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A mathematical model for gas and water production from overlapping fractured coalbed methane and tight gas reservoirs

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ABSTRACT

With the continuous expansion, exploration and development of unconventional natural gas resources, mainly coalbed methane, shale gas and tight gas, some areas overlapped by two or three types of unconventional natural gas reservoirs are explored, e.g., the Linxing, Shilou and Linfen blocks located in the east margin of the Ordos Basin, China. Gas extraction from an individual reservoir becomes not economic as gas resources are not fully recovered; thus, gas coproduction from two or multiple layers is an effective method for improving gas production. In this work, a mathematical model of gas and water two-phase flow for the coproduction of coalbed methane and tight gas is developed. The adsorption characteristics, stress-sensitive and matrix shrinkage effects on coal permeability, and the stress-sensitive effect of tight sandstone are all considered in the model. The gas production related parameters, such as bottom hole flowing pressure, reservoir pressure differences, reservoir properties (e.g., permeability, cleat compressibility of coal, and Langmuir isotherm parameters) are discussed and compared with different geological conditions. The results show that the gas and water flow from the coalbed and sandstone reservoirs show no interference between each other under a constant pressure drainage system; the sandstone reservoirs show a fast pressure drawdown with a high gas production rate decline, while the coalbed reservoir is slow in pressure drawdown and the gas production rate increases gradually. The properties of a specific reservoir have a great influence on its own gas production performance, but with no influence on the other reservoirs. It was found that a lower constant drainage pressure should be adopted in the case of stress-sensitive effects, and coal with a lower cleat compression coefficient and Poisson's ratio value is better for higher gas production. The production contribution from each layer can be acquired if a specific production rate is set. If the reservoir pressure difference between the two reservoirs is too high (for instance at least > 3 MPa in the cases studied in this work), gas and water intrusion may happen, but the reservoirs would be balanced quickly. Thus, the coproduction of coalbed methane and tight gas from one well bore is feasible, and more work should be conducted on proposing a proper drainage strategy to improve the gas resource recovery efficiency in coal-bearing strata.

1. Introduction

Coalbed methane (CBM) has a wide distribution in many basins and is being exploited at increasing burial depths in China, whereas CBM wells are often drilled through sandstone layers with high total hydrocarbon resources (Li et al., 2016). More attention has been paid to understand whether the tight gas resources would be a significant contributor for higher production rate from a single well. Coexisting reservoirs of both CBM and tight gas have been found in the Linxing, Shilou, Liulin and Hancheng areas in the east margin of the Ordos Basin as well as in the southern part of the Qinshui Basin, China (Tang et al., 2012; Li et al., 2016, 2018). At present, most of the vertical CBM wells show relatively low gas production rate in the above mentioned basins, typically around or below 1500 m^3/d, and the tight gas reservoirs are thin in these basins, compared with the tight gas fields in the inner part of the basin (e.g., Sulige gas field); thus, coproduction of the two types of unconventional natural gas resources shows a good prospect from both geological and economic perspectives (Qin et al., 2018). Therefore, fundamental knowledge of how the gas and water flow in the interbedded coal and sandstone layers is important to plan the

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coproduction of natural gas from two different types of unconventional natural gas reservoirs.

The CBM production process is complex, including methane desorption from the matrix pore surface, gas diffusion through the matrix pore system to the cleats/fractures, and gas flowing in the fractures both natural and hydraulically created (Clarkson et al., 2010; Li et al., 2014; Moore, 2012; Palmer, 2009; Pan and Connell, 2012). Different to tight sandstone reservoirs, CBM production is accompanied by strong stress sensitivity (Seidle et al., 1992; Pan and Connell, 2007) and matrix shrinkage effects (Pan and Connell, 2010). Furthermore, water production is generally a necessary part of the process in CBM production, with typically a long time of gas and water two-phase flows (Chen et al., 2013, 2014; Li et al., 2015; Alexis, 2013). To describe the complex process during CBM production, extensive work has been conducted considering different conditions (Recroft and Patel, 1996; Palmer and Mansoori, 1998; Shi and Durucan, 2005; Cui and Bustin, 2005; Clarkson et al., 2011; Wang et al., 2018). Permeability models considering stress sensitivity and the shrinkage effect have been proposed, for instance the Palmer & Mansoori (PM), Shi & Durucan (SD) and Gu and Chalaturnyk models (Palmer and Mansoori, 1998; Shi and Durucan, 2005; Gu and Chalaturnyk, 2010), and they can be used in the reservoir and geomechanical coupled simulation of CBM and enhanced CBM recovery processes.

