because the increase of confining pressure causes the decreases of permeability of coal.



(a) Confining Pressure 2.0MPa

(b) Confining Pressure 4.0MPa

(c) Confining Pressure 6.0MPa

FIGURE 1 Gas seepage in coal samples with different confining pressure

3 Gas non-Darcy percolation theory in coal

Darcy's law is the basic rule of seepage in the problem of gas seepage in coal body, but the gas is compressible fluids, through a coal body of L, the relationship between gas flow Q which Darcy law stated and pressure can be expressed as [18]:

$$Q = \frac{K_0 S}{\mu} \frac{\Delta^2 p}{2 p_2 L} \quad , \tag{1}$$

which, Q is flow, S is cross section for the coal area, K_0 is the permeability related with coal sample pore structure, μ is for the viscosity coefficient, $\Delta^2 p = (p_1+p_2)(p_1-p_2)$,$p_1$、$p_2$ are the test pressure respectively for the import and outlet of gas seepage in the coal.

Formula (1) shows that when the gas percolation obeys Darcy's law, the macroscopic characteristics of the seepage experiment is: the gas flow Q and pressure $\Delta^2 p/L$ is linear, in the Q-$\Delta^2 p/L$ percolation curve is shown as a straight line through the origin.The morphological changes will occur in the process of seepage, and the Reynolds number Re and drag coefficient f are closely related and the gas seepage flow and other parameters, so it can be expressed by the Reynolds number Re and drag coefficient f in double logarithmic coordinates correlation curve representation, the expressions are [18]:

$$\mathrm{Re} = \frac{Q\rho\delta}{\mu S \varphi} \quad , \tag{2}$$

$$f = \delta \frac{\Delta p}{\rho L} \left(\frac{\varphi S}{Q}\right)^2 \quad . \tag{3}$$

In the formula ρ for the gas mass density; φ porosity; δ as the characteristic parameter of coal, with the length dimension, taking the form [20] of $\delta=(Kg/\varphi)^{1/2}$, Kg as the gas permeability. When the fluid seepage meet Darcy's law, the relationship [19] between lg Re and lg f is linear with the slope of -1. If the slope of the relationship between lg Re and lg f is not -1, then the flow deviates from Darcy flow region, namely becomes non-Darcy percolation.

4 Non-Darcy seepage analysis of the gas in coal

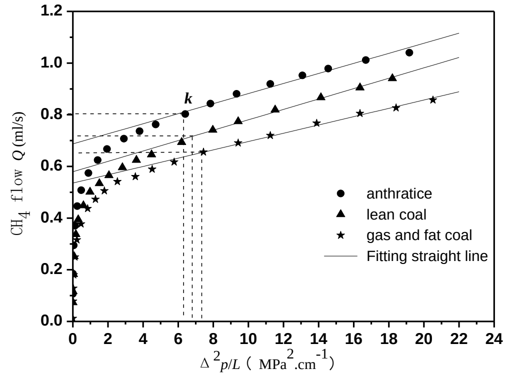
4.1 REGULARITY OF THE FLOW EXPERIIENT CURVES OF Q-$\Delta^2 p/L$

As shown in Figure 2, the percolation curve is concave curves of a lower at low pressure, seepage flow increases rapidly with the pressure, the slope of Q-$\Delta^2 p/L$ is also changing, the performance for the relationship to the deviation from Darcy's law of linear (type 1). While in the high pressure section, the percolation curve linear relationship meet Q-$\Delta^2 p/L$, the linear extension deviates from the origin of the coordinate axis intersection with traffic, exists the quasi initial flow rate Q_0, the value of initial flow Q_0 under different confining pressure and the different degree of coal metamorphism is shown in Table 3.

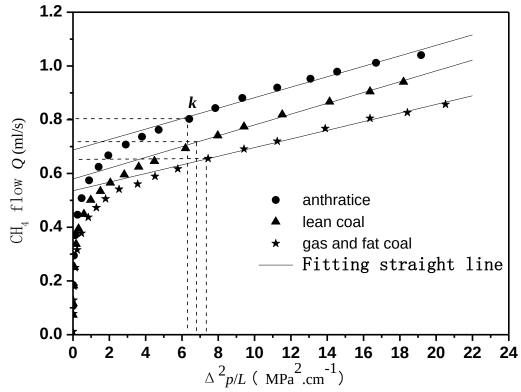
TABLE 3 Initial rate of gas seepage with different confining pressure

