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# Numerical investigation of low-velocity non-Darcy flow of gas and water in coal seams

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Fluid flow in low-permeability coal seams shows characteristics of low-velocity non-Darcy flow. A two-phase mathematical flow model considering the effect of the threshold pressure gradient (TPG) for gas and water transportation and flow in such reservoirs has been developed. The corresponding numerical model has been formulated and solved. From the numerical results, we can conclude that both the gas production rate and cumulative gas production in the case when TPG is considered are always less than those in the cases when TPG is not considered because of the sharply decreased pressure and increased energy consumption. A comparison of the gas production rates obtained from the calculation results and from monitoring data indicates that the gas production rate predicted using the model with TPG is more accurate. Under the calculation conditions, the gas production rates when considering different values of TPG are approximately 35%–70% less than those for cases without TPG. In addition, the gas production rate and total gas production decrease as the bottom hole pressure and TPG increase, but they increase with the fracture half length. However, these factors have little influence on the water production regardless of the incorporation of TPG. The research expands the theoretical basis of gas recovery from the tight coal seams and provides a more accurate method to predict the gas production rate efficiently.


## 1. Introduction

In recent times, problems related to energy and the environment have become the key issues for sustainable development. Unconventional gas serves as the main source of energy in China, and its safe and economical production is being considered with increasing seriousness by various countries (Han et al., 2010). Coalbed methane (CBM), which is the main component of unconventional gas, has been exploited and utilized increasingly in recent years (Connell, 2009; Jamiolahmady et al., 2011). Therefore, it is important to increase the output and utilization of CBM for solving problems related to energy and the environment because methane is a clean fuel with high caloric value.

Although China has a rich CBM reserve, research on CBM indicates that most of the gas reservoirs have low or extremely low permeability. The seepage rule in the case of these low reservoirs does not conform to Darcy's law (Nakayama, 1992; Gidley, 1991). The major characteristic of seepage in these reservoirs is that there exists a threshold pressure gradient (TPG) and that the permeability of porous media changes with the pressure gradient (Thauvin and Mohanty, 1998). At present, Darcy's law is widely used to construct the mathematic model and calculate the CBM output (Belhaj et al., 2003). However, owing to the reasons discussed above, there exist errors between the actual CBM reservoir and these calculated models (Friedel and Voigt, 2006).

According to Darcy's law, the pressure drop is completely determined by the viscous resistance between the surface of fluid and solid. In most cases, the fluid flow in the porous media of rock obeys Darcy's law (Karacan and Okandan, 2000). However, in low-permeability rocks, seepage does not follow Darcy's law because the pressure gradient drops owing to the motion of rock particles, hydro-expansive clay minerals, and other particles (Holditch and

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Morse, 1976). We term such flow as low-velocity non-Darcy flow (Nakayama, 1992; Kumar, 2004). Numerous experiments have proved that fluids can flow in a porous medium when the added pressure gradient exceeds the initial pressure gradient; we term this initial value as TPG, the threshold pressure gradient (fluid cannot flow when the pressure gradient is smaller than TPG) (Phanikumar and Mahajan, 2002).

In early 1885, Newell tested the permeability of tight rock and determined that the relation between fluid velocity and pressure gradient was not linear when fluid flowed through the rock (Karacan and Okandan, 2000). Miller-Brownlie also researched aquifers in 1919 and found that fluids can flow only once the pressure gradient exceeds a certain value (Miller-Bownlie, 1919). In the 1970s, after studying low-velocity water flow through unconsolidated soils and loose mixtures, two research groups concluded that the relationship between velocity and pressure gradient does not follow Darcy's law (Mitchell and Younger, 1967; Russell and Swartzendruber, 1971). At the end of the 20th century, Prada and Civan studied saline flow through tight rocks and found that TPG exists when the velocity is lower than 1.129 m/d (Prada and Civan, 1999). In China, Zeng and Chen researched the nonlinear seepage problem in the case of low-velocity flow and noted that a cubic function relationship exists between flow velocity and pressure gradient in low-velocity flow in porous media; they also proposed the corresponding nonlinear equations of motion (Zeng et al., 2011). Wang and Li systematically analyzed the influence of permeability, viscosity, and the saturation of water on TPG and proposed empirical formulas for calculating TPG in low-permeability oil reservoirs (Wang et al., 2007). The results are important for calculating the parameters for oil recovery engineering in low-permeability oil reservoirs. Although significant research has been conducted on low-permeability non-Darcy flow domestically and abroad, most studies address oil and gas reservoir recovery. Recently, some scholars focused on researching the low-velocity non-Darcy in ultra-low permeability reservoirs by experiments. Ding and Yang studied the influencing factors for TPG in tight reservoir and the results shown that TPG is increasing along with the decrease of reservoir pressure (pore pressure) (Ding et al., 2014; Wang et al., 2015). Song (Song et al., 2014) also researched the $CO_2$ storage efficiency in saline aquifer with effect of TPG and the results shown that the numerical model which considered the TPG effect is appropriate for *in situ* situation. Above all, our research wanted to build a mathematical model to simulate gas production in low-permeability tight reservoir with hydraulic fracture in China, and the TPG effect was considered in our model.

