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A fully-coupled semi-analytical model for effective gas/water phase permeability during coal-bed methane production

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ABSTRACT

Although many breakthrough efforts have been made in recent years, it is still challenging to gain a clear knowledge of the variation regularities of effective gas/water phase permeability with the pressure depletion. The reasons behind this phenomenon can be attributed to the coexistence of multiple effects and the transition of the flow behavior at different production stages. To date, the fully-coupled model for effective gas/water phase permeability in coal-bed methane (CBM) reservoirs is still lacking and is significantly necessary to be developed. Firstly, the Palmer-Mansoori (PM) model is employed to represent the variation relationship between absolute permeability and pressure. Secondly, after rigorous derivation of the gas–water two phase partial differential equations in coal seams, the relationship between pressure and saturation in infinitesimal coal is obtained, which can be solved through an iterative algorithm. Subsequently, combined with the Corey relative permeability model, the relative gas/water phase permeability can be described as a function of pressure. Finally, coupling the absolute permeability model and relative permeability model, the effective gas/water phase permeability can also be quantified as a function of pressure or saturation. And the reliability and the accuracy of the proposed model is successfully verified through comparisons with experimental data and previous model collected from published literature. Furthermore, on the basis of the proposed semi-analytical model, the effects of critical desorption pressure, gas desorption capacity, stress dependence, and matrix shrinkage on effective permeability are identified. And many implications and direct insights are achieved through the sensitive analysis process. The semi-analytical model, for the first time, incorporates nearly all known mechanisms and can achieve more accurate characterization of effective permeability during the production process. Moreover, due to the concise form and precise feature, the proposed model will serve as a simple, practical and robust tool for the development of CBM reservoirs.

1. Introduction

Recently, as one of the unconventional natural gas family members, CBM is an important source of clean energy which has drawn much attention in the USA, Canada, Australia, and China [1–5]. Coal is the source rock and possesses typical dual porosity: primary (micropores and macropores) and secondary (cleats network). Gas flow behavior through matrix system is dominated by diffusion mechanisms because of the ultra-tight feature. In contrast, the cleat network serves as the high permeability pathway for gas and water flow, which can achieve the commercial gas production [6–8]. For the development of CBM reservoirs, the key property required to be captured is critical desorption pressure (CDP), which is utilized to identify whether the gas desorption occurs or not. When the pressure is above CDP, it is generally considered that the single water phase flow dominates the flow behavior in coal seams. Some literature report that the presence of free gas saturation cannot be neglected, which has an important impact on the production performance during the early production stage [9,10]. Thus, the complex gas-water flow expects to occur once the production initiates. Although significant advances have been achieved in recent years, it is still very challenging to predict the production behavior of CBM reservoirs precisely [11–16]. Amongst the most important properties of coal seams is the effective gas/water phase permeability, the accurate evaluation of which will significantly contribute to the obtainment of precise prediction results. Due to the poor mechanical property, the absolute permeability of coal seams is influenced by stress dependence when the formation pressure is above CDP and the simultaneous effects of stress dependence and matrix shrinkage when

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Nomenclature

B_g	the gas formation volume factor, fraction
B_w	the water formation volume factor, fraction
C_d	the desorption compressibility, MPa^{-1}
C_f	the coal compressibility, MPa^{-1}
C_g	the gas compressibility, MPa^{-1}
C_s	the coal matrix compressibility, MPa^{-1}
C_w	the water compressibility, MPa^{-1}
E	Young's modulus, MPa
g	pressure-dependent suppression factor, dimensionless
K	absolute permeability under current pressure condition, mD
K_g	the effective gas permeability, mD
K_w	the effective water phase permeability, mD
K_i	the initial absolute permeability, mD
K_{rg}	the relative gas phase permeability, fraction
K_{rw}	the relative water phase permeability, fraction
K_{rg0}	the endpoint relative permeability of gas, fraction
K_{rw0}	the endpoint relative permeability of water, fraction
K_{rgm}	the relative gas phase permeability of calibrated Corey model, fraction
K_{rwm}	the relative water phase permeability of calibrated Corey model, fraction.
M	axial modulus, MPa
P	the current formation pressure, MPa
P_d	the CDP of the CBM reservoirs, MPa
P_L	the Langmuir pressure, MPa
P_i	the initial formation pressure, MPa
P_{sc}	the pressure under standard condition, MPa
S_g	the gas saturation in the coal seams, fraction
S_w	the water saturation, fraction
S_{gc}	the residual gas saturation, fraction
S_{wc}	the irreducible water saturation, fraction
S_{max}	the maximum Langmuir volumetric strain, dimensionless
t	the production time, h
T	the formation temperature, K
T_{sc}	the formation temperature under standard condition, K
V_L	the Langmuir volume, m^3/m^3
Z	the gas compressibility factor at reservoir condition, fraction
Z_{sc}	the gas compressibility factor at standard condition, fraction
ζ	the bulk modulus, MPa
υ	Poisson's ratio, dimensionless
ϕ	the current porosity, fraction
ϕ_i	the initial porosity, fraction
μ_g	the gas viscosity, mpa·s
μ_w	the water viscosity, mpa·s