Confining pressure	Q_0 **(ml/s)**		
	gas & fat coal	lean coal	**anthracite**
2.0MPa	0.535	0.579	**0.687**
4.0MPa	0.445	0.484	**0.581**
6.0MPa	**0.397**	**0.477**	**0.543**

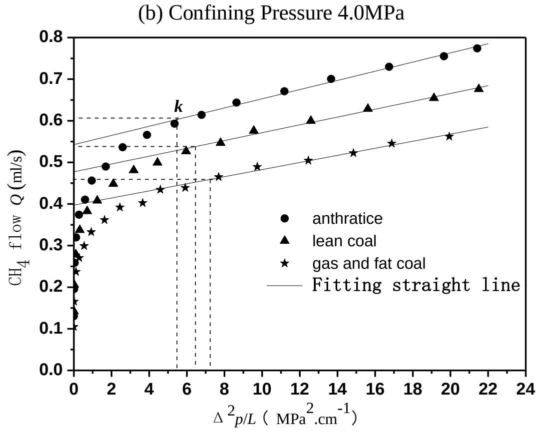
From Table 3 it can be seen that under the same confining pressure, the higher the degree of coal metamorphism, the initial flow is larger, just as shown in the 4.0MPa confining pressure, lower coal metamorphic degree gas fat coal initial flow is 0.445 ml/s, higher metamorphic grade coal lean coal initial flow is 0.484ml/s, and the highest metamorphism degree of coal anthracite initial flow is 0.581ml/s; initial flow rate decreases with the increase of confining pressure for the same coal samples. The gas seepage translate from nonlinear to linear existing critical point K, as shown in Figure 2.



(a) Confining Pressure 2.0MPa



(b) Confining Pressure 4.0MPa



(c) Confining Pressure 6.0MPa

FIGURE 2 Gas seepage curves of Q and $\Delta^2 p/L$

Different metamorphic degree of coal under different con fining pressure on gas percolation transition critical point corresponds to the Q-Δ^2p/L and Q as shown in Table 4.

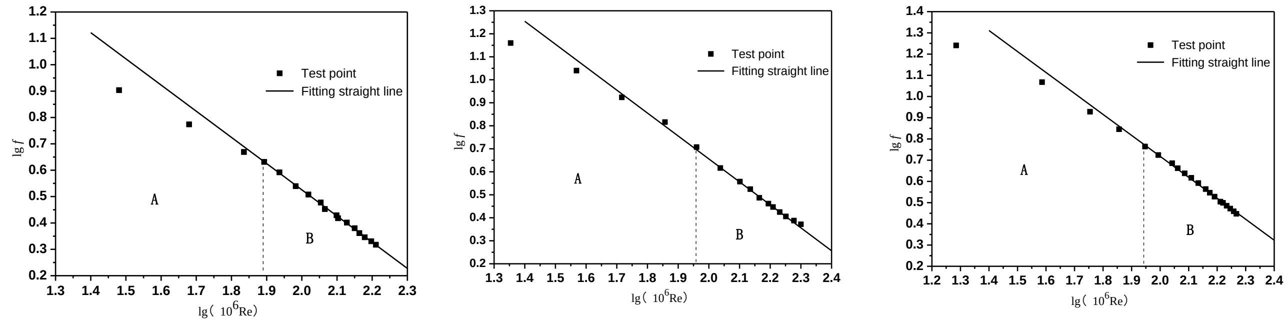
TABLE 4 Experiment Results of Gas Seepage Through Coal of Different Metamorphic Degree with Different Confining Pressure

pressure	**Δ^2p/L（MPa²/cm）**		
	gas & fat coal	lean coal	**anthratice**
2.0MPa	7.38	6.87	**6.36**
4.0MPa	7.29	6.65	**5.89**
6.0MPa	7.21	6.47	**5.26**
pressure	***Q*（ml/s）**		
	gas & fat coal	lean coal	**anthratice**
2.0MPa	0.656	0.719	**0.807**
4.0MPa	0.524	0.580	**0.676**
6.0MPa	**0.467**	**0.542**	**0.604**

Under the same confining pressure, the higher the degree of coal metamorphism, the critical point of nonlinear period of transition from the linear section the Δ^2p/L corresponds is smaller, and the corresponding gas seepage flow is larger; the same metamorphic degree of coal as the confining pressure increases its critical point corresponding to the Δ^2p/L and Q are reduced.

