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Full Length Article

A semi-analytical model for drainage and desorption area expansion during coal-bed methane production

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HIGHLIGHTS

- A practical model for the expansion characteristics of drainage and desorption area is proposed.
- Variable production rate, BHP and saturation distribution are considered in this method.
- The model was verified by numerical simulation with excellent agreements.
- A set of quantitative criteria for the optimization of production system is firstly proposed.
- The optimization criterion was applied to Qinshui CBM region and achieved good results.

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ABSTRACT

In coal-bed methane (CBM) field development plan, more attention is paid to production forecasting, well spacing optimization, pressure transient analysis and adsorption/desorption mechanism within coal matrix. Few studies were carried out to investigate the expansion of drainage and desorption area based on the characteristics of pressure propagation in CBM reservoir. Moreover, the production rate and bottom-hole pressure (BHP) are usually variable, while the production system in current analytical models are either at constant production rate or constant BHP. When optimizing the production system of CBM well, the knowledge of expansion principle of drainage and desorption area can help obtain the critical time of interference and its intensity, which are both key factors for efficient development of CBM reservoirs.

In this paper, a comprehensive method for drainage and desorption area expansion during coal-bed methane production is proposed, in which the variable rate and BHP in different production stages and saturation distribution are considered. The coal seam is divided into two areas, namely desorption and without-desorption area, and the production life is divided into five stages. The pressure profiles at different production stages are detailed investigated utilizing diffusivity equation which is solved by the continuous succession of steady states. By assuming the desorption area with low water-gas ratio and without-desorption area with high water-gas ratio, the pressure-squared approach is applied in desorption area and pressure approach is employed in without-desorption area. Finally, a model for predicting drainage and desorption area is developed by generating pressure profile and material balance equation.

The proposed semi-analytical model is verified by numerical simulation with excellent agreement with the simulation data. Results show that the drainage area expands much faster at early production stage than that at late stage when desorption area starts expanding in the coal-bed reservoir. In addition, the production system of CBM well is found to play a significant role in the expansion characteristics of desorption area. Considering these characteristics of CBM, we shed light on the production system optimization in different production stages and apply the developed production system to a CBM well in Qinshui field, China. In summary, this method only requires BHP, gas and water production, and turns out to be simple, reliable and powerful in application.

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Nomenclature

P_i	initial formation pressure (MPa)
P_d	critical desorption pressure (MPa)
P_e	pressure of reservoir boundary (MPa)
P_L	Langmiur pressure (MPa)
P_{wf}	well bottomhole pressure (MPa)
P_{ab}	fixed BHP during the late production period (MPa)
K	absolute permeability (md)
K_g	gas phase permeability (md)
K_w	water phase permeability (md)
B_g	gas FVF (fraction)
B_w	water FVF (fraction)
S_g	gas saturation (fraction)
S_w	water saturation (fraction)
S_{wi}	initial water saturation (fraction)
R_{dr}	drainage radius (m)
R_{de}	desorption radius (m)
R_e	radius of boundary (m)
R_w	wellbore radius (m)
V_L	Langmiur volume (m^3/m^3)
h	thickness of coal seam (m)
Z	compressibility factor (fraction)
Z_{sc}	compressibility factor at standard conditions (fraction)
T	absolute temperature (K)
T_{sc}	absolute temperature at standard conditions (K)
P	formation pressure (MPa)
P_{sc}	formation pressure at standard conditions (MPa)
C_t	total compressibility (MPa^{-1})
C_t^*	modified total compressibility (MPa^{-1})
C_g	gas compressibility (MPa^{-1})
C_g^*	modified gas compressibility (MPa^{-1})
C_w	water compressibility (MPa^{-1})
C_w^*	modified water compressibility (MPa^{-1})
C_d	desorption compressibility (MPa^{-1})
t	production time (days)
Q_g	gas production (m^3/d)
Q_w	water production (m^3/d)

Greek letters

μ_g	gas viscosity (mpa·s)
μ_w	water viscosity (mpa·s)
φ	cleat porosity (fraction)
φ_i	initial cleat porosity (fraction)
λ_t	total mobility of gas and water (md/(mpa·s))
ε_{max}	maximum volumetric strain of coal (dimensionless)
ρ_g	gas density (kg/m^3)
ρ_w	water density (kg/m^3)
ρ_B	coal density (t/m^3)

1. Introduction

Rapidly rising population from today's 7 billion to estimated 9 billion by 2050 will place tremendous energy demand around the world [1]. As one of the most promising and potential alternatives to conventional resources, the coal-bed methane becomes progressively more attractive [2,3]. Coal seam has a unique and complicated reservoir characteristic. Apparently different from the gas storage mechanism for the conventional reservoirs in which gas is stored in rock porosity system, methane is mainly adsorbed on surface of coal micropores by adsorption mechanism. Thus, the gas production performance from coal-bed is significantly different from conventional reservoir [4,5]. Moreover, the coal is a heterogeneous and anisotropic porous medium which is characterized by two distinct porosity systems: macropores (cleat structure) and micropores. Due to its huge specific surface area, micropores contain the majority of gas content of the coal seam which can be described by an adsorption isotherm, only a little of free gas stores in the macropores or the cleat structure [6–8]. When a CBM well starts production, there exists the gas-water two phase flow from the cleat system to the wellbore and the drainage area expands in the early production stage. With the process of production and the pressure propagation, the gas begins to desorp from the coal matrix and diffuses into the macropore. The desorption area begins to expand outward when the reservoir pressure is reduced below the critical desorption pressure by dewatering operation.

To date, a large number of analytical methods have been documented to deal with the pressure transient behaviors in coalbed, most of which assumed that the CBM recovery followed single-phase flow principle, thus failling to capture the complexity of gas-water two phase flow. The first effort to consider gas-water two-phase flow in the coalbeds was implemented by Kamal and Six, while their method required relative permeability data which was often not available for coal-bed wells [9]. By assuming the water saturation remaining unchanged throughout the production life of CBM wells, Seidle utilized the flow equations that describe dry gas wells to investigate dewatered CBM wells [10]. Spivey extended the work by accounting for nonlinear Langmiur sorption isotherm in the diffusivity equation [11]. Moreover, the previous analytical models were all established based on constant production rate or BHP, neglecting the variable production systems at different production stages [12–14]. In terms of the complex flow behavior of coal-bed methane, the best way to investigate the pressure profile is the numerical simulation which accounts for all emerging mechanisms during production [15–17]. However, although recent advances have greatly enhanced computational performance, the numerical simulation is still computationally expensive and time-consuming, with each study case requiring a separate modeling, compared with analytical model. In contrast, a practical mathematical model based on reasonable assumptions and approximations, can not only provide instantaneous calculation results and identify the effect of each key physical parameter but can also reveal undiscovered phenomena. Xu established an analytical model to predict the expansion of desorption region by using pressure squared approach in late times and the pressure approach in early times. However, he neglected the influence of the drainage area on the interference and the model would become inapplicable after the desorption front reached the boundary [18,19]. In addition, the proposed model by Xu was based on the constant BHP without considering the variable production system at different production stages.

To our best knowledge, there is few practical analytical method for analyzing the spreading mechanism of drainage and desorption area considering the variable production rates and BHP at different production stages. In these regards, by assuming the desorption area of high gas-water ratio and the without-desorption area of low gas-water ratio, the pressure-squared approach is applied in desorption area where the gas production dominates. And the pressure approach is employed in without-desorption area. Furthermore, the production life of CBM well is divided into five stages. We firstly propose the semi-analytical model to investigate