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A new mathematical simulation model for gas injection enhanced coalbed methane recovery

Xiaofei Sun [a,b,*], Yanyu Zhang [a,*], Kai Li [c], Zhiyong Gai [a]

[a] College of Petroleum Engineering, China University of Petroleum (Huadong), Qingdao 266580, PR China
[b] School of Geosciences, China University of Petroleum (Huadong), Qingdao 266580, PR China
[c] Research Institute of Experiment and Detection, Xinjiang Oilfield Company, Karamay 834000, PR China

HIGHLIGHTS

- The 2D PR-EOS model exhibits a good performance in predicting mixed gas adsorption.
- A MS-BPD model provides a superior prediction of mixed gas diffusion.
- A new mathematical model was proposed to analyze the CBM/ECBM processes.

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ABSTRACT

The main purpose of this study is to improve the numerical evaluation of gas injection enhanced coalbed methane (ECBM) recovery by establishing a new mathematical coalbed methane (CBM) simulation model, in which the two-dimensional Peng–Robinson equation of state (2D PR EOS) model and the Maxwell-Stefan bidisperse pore diffusion (MS-BPD) model for multicomponent gas adsorption and diffusion are implemented. First, the extended Langmuir, ideal adsorbed solution and 2D PR-EOS models were investigated and compared with the experimental data of pure and mixed gas for modeling multi-component gas adsorption behavior. Then, the MS-BPD model was developed based on the 2D PR-EOS model, bidisperse diffusion mechanisms, and Maxwell-Stefan diffusion theory, which provided an improved simulation of multicomponent gas diffusion behavior. On the basis of previous research, we developed a new CBM simulation model to analyze the effects of injection gas composition on the gas injection ECBM recovery process. The results indicate that mixed-gas injections are able to enhance methane recovery. The optimum composition of injected gas is 75% N_2 and 25% CO_2, which increases methane recovery by 25% over the pressure depletion production process. This CBM simulation model will provide an effective technical approach for research and development of CBM by gas injection.

1. Introduction

Worldwide coalbed methane (CBM) resources have been estimated at 84–262 trillion m^3. The majority of these CBM reserves are mainly located in Russia, Canada, China, Australia, and the USA [1]. In China, six main CBM production bases (Qinshui, eastern Hubei province, Southwest China, Changqing, Northwest China, and Northeast China) have been constructed in 2015. The cumulative production and peak production of the six bases are expected to reach 3–4 trillion m^3 and 35–45 billion m^3, respectively, in 2020 [2,3]. In addition, the worldwide development of CBM is also accelerating in some other countries, such as the USA, Canada, and Australia.

At present, CBM is mainly recovered by pressure depletion production. However, the primary recovery only produces a portion of gas in place, which normally ranges from 20% to 60% [4]. Thus, enhanced coalbed methane (ECBM) production by injecting gases (N_2, CO_2, or flue gas) has been the focus of increasing attention as an efficient approach to recover residual gas reserves.

Feasible evaluation and prediction by reservoir simulation are important steps in gas injection ECBM production process [5]. A simulation model has to consider certain features, such as coal matrix shrinkage and swelling, multicomponent gas sorption, and diffusion processes, to simulate the complicated mechanisms involved in the ECBM recovery process correctly. Over the past decades, a number of proposed mathematical models attempt to account for the mechanisms mentioned above.

* Corresponding authors at: College of Petroleum Engineering, China University of Petroleum (Huadong), Qingdao 266580, PR China (X. Sun).
E-mail address: sunxiaofei540361@163.com (X. Sun).

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(1) Coal matrix shrinkage and swelling

The values of fracture porosity and permeability may vary during the course of gas injection/production because of coal matrix shrinkage and swelling [6]. The effect of coal matrix shrinkage on permeability was first studied quantitatively by Gray [7]. Then, a number of theoretical and empirical permeability models were developed. Seidel et al. [8] described the mathematical basis for the change of permeability with applied stress. Analytical models such as the P&M and S&D models were then developed and applied to history match the data from San Juan basin fields [9,10]. These two models are widely used because of their simplicity and good agreement with field observations [11,12].

(2) Multicomponent gas sorption models

The knowledge of the sorption behavior of multicomponent gas on coal is the information needed for simulation of gas injection ECBM processes. Many studies were conducted to describe the sorption dynamics of mixed gas with competitive sorption models at reservoir conditions. Among these studies, the extended Langmuir isotherm is widely used to model gas sorption in coal [13,14]. In later studies, thermodynamic approaches such as the two-dimensional equation of state (2D EOS) and the ideal adsorbed solution (IAS) theory were developed [15,16]. Clarkson and Bustin compared the predictions of the IAS model and extended Langmuir model with experimental binary- gas isotherms ($CH_4 + CO_2$). The results indicated that the IAS model is more accurate than the extended Langmuir isotherm because the IAS model predicts a decreasing selectivity with an increase of CO_2 concentration [17].