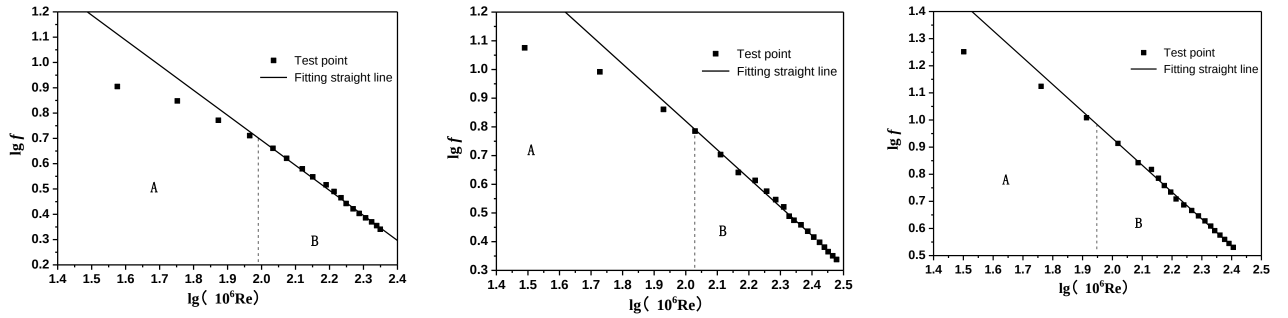
4.2 REYNOLDS EXPERIMENT CORRELATION CURVE

Figures 3-4 are the correlation curve of gas seepage Reynolds experiment under different degree of coal metamorphism in different confining pressure, it can be seen from Figures 3-4 that, at high Reynolds number stage, gas flow Reynolds experiment curves $\lg(10^6Re)$ and lgf shows a linear relationship, and the experimental fitting equation is lg f =K $\lg(10^6Re)$+C, the fitting parameters is shown in Table 5.



(a) Confining Pressure 2.0MPa (b) Confining Pressure 4.0MPa (c) Confining Pressure 6.0MPa

FIGURE 3 Reynolds Experimental Curves Gas Seepage Through Gas & Fat Coal Samples.
A: Region Deviate from Darcy Law; B: Region Obedience to Darcy Law



(a) Confining Pressure 2.0MPa (b) Confining Pressure 4.0MPa (c) Confining Pressure 6.0MPa

FIGURE 4 Reynolds Experimental Curves Gas seepage Through Anthracite

It can be seen from Table 5 that, in the region obedience to the Darcy law, $\lg(10^6Re)$ and lg*f* meet the experimental curves approximately linear relationship with the slope K value of -1, show that seepage in coal at high Reynolds number stage obeys Darcy's law.

But at low Reynolds number section, gas flow Reynolds experimental correlation curves with different degree of coal metamorphism $\lg(10^6Re)$ and lg f were showed deviation from the linear relationship, the dotted line left test points such as 3~ in Figure 5 (low Reynolds number region) as the Reynolds number decreases gradually deviated from the $\lg(10^6Re)$ and linear fitting of lg f this description, and deviate from Darcy flow at low Reynolds number stage, that the performance of non-Darcy flow. This is because the slippage phenomenon caused by the linear relationship of Darcy deviate in the Renault on the correlation curve is reflected in the low Reynolds number segment.

TABLE 5 Straight Line Fitting Parameters of $\lg(10^6Re)$ and lg*f*

Coal sample	gas & fat coal		lean coal		anthracite	
P（MPa）	K	C	K	C	K	C
2.0	-0.994	2.513	-0.999	2.681	-0.989	2.671
4.0	-0.998	2.651	-0.984	2.813	-0.996	2.811
6.0	-0.988	2.694	-0.995	2.897	-0.992	2.917

4.3 ANALYSIS OF PHENOMENON OF NON-DARCY GAS FLOW IN COAL SEAM

The mechanical mechanism of gas seepage in coal is: when the gas flow velocity is not big, neglecting the inertial force, at the same time to meet the balance between gas viscous force is equal to the external pressure. The internal friction of the viscous force from the gas, which obey the Newton inner friction law. Considered from the micro perspective, gas viscous force is due to the flow of gas, due to gas molecules of different velocity layer collision and exchange of momentum, resulting in a directional momentum transfer resulting; at the same time, the gas seepage in coal, not only between the gas molecules collide, also between gas molecules and the pore wall collision; the physical mechanism of the two kinds of collision of is different, and reflect on the seepage law of macro is different, but what exactly happened that a collision is associated with the mean free path of gas molecules. The mean free path of the gas molecules can be expressed as[21]:

