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Technical Note

Dynamic behaviours of reservoir pressure during coalbed methane production in the southern Qinshui Basin, North China

Rui Li[a], Shengwei Wang[a,*], Shuaifeng Lyu[a], Yuhang Xiao[a], Dongmei Su[a], Jiacheng Wang[b]

[a] Faculty of Earth Resources, China University of Geosciences, Wuhan 430074, China
[b] Department of Petroleum and Geosystems Engineering, University of Texas at Austin, Austin, TX 78731, USA

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ABSTRACT

During the coalbed methane (CBM) reservoir depletion, accurate determination of the dynamic characteristics of reservoir pressure is essential to evaluate the effective desorption intensity, interwell interference, multi-layer production, and productivity. Based on the study on the propagation of pressure perturbation and gas desorption area in the stage above and below the critical desorption pressure (CDP) respectively, an analytical mathematical model is established to characterize the dynamics of reservoir depressurization. Then with a field case study on the reservoir pressure depletion in the southern Qinshui Basin, North China, the variation laws of reservoir pressure during CBM production are analysed and discussed. In the stage above CDP, the average reservoir pressure decreases linearly under the constant water production rate. With the location farther away from the wellbore, pressure gradient progressively decreases and rate of pressure change at a fixed location shows a fast to slow pattern. In the stage below CDP, the gas desorption area expands gradually and similar variations are observed between the average reservoir pressure and bottom-hole pressure, both showing a fast to slow pattern. This shows that the reservoir pressure depletion depends dramatically on the variations of bottom-hole pressure. It verifies the reasonability of this mathematical framework after a comparison of calculation results and changing laws between this study and tank-type model. This study is meant to provide a theoretical guidance for the management and optimization of wellbore dewatering during CBM extraction.

1. Introduction

Coalbed methane (CBM) is a form of unconventional natural gas which is extracted from coal beds. The extraction and utilization of CBM resource is known to be beneficial for the safety of coal mining and reduction of the harm of green-house gas emission (Su et al., 2005a; Karakurt et al., 2012; Vishal et al., 2013a,b; Pan and Wood, 2015). Also, it plays an important role in providing clean energy over the world in recent decades. The Qinshui Basin, located in the Shanxi Province, North China, is a main coal-bearing basin in China and one of the largest CBM fields with high-rank coal in the world (Liu et al., 2015). As a hot area of CBM exploration and exploitation, the amounts of CBM resource in this basin is approximately $3.28 \times 10^{12}\,m^3$ (Su et al., 2005b; Meng et al., 2011). The exploitation of CBM resource in the southern Qinshui Basin (SQB) has been performed for more than 20 years and advantages on geological conditions make it the most successful area for CBM production in China. However, the drainage technique of CBM wells adapted the geological condition is always unsatisfactory, which has restricted the development of ground CBM exploitation and coalmine gas extraction.

Generally, more than 80% CBM in the coal is adsorbed in the coal matrix. During the CBM exploitation, methane can be desorbed into free gas phase and flows towards the wellbore only after the reservoir pressure sufficiently depletes below the critical desorption pressure (CDP). This property of coal is significantly different from that of conventional hydrocarbon reservoirs. With CBM reservoir depletion, the reservoir pressure varies dynamically with time and space. And accurate determination of reservoir pressure dynamics is one of the key factors affecting the effective desorption intensity, interwell interference, multi-layer production, and gas productivity (Ziarani et al., 2011; Salmachi and Yarmohammadtooski, 2015). In addition, the difference between reservoir pressure and bottom-hole pressure (BHP) is a key factor on controlling the effectiveness of the gas extraction. Therefore, it is necessary to investigate the transmission characteristics and quantify the pressure dynamics during CBM production and the results can be used to provide guidance for the evaluation of reservoir dynamics and management of wellbore depressurization.

Since 1980s, there have been many related studies discussing the

* Corresponding author.
E-mail address: swwang@cug.edu.cn (S. Wang).

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dynamics of reservoir pressure during CBM production. Clarkson et al. (2007) and Clarkson (2009) believed that average reservoir pressure can be obtained from material balance equation and investigated the variations of reservoir pressure of saturated reservoirs in Canada. Seidle (2011) presented a mathematical model named tank-type model to describe the dynamics of average reservoir pressure for the bounded CBM wells, which is based on Darcy's pseudosteady-state equations and mass balance. With this framework, they simulated the depressurization progresses of the Big George coal of the Powder River Basin. Liu et al. (2012) discussed the influencing factors of pressure depletion funnel by analysing several CBM wells in the SQB, based on the plane radial flow theory and the superposition principles of pressure drop. Zou et al. (2013) classified the CBM reservoir into three types, including gas pressure reservoir, water pressure reservoir, and hybrid pressure reservoir, and discussed the transmission process of reservoir pressure. Chen et al. (2015) believed that variations of reservoir pressure can be calculated based on the production data combined with some basic reservoir parameters, when they were studying the permeability changes during CBM production. Li et al. (2016) analysed the process of reservoir pressure depletion based on the fracture systems in CBM reservoir, proposed two transfer modes for the depressurization, and established a preliminary mathematical framework to calculate the reservoir depressurization for bounded drainage. The previous studies especially the recent studies have greatly improved the understanding of the reservoir pressure depletion especially the average reservoir pressure during CBM production. However, the aforementioned mathematical models mainly focus on the gas-saturated reservoirs in which the coal is fully adsorbed with gas under the initial reservoir pressure. Actually, many CBM reservoirs, especially those in China, are undersaturated and reservoir pressure requires to be reduced to the CDP before gas production commences. Up to now, there is no mathematical framework presented to quantify the dynamics of reservoir pressure in both spatial and temporal dimensions for the high-rank CBM reservoirs. Furthermore, in the numerical modelling, many different parameters required to run the simulation are hard to obtain in fact such as coal and fluid properties, and relative permeability curves (Gentzis and Bolen, 2008; Ziarani et al., 2011; Xu et al., 2013). To further understand the dynamic behaviours of pressure depletion and provide guidance for the management of dewatering, it is necessary to develop a new method to quantitatively characterize the process of reservoir pressure depletion profile for the undersaturated reservoirs and investigate the variation laws of reservoir pressure both with time and space during CBM production.