The CBM reservoir is a dual porous rock composed of matrix and cleat. The cleat system is the main flow channel, but it is full of water at the beginning (Connell and Detournay, 2009). After draining water from the well in the initial stage, the adsorbed CBM in the matrix gradually desorbs from the coal particles and diffuses into the cleat, which is the source of flow. The main distinction between the exploitation processes for CBM and natural gas is that the former is a desorption-diffusion-seepage process (Crosdale et al., 1998). Therefore, the characteristics of both low-velocity non-Darcy flow and features of desorption and diffusion of the CBM should be considered simultaneously in the theoretical research on the seepage of low-permeability CBM *reservoirs*. TPG was rarely considered in the theoretical research of CBM exploitation in past years despite previous studies verifying the existence of TPG for low-velocity flows in low-permeability porous media. Hence, constructing a mathematic model by considering the effect of TPG and desorption and diffusion of CBM in a low-permeability coalbed reservoir is important for increasing the output and utilization of CBM, which in turn has important implications for resolving energy and environmental problems.

There are two methods of exploiting CBM from underground gas *reservoirs*; one involves drilling from the earth's surface and draining gas from an underground coalbed (Bustin and Clarkson, 1998). However, the main method is vertical well exploitation. To increase the daily output and utilization of CBM, high-pressure water is injected into the vertical well, and the coalbed around the well is fractured by water. The porous media of such a seepage system includes matrix, cleat, and fractures (Shi and Durucan, 2005). We established a seepage mathematical model by considering the effect of TPG and desorption of CBM in the porous media on the basis of mass conservation and momentum conservation according to seepage theory. We also proposed the equations for the mathematical model of hydraulic fracture. Next, we applied the finite difference method to solve the partial differential equations of the mathematical model and analyzed the factors that influence the output and utilization of CBM.

To summarize, the contents of this paper are as follows: (1) First, a gas/water two-phase low-velocity non-Darcy flow model is described. This model is used to examine water and methane flow in the low-permeability porous media of a coalbed. The solving conditions based on the geological characteristics of the coalbed are discussed. (2) Thereafter, a numerical model based on the mathematical model is described, and the related initial and boundary conditions are provided. (3) Further, the results of numerical simulation of water/gas flow in the porous media of tight coalbed are described. (4) The effects of different factors, in particular, TPG, hydraulic fractures of the vertical wells, and the length of fractures, on water/gas flow in the low-permeability tight coalbed and thus on the output and utilization of CBM are discussed. The research results will provide guidance for increasing the daily CBM outputs in low-permeability tight coalbeds.

## 2. Description of physical model

Currently, the hydraulic fracturing method is widely applied for oil and gas recovery because it usually increases the CBM output (Karacan and Okandan, 2000). A fracture is produced by injecting high-pressure water into the well. Hence, a two-phase flow system exists in the porous media. Roberts and Thompson separately studied the output results for a vertical fractured well in a tight CBM reservoir and concluded that analogous elliptic flow plays a major role in the performance of a fractured tight gas well (Roberts, 1981; Thompson, 1981). According to Liu and Wang (Liu, 1987; Wang and Zhang, 2010), two regions exist around the well and hydraulic fracture, as shown in Fig. 1. One is the high-permeability

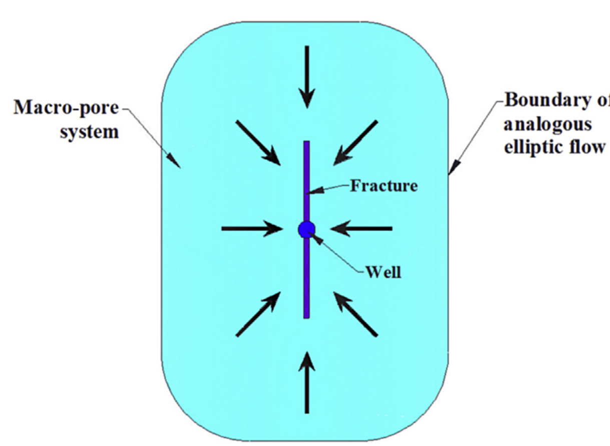


**Fig. 1.** Schematic diagram of tow-phase analogous elliptic flow around a hydraulic fracture.