$$\lambda = \frac{bT}{\sqrt{2}\pi d^2 p} \qquad (4)$$

In the formula, *b*, *d*, *T* and *p* respectively for the Boltzmann gas constant, gas molecular diameter, temperature and pressure. In this paper the gas seepage experiment, *b*, *d*, *T* does not change, it can be seen from the formula (4), the mean free path of the gas molecules is proportional to pressure intensity. And at a certain temperature and pressure, gas molecular free path larger than *x* numbers *N* accounts for the total proportion of gas molecules N_0, the distribution law of gas molecules with the number of free path can be expressed as:

$$\frac{N}{N_0} = e^{-x/\lambda} \quad . \qquad (5)$$

When gas seepage in coal, gas molecular motion is limited by pore size of *D*, the gas molecular free path is less than *D*, the likelihood is the collision between molecules, and when the gas molecular free length is larger than *D*, the gas molecules collisions between coal wall. With the pore diameter of *D* instead of x in the formula(5), classified by the collision between molecules in gas and gas molecules and coal wall, molecular gas molecules and coal wall collisions accounted for the proportion of the total number of molecules [17]:

$$\frac{N}{N_0} = e^{-D/\lambda} = \alpha \qquad (6)$$

Then the gas molecular collision between molecular number with the ratio of 1-α . But the gas seepage in the coal pores, especially the small holes and the micropore, the collision probability of gas molecules and coal wall is bigger, α cannot be ignored. It must take the impact of such collisions on percolation into account, the macro performance is *slippage phenomenon* [17]. Therefore, coal gas seepage flow is composed of two parts: slip flow gas molecules and coal wall collision; viscous flow obeys Darcy's law of the collision between molecules. The percentage of α and 1-α . Here, can be used with the formula (1), the gas seepage flow includes considerable slippage phenomenon, expressed as a [16]:

$$Q = K_0[1 + c\exp^{-D/\lambda}]\frac{S}{2\mu}\frac{\Delta^2 p}{p_2 L} \qquad (7)$$

In the formula: *c* = 9.7. As formula (4) shows, the mean free path of gas molecules is proportional to pressure intensity, that is:

① When *p* is large, the λ is small, $\exp^{-D/\lambda} \to 0$,formula (7) into formula (1), which obeys the Darcy's law;

②When p is low the λ is big, $\exp^{-D/\lambda}$ cannot be ignored, formula (7) is no longer meet Darcy's law, which becomes non-Darcy percolation.

From formula (7) can also be seen that the change of the nonlinear section to linear segments is gradual, namely the gas seepage in the coal from the non-Darcy flow to the Darcy flow is a gradual process, the division is bounded according to the seepage experiment (Figure 2) critical point in *K*.

5 Conclusions

This paper selects the gas-fat coal, lean coal and anthracite coal in different metamorphic degree, under different confining pressure to carry on the gas seepage experiment, studied the seepage characteristics of gas in the coal. experimental and theoretical analysis of results shows:

I. With the increase of inlet gas pressure, gas flow rate increases rapidly at first and then increased gradually. Under different confining pressure, different metamorphic degree of coal gas seepage law is the same, but under the same confining pressure and inlet gas pressure are the same, the higher the degree of metamorphism, the gas seepage flow is larger.
II. When the gas pressure is low, performance for the relationship to the deviation from Darcy's law of linear. While in the high pressure section, the percolation curve linear relationship meet Q-$\Delta^2 p/L$.
III. Under the same confining pressure, the higher the degree of coal metamorphism, the initial flow is larger, the same sample, initial flow rate decreases with the increase of confining pressure.
IV. Under the same confining pressure, the higher the degree of coal metamorphism, the critical point of nonlinear period of transition from the linear section the $\Delta^2 p/L$ corresponds is smaller, and the

corresponding gas seepage flow is larger; the same metamorphic degree of coal as the confining pressure increases its critical point corresponding to the $\Delta^2 p/L$ and Q are reduced.

V. At high Reynolds number stage, gas percolation obeys Darcy's law, lg(10^6Re) and lg f meet the experimental curves approximately linear relationship with the slope K value of -1; But at low Reynolds number section, gas flow Reynolds experimental correlation curves with different degree of coal metamorphism lg(10^6Re) and lg f were showed deviation from the linear relationship, which shows the non-Darcy percolation.

VI. Collision of gas molecules and coal is the physical mechanism of generating gas non-Darcy flow phenomenon, which is determined by the mean free path of the gas molecules and the pore structure of coal. Using the theoretical anises, formula (7) well reveals non-Darcy percolation mechanism of gas in coal.

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