The objective of this study is to establish a theoretical framework to quantify the reservoir pressure profile both in spatial and temporal dimensions for the CBM reservoir. The conceptual process of reservoir pressure transmission and drop are analysed firstly. Then, an analytical mathematical model to estimate the dynamics of gas desorption range and reservoir depressurization is proposed, based on the study on the propagation of pressure perturbation and gas desorption area. On this basis, a field case in the SQB is employed to study the variations of reservoir pressure profile, and the variation laws of depressurization with time and space are analysed and discussed.

2. Geological setting

Qinshui Basin is a large compound synclinal basin surrounded by the uplifts of Wutai Mountain, Taihang Mountain, Zhongtiao Mountain, and Huo Mountain (Su et al., 2005b; Cai et al., 2011). The geological structures are relatively simple and the faults in this area are undeveloped. In the SQB, it is nearly a horizontal monocline structure, inclining towards the northwest (Cai et al., 2011) and two main series of paralleled folds striking NNE and NEE are in the study area with an amplitude generally less than 30 m. The strata in this area consist of Majiagou Formation (O_2m) of Ordovician system, Benxi (C_2b) and Taiyuan Formation (C_3t) of Carboniferous System, Shanxi (P_1s), Shihezi

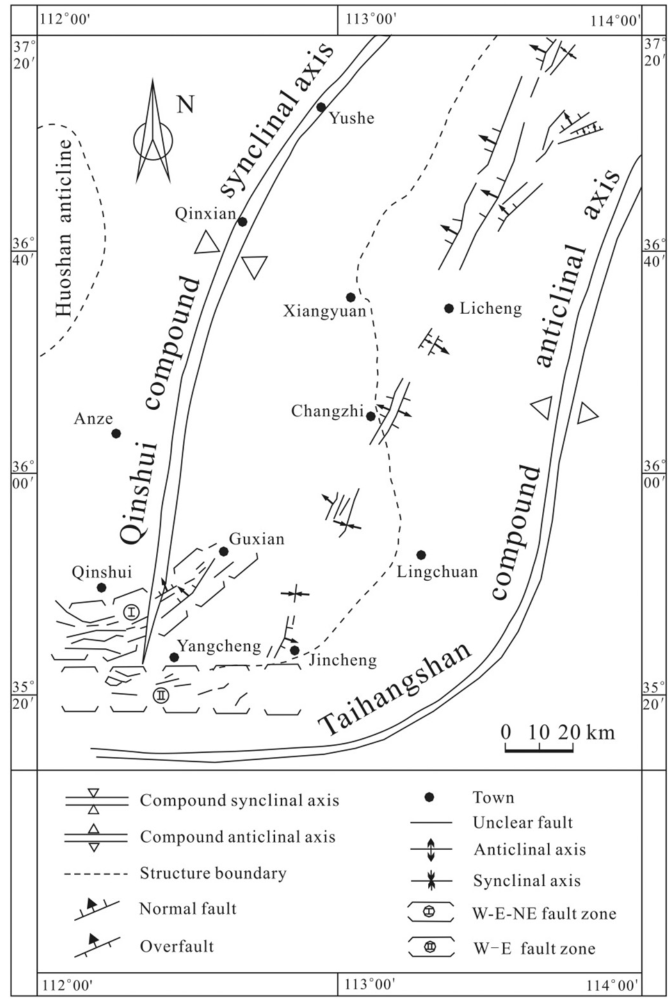

Fig. 1. Major geological structures of the southeast Shanxi Province (Li et al., 2016).

($P_{1-2}s$) and Shiqianfeng Formation (P_2sh) of Permian System (Su et al., 2005b). No. 15 coal seam of Taiyuan Formation and No. 3 coal seam of Shanxi Formation are the target coal seams for CBM extraction in this area, with an average thickness of 3.28 m and 5.28 m respectively. The depth of No. 15 coal seam is generally less than 800 m and No. 3 coal seam is 80–110 m shallower than that of No. 15 coal seam (Lv et al., 2012). The major geological structures of the southeast Shanxi Province are shown in Fig. 1.

The coal in the SQB is anthracite with a maximum reflectance value of 2.7%–3.7% for the vitrinite ($R_{o,\ max}$) (Liu et al., 2015). The permeability of coal seam gained by well test ranges between 0.01 and 3.61 mD with an average of 0.5 mD, and drops sharply with the increasing of coal seam burial depth (Meng and Li, 2013). The effective porosity of the coal seams is 1.15%–7.69%, normally less than 5%, which is relatively low in general. The gas content in this area is very high, varying between 10 and 37 m^3/t with an average of 14 m^3/t (Chen et al., 2015). The gas saturation is generally low and most of reservoirs in this area are undersaturated.

3. Process of reservoir pressure depletion

Before the dewatering, CBM reservoir is in a virgin equilibrium state and the reservoir pressure is termed as initial reservoir pressure. For the undersaturated reservoirs, in the beginning of production, reservoir pressure is higher than the CDP and desorption of adsorbed gas does not occur. During dewatering, with the process of the formation water flowing to wellbore through fracture networks in the reservoir, the