However, little has been dedicated to multilayer coproduction of gas from different types of unconventional gas reservoirs. Most of the work related to multilayer gas production have been focused on conventional gas reservoirs. The flow model of a multilayer reservoir considering no cross flow between different layers was proposed by Lefkovits et al. (Taria and Ramey, 1978), and the skin effect was then being considered with a Lagrangian solution of the bottomhole pressure (Lefkovits et al., 1961). A review study on multilayer reservoir flow showed that the bottomhole pressure of multilayer reservoirs varies more significantly than that of a single reservoir, and the tested pressure data of the bottomhole flowing pressure (*BHFP*) cannot accurately reflect each single reservoir (Prijambodo and Raghavan, 1985). A multilayer reservoir numerical simulator that can fit pressure and gas production rate of each single layer was proposed later (Raghavan et al., 2001), and the application of multilayer reservoir pressure data for analyzing the gas and water flow pattern and production curve fitting was conducted (Spivey, 2007). For CBM wells, most of the work are focused on two-phase flow of a single-layer, with several mathematical simulation work of multiple coal seams being conducted, including two-phase flow mechanisms (Kissell and Edwards, 1975), production dynamics based on material balance and numerical simulations (King, 1985; Taria and Ramey, 1978), and a multiphase flow mathematical model for dissolved gas flooding reservoirs (Lefkovits et al., 1961).

In order to increase gas production and recovery efficiency, it is necessary to develop the CBM and tight gas together. However, to date, no mathematical modelling work associated with gas and water flow in both CBM and tight gas combined reservoirs has been reported to our best knowledge. The purpose of the present work is to establish a practical mathematical model to clearly reflect the gas and water flow behaviors in coal seams and sandstone separately and coherently in a single well with vertical hydraulic fractures. Then, the gas production process can be clearly studied, and the interference between the CBM and tight gas reservoirs can be understood. This is highly desirable as the gas production behaviors for such wells are not well understood, especially for the several such wells been drilled and completed with one well now producing in Linxing area, eastern Ordos Basin.

2. Methodology

During the model derivation process, the following factors are considered: (1) methane desorption, stress sensitivity, and the matrix shrinkage effect of coal; (2) stress sensitivity of sandstone; (3) physical parameters that affect the production of CBM and tight gas. The sandstone-coal overlap gas reservoir is commonly seen in the coalbed methane wells drilled in the east margin of the Ordos basin, and our study is focused on two layers with no connection between each other.

Therefore, for a better discussion of the gas and water flow model, some assumptions were made: (1) a vertical fractured well penetrates the two layers, with the perforation located in the center of each layer, and the initial pressure of each layer is uniformed; (2) the permeability of coal and sandstone changes with pressure; (3) the matrix shrinkage and stress sensitive effects are considered in the coal reservoir; (4) the porosity of coal and sandstone is constant, and the thicknesses of the coal and sandstone are also constant; (5) the initial pressure system of the two layers can be the same or different; (6) the gas and water flow are under isothermal conditions; (7) the drainage radius can be the same or different for the two layers; (8) the inner boundary conditions can be fixed production rate, bottomhole pressure or variable pressure production, and the external boundary conditions are closed; (9) the skin effect is temporarily disregarded, and the temperature and fluid properties of the two layers are the same; and (10) Darcy flow occurs in two layers.

2.1. Isothermal adsorption model

The Langmuir adsorption isotherm model describes the single molecular layer adsorption and the adsorption process is as result of a dynamic balance (Cui and Bustin, 2005). The absorbed gas content that increases with pressure could be described by using Langmuir isotherm model (Langmuir, 1918):

$$V = \frac{V_L p}{\mathrm{p}_L + p} \tag{1}$$

where V_L is the Langmuir volume, m^3/tonne; p_L is the Langmuir pressure, Pa; and p is the pore pressure, Pa.

The above equation shows that when $p = p_L$, $V = V_L/2$, and the Langmuir pressure P_L is the pressure when adsorption is half of the maximum adsorption capacity, V_L. The P_L value can reflect the difficulty of methane desorption, and the smaller the P_L value is, the more difficult the methane desorption is. After comparing various adsorption models, the Langmuir model shows a good agreement with methane desorption and was adopted to describe methane desorption behavior (Moore, 2012).

2.2. Matrix shrinkage and stress sensitivity model of permeability

During the production of methane, the effective stress increase causes the coal seam permeability to drop, which is a negative effect. The matrix shrinkage effect and the Klingenberg effect are two positive effects that can improve the permeability of the coal seam and promote the rebound of the permeability as gas pressure decreases. The combined effect of the positive and negative effects determines the final variation trend of coal reservoir permeability. When the positive effect is greater than the negative effect, the permeability of the coal seam is improved, and even the rebound increases; when the negative effect is greater than the positive effect, the coal seam permeability decreases (Chen et al., 2013, 2014; Li et al., 2015; Alexis, 2013; Gray, 1987).

The SD model was used for coal permeability variation in our model. The SD model was proposed by Shi & Durucan (Shi and Durucan, 2005). The SD model is based on the permeability variation due to stress change caused by desorption of methane, while the strain change results in permeability change. That is, the coalbed methane desorption changes the volume strain, which then changes the horizontal stress, which eventually changes the reservoir permeability. Therefore, the pore permeability of the model is affected by the horizontal effective closure or opening effect caused by the horizontal effective stress, while the cleat/fracture closure is not caused by the vertical effective stress in the PM model. The SD model is described as follows (Shi and Durucan, 2005):