(3) Multicomponent gas diffusion kinetics

Three types of models are currently available to simulate multicomponent gas diffusion in coals: equilibrium models with instantaneous diffusion, non-equilibrium models with unsteady-state diffusion governed by Fick's law and bidisperse diffusion models [18]. The first two models governed by Fick's law treated the gas diffusion process as one-step diffusion, which are now used in most commercial CBM simulators to simulate coal gas sorption kinetics because of its simplicity [19]. However, its validity is severely restricted and likely to be misleading in many practical situations where the diffusion coefficients of the fluid species depend on composition [18].

More recently, the Maxwell–Stefan diffusion model was proposed to multicomponent gas diffusion, which assumes two-step gas diffusion in a coal matrix: surface diffusion in the microporous system and pore diffusion in the meso/macropore system [20]. ECBM production is assumed to be largely controlled by the multi-step transport process. Therefore, the Maxwell–Stefan diffusion model is more appropriate than Fick's law for describing the multicomponent gas diffusion dynamics and consequently should be applied in the ECBM models [21,22].

Based on the aforementioned studies, three types of CBM reservoir models are developed currently to simulate gas injection ECBM processes. The first type is black-oil and compositional models (GEM, ECLIPSE and GCOMP). The gas diffusion in coal is generally assumed to occur instantaneously and a single porosity approach is used instead of the dual porosity approach, which ignores the gas diffusion in the micropores [23]. In addition, the CBM model in ECLIPSE is only capable of handling two gas components, which cannot be applied to model ECBM recovery processes with flue gas [24].

The models, such as COMET and SIMED II are specially developed to simulate CBM recovery processes [25]. In these types of models, Fick's law is used to describe mixed-gas diffusion and flow in coals, which has been proven inaccurate for describing early stage diffusion, and for coals with multiscale pore structures. Therefore, most of such models are still unable to give an acceptable accuracy in describing ECBM processes.

More recently, many attempts have been made to improve the ECBM simulation with alternative models, such as the unsteady-state model, the bidisperse pore diffusion model, and the triple-porosity simulation model [10,26,29]. Consequently, this type of model is superior to the other CBM models.

Although considerable efforts have been made in modeling the gas injection ECBM processes, significant limitations exist in current models.

(1) The extended Langmuir model is widely used to predict multicomponent gas adsorption in ECBM simulators because of its simplicity. Further studies are needed to determine whether new developed adsorption models are appropriate for implementation into ECBM simulators. Although some studies compared the predictions of various models with experimental binary-gas systems, only a few studies on ternary gas system have been conducted.
(2) For multicomponent diffusion processes, one significant deficiency in the current CBM models is that most models are based on a single pore structure and Fick's Law. These models are unsuitable for simulating the multicomponent gas counter diffusion and flow behavior. Although the bidisperse diffusion model was proposed in some studies to simulate a multicomponent gas diffusion process, the calculation is still based on the extended Langmuir model, which may also affect the accuracy of simulating a mixed-gases diffusion process. Furthermore, implementing the Maxwell-Stefan bidisperse diffusion model in combination with newly developed adsorption models and coal matrix shrinkage and swelling models into ECBM simulations is still difficult because of the complicated calculation associated with ECBM recovery.

This study presents a new mathematical CBM simulation model to address the issues mentioned above. First, several adsorption models were investigated and compared with the experimental data for modeling multicomponent gas adsorption behavior. Then, a Maxwell–Stefan bidisperse pore diffusion (MS-BPD) model was developed based on the selected adsorption model to simulate the diffusion dynamics of mixed gases in coal matrix. Finally, a new CBM simulation model was developed and applied to analyze the effects of injection gas composition on gas injection ECBM recovery process.

2. Adsorption models evaluation

For simulation of gas injection ECBM recovery process, predicting complete adsorption behavior of methane and injecting gases on coals is essential [30]. Therefore, a study was conducted to evaluate the accuracy of various models in predicting multicomponent gas adsorption behavior on coals. First, a brief review of extended Langmuir, IAS and 2D PR EOS models was provided as follows [15,16]:

(1) Extended Langmuir model

For the extended Langmuir model, it predicts the adsorption of multicomponent gas mixture solely from pure component data. The specific amount n_i of a given species adsorbed onto the coal surface in the equilibrium with a bulk gas phase of composition y is calculated from: