International Journal of Heat and Mass Transfer 125 (2018) 866–875

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

A fully coupled thermo-hydro-mechanical model for heat and gas transfer in thermal stimulation enhanced coal seam gas recovery

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ARTICLE INFO

Article history:
Received 6 November 2017
Received in revised form 23 March 2018
Accepted 23 April 2018

Keywords:
Coal seam gas recovery
Thermal stimulation
Thermo-hydro-mechanical model
Heat and mass transfer
Modeling and simulation

ABSTRACT

Thermal stimulation is an important artificial technique in enhanced coal seam gas (CSG) recovery, where temperature change is often coupled with coal deformation and gas flow. The fully coupled thermo-hydro-mechanical condition in thermal stimulation enhanced coal seam gas recovery triggers a series of thermal coal-gas interactions for the heat or gas transfer. However, prior studies normally ignored the thermo-mechanical interaction of thermal fracturing, the combination of heat and gas transfer, and have not validated their models with actual data. In this study, a fully coupled thermo-hydro-mechanical (THM) model of coal deformation, gas flow and heat transport was developed considering the competitive effects of thermal expansion, non-isothermal gas sorption and thermal fracturing. Subsequently, the model was well validated by historic experimental data, in-situ production data and numerical simulation data, respectively. Finally, the coupled THM model was implemented into a numerical simulation of thermal stimulation enhanced coal seam gas recovery by using the finite element approach. The heat and gas transfer properties, as well as the efficiency of gas production were evaluated.

The modeling results show that: thermal stimulation has promoting effects on gas recovery, however higher temperature does not mean higher efficiency of thermal stimulation to gas recovery; larger thermal sorption coefficient and lower fracturing coefficient correspond to higher gas production; thermal stimulation enhances gas recovery by promoting gas desorption. Our fully coupled THM model can improve current understandings of heat and mass transfer in thermal stimulation enhanced coal seam gas recovery.

1. Introduction

Thermal stimulation technique is an alternative/supplementary method for enhanced gas production from unconventional reservoirs. It has gained great attentions in recent years. According to Wang et al. [1] and Salmachi et al. [2], thermal stimulation dramatically increases gas production by 58% and 12%, respectively, compared with conventional production. Research results show that the thermal stimulation method is more suitable for long-term gas production as it can actually enhance gas recovery by altering gas desorption behavior [3]. In recent years, a variety of unconventional technologies have been discussed. For example, Shahtalebi [4,5] has been working on the microwave and radio frequency energies in the enhancement of shale gas recovery. Microwave heating for industrial processing is characterized by its fundamental differences in the structural and chemical properties from conventional heating methods. By using depressurization, thermal stimulation and combined method, gas production from methane hydrates is evaluated [6]. Salmachi et al. [2] and Thoram et al. [7] studied on the thermal stimulation of injected hot water from geothermal resource for enhanced coal seam gas production through created hydraulic fractures. Moreover, Zhou et al. [8] and Qu et al. [9] discussed the potential method of enhanced gas recovery by hot gas, such as N_2 and CO_2.

Thermal stimulation of gas reservoirs triggers complex interactions among coal, gas and temperature. It changes the behaviors of coal deformation, as well as the flow of heat and gas. Experimental tests of gas adsorption isotherms indicate that temperature has a significant influence on coal methane adsorption capacity [2,9]. Many researchers have found that methane adsorption capacity

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.112
0017-9310/

demonstrates an inverse relationship with the increasing temperature [10–12]. By using small angle X-ray scattering, Nakagawa et al. [13] observed the change of coal surface fractal dimension with heat treatment. Akbarzadeh and Chalaturnyk [14] pointed out that coal was heterogeneous organic–inorganic porous rock containing inherent cleat network and different constituents. As different constituents respond differently to temperature change, the coefficient of thermal expansion is heterogeneous and anisotropic, thus thermal fracturing is induced when coal is heated. Based on this concept, a mathematic model for thermal fracturing based on the fractal assumptions of the micro-pore distribution was established [15,16]. Not only high temperature treatment, low temperature treatment of coal is also researched. King [17] examined the usage of gelled liquid carbon dioxide to stimulate tight gas sand formations. After performing the cryogenic fracturing, the carbon dioxide would evaporate and not cause swelling at the wellbore. By injecting cryogenic fluids into a borehole, Cha et al. [18] found that cracks were created in the surrounding rocks due to the local tensile stress generated by a strong thermal gradient. Coal is thermally expansible. Increasing temperature of coal induces volumetric strain which compacts the channels for heat and gas flow [9,19]. Moreover, when temperature is high, moisture evaporation and thermal volatilization in fractured coal seams cannot be ignored during gas extraction process [20–22]. A critical temperature for notable weight loss rates is about 100 °C [13,14].

Thermal stimulation enhanced coal seam gas recovery is a coupled thermo-hydro-mechanical problem of heat and mass transfer. In 2011, Zhu et al. [23] considered the coal-gas interactions of thermal expansion, gas sorption and gas pressure under variable temperature, and proposed a coupled multi-physical model in International Journal of Coal Geology [23]. Meanwhile, Tong et al. [24] and Jahangir et al. [25] established similar thermo-hydro-mechanical models for heat and mass transfer in soil and rock, respectively. These models provide certain reference meanings for thermal stimulated gas recovery. To provide suggestions in retarding or suppressing the spontaneous combustion of porous coal media, Xia et al. [26,27] developed a fully coupled model for spontaneous combustion of underground coal seams by establishing a set of partial differential governing equations, involving a coal deformation equation, an oxygen flow and transport equation and an energy conservation equation. Li et al. [28] thought that the temperature and groundwater might bring a large deviation for coalbed methane (CBM) extraction design. By taking the effects of these two factors into account, they developed a fully coupled thermal-hydraulic-mechanical model for two-phase flow in CBM extraction. To investigate the effect of thermal recovery from hydraulic fracture heating, a fully coupled numerical model of a fractured horizontal well was developed, and the real gas flow behaviors in shale gas reservoir were captured. In the model, discrete fracture, dual continuum media and single porosity media were employed to describe the hydraulic fractures [3]. Teng et al. [15] demonstrated the thermal stimulation induced physical phenomena such as thermal expansion, thermal sorption and thermal fracturing. They also developed a permeability model under coupled conditions and a complicated thermo-hydro-mechanical model for gas recovery.

Based on the brief reviews above, one can conclude two imperfections. The first is that previous studies have not addressed the full couplings among multi-physics of coal deformation, gas flow and heat transfer systematically. For example, the effect of thermal fracturing is ignored. The second is that a fully coupled thermo-hydro-mechanical model is scarce, especially for heat and gas transfer in thermal stimulation enhanced coal seam gas recovery. Moreover, the validation of established mathematical model must be strengthened. In this paper, we modified our recent research [15] to a fully coupled hydro-thermo-mechanical (THM) model by considering the complex interactions among geo-mechanical effects, coal seam gas flow and energy transport. To validate the accuracy of the proposed mathematical model, numerical experiment and field modeling were carried out, respectively. The results were compared with the experimental data, production data and related simulation work. At last, the hydro-thermo-mechanical model was implemented into a finite element (FE) model for thermal stimulation enhanced coal seam gas recovery to quantitatively predict the properties of heat and mass transfer in porous reservoirs.

2. A Fully coupled thermo-hydro-mechanical model

This section will establish a fully coupled thermo-hydro-mechanical model including a series of couplings among coal deformation, gas flow and heat conduction and convection. As coal is heterogeneous and discontinuous media with complex porous structure, the modeling of heat and gas transfer in real coal seam is unpractical. This study assumes a homogeneous isotropic coal with acceptable errors as many researchers have done [9,23,26,27], and focuses on the mathematical modeling method. Before any further development, following assumptions are summarized:

(a) Coal is homogeneous, isotropic, porous continuum, and it has constant elastic modulus and Poisson's ratio [23,26,27].
(b) Coal seam gas is ideal, and the effect of temperature on viscosity is ignored [9,15].
(c) Gas flow obeys the Darcy's law [29,30].

2.1. Coal deformation

Coal deformation is induced by the aggregated changes of external loading, gas pressure, gas sorption and coal temperature. According to assumption (a), the deformation of coal seam is defined as:

$$\varepsilon_{ij} = \frac{\sigma_{ij}}{2G} - \left(\frac{1}{6G} - \frac{1}{9K}\right)\sigma_{kk}\delta_{ij} + \frac{1}{3k}\alpha p \delta_{ij} + \frac{1}{3}\varepsilon_s\delta_{ij} + \frac{1}{3}\varepsilon_T\delta_{ij} \tag{1}$$

where ε_{ij} is the component of total strain tensor, σ_{ij} is the component of stress tensor, p is the coal seam gas pressure, MPa, σ_{kk} is the total stress tensor, δ_{ij} donates the Kronecker delta. $G = 0.5E/(1+\nu)$ and $K = E/(3(1-2\nu))$ represent the shear modulus and the bulk modulus of coal, respectively. E is the Young's modulus of coal and ν donates the Poisson ratio. The Biot's coefficients for coal is defined as $\alpha = 1 - K/K_s,\ (\alpha < 1)$, in which K_s is the modulus of coal grains. According to the previous researches [23,31,32], the gas sorption (ε_s) and temperature change induced volumetric stain (ε_T) are defined as:

$$\varepsilon_s = \frac{\varepsilon_L p}{p_L + p}\exp - \left[\frac{c_2(T - T_{ref})}{1 + c_1 p}\right], \varepsilon_L = \alpha_{sg}V_L \tag{2}$$

And

$$\varepsilon_T = \alpha_T \Delta T \tag{3}$$

where, V_L and P_L donate the Langmuir volume constant and pressure constant, m^3/kg, Pa, respectively. T_{ref} is the reference temperature for gas sorption, K. c_1 and c_2 are the coefficients for pressure and temperature, Pa^{-1} and K^{-1}, respectively. α_T donates the average thermal expansion coefficient which represents the comprehensive strain induced by homogeneous thermal expansion and thermal fracturing, K^{-1}. $\Delta T = T - T_0$ is the increment of temperature, K. ε_L