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A dynamic prediction model for gas-water effective permeability in unsaturated coalbed methane reservoirs based on production data

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ABSTRACT

Effective permeability of gas and water in coalbed methane (CBM) reservoirs is vital during CBM development. However, few studies have investigated it for unsaturated CBM reservoirs rather than saturated CBM reservoirs. In this work, the dynamic prediction model (PM-Corey model) for average gas-water effective permeability in two-phase flow in saturated CBM reservoirs was improved to describe unsaturated CBM reservoirs. In the improved effective permeability model, Palmer et al. absolute permeability model segmented based on critical desorption pressure and Chen et al. relative permeability model segmented based on critical water saturation were introduced and coupled comprehensively under conditions with the identical reservoir pressures and the identical water saturations through production data and the material balance equations (MBEs) in unsaturated CBM reservoirs. Taking the Hancheng CBM field as an example, the differences between the saturated and unsaturated effective permeability curves were compared. The results illustrate that the new dynamic prediction model could characterize not only the stage of two-phase flow but also the stage of single-phase water drainage. Also, the new model can accurately reflect the comprehensive effects of the positive and negative effects (the matrix shrinking effect and the effective stress effect) and the gas Klinkenberg effect of coal reservoirs, especially for the matrix shrinkage effect and the gas Klinkenberg effect, which can improve the effective permeability of gas production and render the process more economically. The new improved model is more realistic and practical than previous models.

1. Introduction

Coal seams are naturally-fractured reservoirs consisting of matrix blocks, where most gas is adsorbed onto coal inner surfaces, and a network of cleats, usually saturated with water at the in-situ state, provides the main flow paths for gas and water flow in coal seams (Chen et al., 2014). Based on the relative gas content (the ratio of the measured gas content to the theoretical gas content calculated by Langmuir equation, S_r, %) in the matrix, coalbed methane (CBM) reservoirs are divided into two types: saturated ($S_r \geq 100\%$) and unsaturated ($S_r < 100\%$) ones. According to statistical data, CBM reservoirs in China are typically unsaturated (Su et al., 2005; Yao et al., 2008; Keim et al., 2011). As unsaturated CBM reservoirs will not produce commercial quantity gas until the reservoir pressure drops below the critical desorption pressure, the production wells must experience a long water drainage and unstable gas production stage (Carlson, 2006). Thus, the flow regime change during CBM production mainly depends on the relationship between the critical desorption pressure and the reservoir pressure (Zhao et al., 2013). Additionally, the dynamic change of the reservoir pressure, which is determined by water production, has an immediate impact on the CBM desorption in the saturated reservoirs (Karacan and Goodman, 2012).

In the system of reservoir evaluation, the permeability (primarily controlled by the effective stress, matrix shrinkage and gas Klinkenberg effects) is a key parameter used to characterize the ability of fluid migration and production (Sparks et al., 1995; Palmer, 2009; Tao et al., 2012; Pan and Connell, 2012). The gas production rate strongly depends on the gas-water relative permeability (Ham and Kantzas, 2008), which is an indispensable part of the simulation of CBM production (Shi et al., 2008). Various relative permeability models have been developed on the basis of conventional hydrocarbon theory and experimental data (Gash,

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1991; Hyman et al., 1992; Meaney and Paterson, 1996; Ahsan, 2006; Shen et al., 2011; Chen et al., 2014), log data (Conway et al., 1995), capillary pressure data (Corey, 1954; Corey and Rathgens, 1956; Wyllie and Gardner, 1958; Pirson, 1958; Brooks and Corey, 1966; van Genuchten, 1980; Zhou et al., 2007; Li, 2010), or production data (Clarkson et al., 2007, 2011). However, compared with the conventional oil and gas reservoirs, significant errors may occur when these above-mentioned models are applied directly to coal reservoirs which have many special characteristics (Moore, 2012; Chen et al., 2013). Although the effective permeability is the most directly relevant permeability parameter related to well production (Xu et al., 2014), few scholars have analyzed its change in unsaturated CBM reservoirs during production. Xu et al. (2014) established the first average gas and water effective permeability dynamic prediction model (PM-Corey model) using CBM production data. However, this model lacks the representation of a single-phase water drainage stage, as is likewise the case for the relative permeability models described above. Therefore, these models do not reflect completely the actual development process of unsaturated CBM reservoirs. Knowledge of the unsaturated characteristics of CBM reservoirs is very important for establishing an effective permeability dynamic prediction model.

In this study, all the theoretical models were improved and segmented on the basis of the critical desorption pressure and the corresponding water saturation, resulting that the effective permeability was divided into two stages by the critical desorption pressure. Then, an improved prediction model for the effective permeability of gas and water in unsaturated CBM reservoirs was developed based on segmented theoretical models. Finally, taking the Hancheng area as an example, the dynamics of the gas-water effective permeability was analyzed using the new model.