the pressure is below CDP [17–21]. Moreover, due to the gas desorption, the gas-water two phase flow will gradually dominate the flow mechanism in the coal cleats, which further aggravate the complexity of describing gas/water phase permeability.

At present, the most widely and directly utilized methods for quantifying the effective gas/water phase permeability is the laboratory experiments, including steady state method and unsteady state method [22–24]. However, these methods are designed for the conventional gas and oil reservoirs, which may be inappropriate for the CBM reservoirs. Moreover, the fatal deficiencies of the experiments are that the gas desorption and associated matrix shrinkage cannot be taken into account. The other way to accurately simulate the dynamic changes of effective gas/water phase permeability is employing a calibrated full-physics numerical reservoir-simulation [25–28]. However, the process is time-consuming and computationally expensive, with each study case requiring a separate modeling, which is not applicable compared with mathematical models. In contrast, a practical analytical or semi-analytical model, based on some reasonable assumptions and approximations, not only provides instantaneous calculation results but also facilitate identifying the effect of each key physical parameters. To date, much attention has been focused on the relative permeability curve for CBM reservoirs and several comprehensive calculation methods has been established for the issue. However, compared with the relative permeability curve, the variation of effective gas/water phase permeability has much more direct influence on the production behavior and few studies has been performed to investigate it. Xu proposed a dynamic prediction model for effective gas/water phase permeability [29]. The change of absolute permeability was captured by employing the PM model, which described the relationship between pressure and absolute permeability. And the Corey relative permeability model was calibrated by endpoint relative permeability in Xu's model, which described the relationship between saturation and relative phase permeability. With the intent of combining the PM model and calibrated Corey model, the key relationship between pressure and saturation was generated by Xu through the material balance equation, which assumed that the whole CBM reservoir has the same pressure and saturation at a certain production time. However, both the PM model and Corey relative permeability model represented the relationship within the infinitesimal coal seam. Therefore, in Xu's model, the adopted average pressure and average saturation for whole coal seams would inevitably result in large deviation compared with the actual variation characteristics of effective water/gas phase permeability. In addition, Xu's prediction model was heavily dependent on the production data. That is to say that the effective water/gas phase permeability cannot be predicted if the production data is not available. Thus, Xu's model can only be utilized to investigate the variation regularity during the CBM production process, but fails to provide practical advice for the development of CBM reservoirs before the production initiates. Furthermore, Xu's model is difficult to analyze the effect of each key physical parameters due to the complicated calculation process. Zhao developed a dynamic model for effective permeability for unsaturated CBM reservoirs, which incorporated the representation of a single-phase water drainage stage and could be utilized for the entire production process of unsaturated CBM reservoirs [30]. However, similar with Xu's model, Zhao obtained the important relationship between pressure and saturation in terms of the material balance equation. Therefore, Zhao's model suffered the similar deficiency of Xu's model, such as the usage of the concepts of average pressure and average saturation and dependence on the production data. After the above necessary literature review, it can be concluded that the efficient model for effective gas/water phase permeability is still lacking and is significantly necessary to be established.

In this work, in order to overcome the deficiency of the aforementioned previous models, the relationship between pressure and saturation within infinitesimal coal seams is developed, which is derived through partial differential equations for gas/water two phase flow. Thus, the proposed new model can reasonably combine the PM model with Corey model. The research in this work is significant and necessary modification for the previous models, which can give a clear knowledge of the variation characteristics of effective gas/water phase permeability during CBM production.

2. Modeling

2.1. Model construction

In order to develop the practical model for effective gas/water phase permeability in coal seams, the PM model for dynamic variation