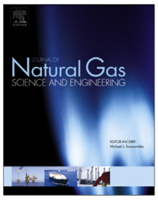
Journal of Natural Gas Science and Engineering 38 (2017) 597–607

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse



Interactions between coal seam gas drainage boreholes and the impact of such on borehole patterns

Zhengdong Liu [a, b, c], Yuanping Cheng [a, b, c, *], Jingyu Jiang [a, b, c], Wei Li [a, b, c], Kan Jin [a, b, c]

[a] *Key Laboratory of Coal Methane and Fire Control, Ministry of Education, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China*
[b] *National Engineering Research Center for Coal and Gas Control, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China*
[c] *School of Safety Engineering, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China*

ARTICLE INFO

Article history:
Received 22 September 2016
Received in revised form
6 January 2017
Accepted 9 January 2017
Available online 10 January 2017

Keywords:
Borehole interaction
Gas extraction
Borehole pattern
Numerical modeling

ABSTRACT

Borehole drainage is the most effective means of extracting coal seam gas. However, numerous boreholes are usually needed to create strong drainage from a single coal seam. When multiple boreholes work at the same time, borehole interactions will occur, which strongly affect the gas production and the area controlled by each borehole. To accurately quantify the degree of interaction, this paper utilizes the changes in the gas pressure at points around the borehole to calculate the pressure decrease coefficients, which reflect the degree of disturbance between the boreholes. The relationships between the physical parameters of the coal seam and the pressure decrease coefficients are studied with a typical double borehole interaction model. The results illustrate that the pressure decrease coefficients are positively correlated with the coal permeability in the disturbance region. Furthermore, the relation between the pressure decrease coefficients and borehole separation forms a negative exponential function, whereas the relation between the pressure decrease coefficients and the distance from the borehole forms a positive index function. Multi-borehole patterns are also analyzed to investigate the ability of the pressure decrease coefficients to determine which common borehole pattern is most suitable for efficient gas extraction.

1. Introduction

Coal seam gas is a clean and efficient form of energy. However, this gas can cause disasters, such as coal and gas outbursts (An et al., 2013; Lunarzewski, 1998; Skoczylas et al., 2014) and gas explosions (Bao et al., 2016; Yang et al., 2014). Gas extraction remedies this issue and provides the opportunity to both furnish efficient energy and prevent gas disasters (Flores, 1998; Gilman and Beckie, 2000; Karacan et al., 2011). Gas extraction technology can generally be divided into two categories: borehole drainage and well extraction (Kong et al., 2014). Borehole drainage technology is the most widely used method in practical situations (Frank et al., 2013; Karacan et al., 2007; Zhai et al., 2016; Zheng et al., 2016).

Engineers are most concerned with the effects of borehole drainage. Thus, they often use the drainage radius of the borehole to assess the effect of extraction (Lin et al., 2016). Lee and Lam (2008) proposed that each borehole can be approximated by a square column that is circumscribed by the borehole radius. The methods of evaluating the borehole drainage radius can be divided into two categories: field measurements and theoretical analyses derived via numerical simulations. Field measurements are more accurate, but many boreholes must be drilled. Numerical simulations require considerably shorter processing and computational time, and although they may generate some errors, they provide values within acceptable ranges (Hao et al., 2012).

Both methods of drainage radius estimation tend to use a single borehole measurement. However, gas extraction systems consist of multiple boreholes, and the interactions between the boreholes will significantly influence the drainage radius of each borehole in the system. Thus, for the results to accurately represent multi-borehole systems, the theory of multiple-boreholes in a coal seam must be studied. Studies of multi-lateral wells have been conducted and are relatively mature. The former Soviet Union was the first country to apply multi-lateral well technology to extract oil and gas. This technology was widely applied in Russia, the North Sea, and North America during the 20th century (Murillo et al., 2009). Eric Diggin's organization in the Shell Company held a forum on the

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[*] Corresponding author. National Engineering Research Center for Coal and Gas Control, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China.
E-mail address: ypcheng@cumt.edu.cn (Y. Cheng).

http://dx.doi.org/10.1016/j.jngse.2017.01.015

technical progress on the use of multi-lateral wells and established the TAML (Technology Advancement of Multilaterals) ranking system (Fipke et al., 2008). Based on an incomplete set of statistics, approximately 1000 multi-lateral wells were drilled prior to 1998; by the end of the year, however, approximately 450 additional multi-lateral wells had been completed. By 2001, Baker Hughes and the Halliburton Company had developed more than 20 multi-lateral well systems independently, and approximately 2000 multi-lateral wells had been drilled around the world.

Current studies of multi-lateral wells focus on productivity prediction. The earliest method for productivity prediction was proposed by Табаков, who assumed that the pressure is equal at every point when there are 1 or 2 multi-lateral wells. However, with 3 or 4 multi-lateral wells, he assumed that the yield per unit length remains constant. This method clearly has several limitations, and the two assumptions are contradictory. S.D. Joshi proposed a new method that is based on Табаков's method but uses different assumptions; for example, the three-dimensional seepage problem was simplified as a vertical seepage and horizontal plane seepage problem, and the multi-lateral wells were assumed to be fractures with infinite flow conductivity. His method can address the problems with Табаков's method and is more suitable for practical reservoir situations, so it is widely accepted (Joshi, 1988). Larsen (1996) developed a productivity prediction equation that incorporates quasi-steady-state flow. However, several assumptions are used in the equation for computing the productivity of multi-lateral wells; for example, all of the multi-lateral wells must be in a homogeneous reservoir with a constant thickness, and the distance between the midpoints of the multi-lateral wells is constant. These two assumptions restrict the application of the equation to a single reservoir; the first assumption is invalid when there is more than one reservoir, and second assumption is invalid when the multi-lateral wells are located in different reservoirs. Salas et al. (1996) divided fishbone multilateral wells into several small pieces and developed a one-way analytical model, but the interaction between wells was not considered. Turhan (2003) developed an unsteady, three-dimensional analytical model that was based on anisotropy and the skin effect. Chen et al. (2000) and Zhu et al. (2002) proposed a productivity prediction model that considered the cross-flow effect; however, it can only be used in the later quasi-stable period. Abdelhafid et al. (2003) applied the principle of potential superposition to develop a two branch well model and used it to calculate the infinite deflector solution.

The core of multi-lateral well research is the interaction phenomenon. Most of the aforementioned scholars considered the effect of interaction when they developed their productivity prediction models. Several investigators have conducted studies specifically on the interactions between wells. Zhang (1998) proposed that interactions between wells always occurred when two or more wells were used in the production of a single oil reservoir. He believed that the pressure drop at any point should be equal to the sum of the pressure drop caused by each well at that point. Kong (1999) assumed that the area of the well groups was smaller than that of the reservoir and that each well was located far from the boundary of the reservoir. He utilized the pressure drop superposition principle to quantitatively represent the yield when one well is affected by other wells. Cases with different numbers of extraction wells and different patterns, both of which influence the interactions between the wells, were also discussed.

Inter-well interference is ubiquitous in the field of coalbed methane extraction and several researchers have studied this phenomenon in detail. Xu et al. (2013) developed an analytical model to predict the desorption area in coalbed methane (CBM) reservoirs and applied it to a CBM well group in the Hancheng field, China. He found that the desorption area expands with an elliptical geometry, and the final results predicted that well A and well B interfered with each other after 525 days of production. Xia et al. (2015) proposed a new convenient, efficient and reliable method to quantify well interference. The reliability of the method was verified by comparing the results with theoretical results for the real case of the Baode block. Well interference of coalbed methane wells is an effective technology to achieve high and stable gas production rates. Multi-branch horizontal coal bed wells have been used over the past 15 years to increase gas production rates considerably (Baoan et al., 2005). A Z-pinnate well pattern that is drilled underbalanced in a low-permeability but high gas content coal seam can deplete 1200 acres from a single small well site and typically recover 85%–90% of the original gas-in-place within 30 months (Wight, 2006). The performance of multi-branch horizontal wells was analyzed and compared to that of vertical wells (Ren et al., 2014). Field data indicate that the gas production rate of most vertical wells decreased rapidly after a short period of time, while the performance of multi-branch horizontal wells was stable over 3 years of production.

Because the multi-borehole coal seam theory can be applied to research on multi-lateral wells and inter-well interference during coalbed methane extraction, we can also use the yield fluctuations of boreholes to express the degree of borehole interaction. However, this paper proposes a new quantitative parameter that can better describe the interactions between boreholes; the parameter is defined as the "pressure decrease coefficient" (PDC). The way in which the PDC can be represented and the relationship between the PDC and the physical parameters of coal are discussed. Finally, this paper proposes that the PDC can be used as a new criterion to evaluate which common drainage borehole layout pattern is best suited for coal seam gas extraction.

2. Description of the numerical model

2.1. Pressure decrease coefficients

When a coal seam is subjected to multi-borehole drainage, all of the boreholes contribute to the change of coal seam gas pressure. If one of the boreholes i is taken as the benchmark, and a point is regarded as the detection point, the linear distance between the point and borehole i is denoted by d. The gas pressure at this point is defined as $p_{id}(x,y,z)$. We note that the detection point is located on the line between the boreholes; $0<d<\frac{1}{2}L$, where L represents the linear distance between the boreholes. If the interaction between the boreholes is ignored, the gas pressure at the detection point, $p_{id}(x,y,z)$, can be expressed as:

$$p_{id}(x,y,z) = p_{od}(x,y,z) - \sum_{j=1}^{N} p_j(x,y,z) \tag{1}$$

where $p_{od}(x,y,z)$ represents the gas pressure at the detection point when it is not disturbed by any boreholes, and $p_j(x,y,z)$ is the reduced gas pressure value at the detection point when it is affected by the boreholes, j. While the value of $p_j(x,y,z)$ is influenced by numerous factors, the relationship between them can be expressed as a function of f:

$$p_j(x,y,z) = f(k, ps, t, ds) \tag{2}$$

where k is the coal permeability, ps is the suction pressure of borehole$j$, t is the time of drainage, and ds is the linear distance between borehole j and the detection point. The coal permeability, the suction pressure of the borehole, and the extraction time are positively correlated with $p_j(x,y,z)$. In contrast, the linear distance