2. Overview of the Hancheng area

The Hancheng area is located in Shanxi Province, at the south-eastern margin of the Ordos Basin in China (Yao et al., 2009b), with an area of 1120 km^2 and an estimated 1.7 $\times$ 10^{12} m^3 of total CBM reserves (Chen et al., 2006; Ma and Yin, 2002). The main coal-bearing sequences in the area occur in the Permian Shanxi Formation and the Carboniferous Taiyuan Formation. The location of Hancheng area and the coal-bearing formations stratigraphic column are showed in Fig. 1. The Shanxi Formation is approximately 35–115 m thick and is deposited mainly in a shallow water delta environment. The No. 3 seam is the main mineable coal seam with simple structures in the Shanxi Formation. The Taiyuan Formation is approximately 26–87 m thick, predominantly deposited in a coastal plain environment. The No. 5 and No. 11 seams are the main mineable coal seams with complex structures. The injection/falloff well tests demonstrate that the initial reservoir pressure is between 2.39 and 6.96 MPa and most of the coal reservoirs are under-pressured since the pressure coefficient is generally 0.6–0.9 (Table 1). The coal rank in the Hancheng area ranges from low volatile bituminous to semi-anthracite (Yao et al., 2013).

The main lithotypes are semi-bright and bright coals in study areas. The vitrinite reflectance ranges from 1.58% to 1.90%. Coal composition analysis shows that coals in this area are dominated by a maceral assemblage of vitrinite and inertinite. Proximate analysis indicates that the coals contain 0.43–1.30% moisture, 7.50–19.76% ash and 9.72–22.18% volatile (Table 2).

3. Methodology

In order to establish the new model, the following assumptions are put forward in the unsaturated CBM reservoirs: 1) the single-

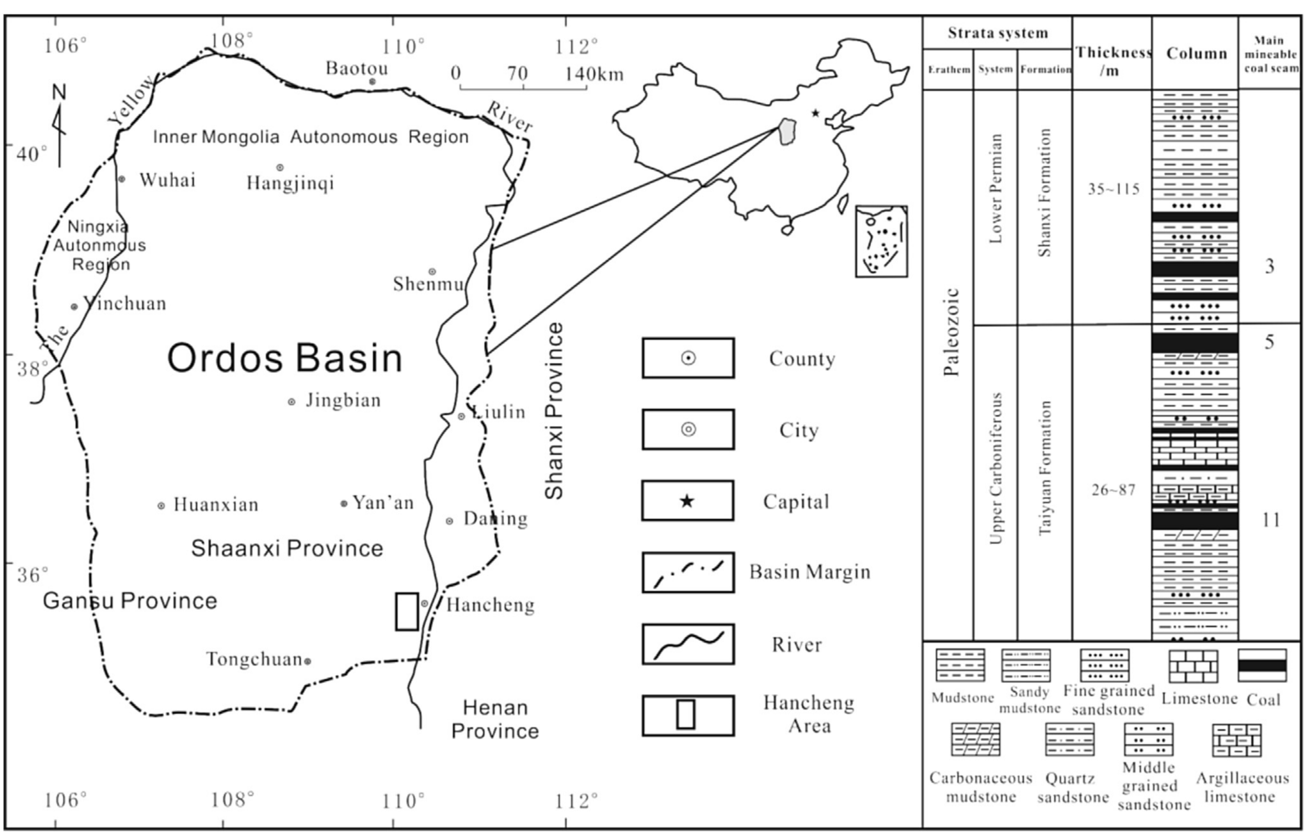

Fig. 1. Location and stratigraphic column showing the coal-bearing formations in the Hancheng area of Ordos Basin.