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Simulation of coal self-heating processes in underground methane-rich coal seams

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ABSTRACT

In this work, we revised our previous fully coupled model of coal deformation, methane diffusion from matrix and compositional gas flow in fractures, and thermal transport to investigate coal self-heating processes in underground methane-rich coal seams. The coal self-heating in underground coal seams involves a chain of physico-chemical reactions, which are linked together through compositional gas flow and diffusion, reaction kinetics, energy transport and coal deformation mechanisms. Although coal–oxygen reactions have been comprehensively investigated, fewer studies consider the collective impacts of methane-desorption induced coal deformation and compositional gas concentration changes on the methane-rich coal self-heating. We included these self-heating mechanisms of underground methane-rich coal seams in the revised model.

The validation and superiority of the new model were demonstrated against previous results. The model was applied to quantify the self-heating susceptibilities associated with methane desorption diffusion time, coal permeability, differential pressure of leakage, coal-oxidation reaction heat and coal-oxidation rate. The simulation results show that (1) The compositional gas flow in fractures is related not only with coal permeability and methane desorption rate, but also with gas thermal expansion induced self-acceleration effect. (2) The desorption methane in coal matrix infiltration into the fractures can not only dilute oxygen concentration and inert combustible coal, but also hinder outside air leakage into porous coal media, even promote the coal self-heating at the later stage due to gas self-accelerating effect and matrix shrinkage. (3) The larger differential pressure of leakage, coal permeability, coal-oxidation reaction heat and pre-exponential factor can enhance coal self-heating, whereas the larger coal-oxidation activation energy may retard coal self-heating. The simulation results can be used to better understand the coupling mechanism of coal–gas-heating interactions associated with methane and coal spontaneous combustion, and provide some suggestions as to how to control the variables or parameters to retard or suppress the symbiosis disasters of gas and coal spontaneous combustion in underground porous coal media.

1. Introduction

Underground coal fires have long been known to be responsible for huge economic losses, personal casualties, perilous land subsidence and massive environmental contamination (Liu and Zhou, 2010; Wang et al., 2003). Coal fires are most frequently occurring in underground coal seams and mainly ignited through a self-heating process (Wessling et al., 2008a). Self-heating derives from the exothermic reaction and the related release of thermal energy during coal–oxygen interactions (Xia et al., 2014a; Yuan and Smith, 2008). If oxygen is sufficiently supplied but the energy is not released either by conduction, convection, or radiation, the reaction becomes self-accelerating until combustion occurs (Kuenzer and Stracher, 2012). Some of the oldest and largest coal fires in the world occurred in China, the United States, India, Indonesia, and South Africa (Ide and Orr, 2011; Wessling et al., 2008a). In China's 25 major coal-producing provinces except Beijing, more than 130 large and medium-sized mining areas have been to varying degrees jeopardized by spontaneous combustion, and coal fires reported in 90–94% of coal mines. Xinjiang coalfield is the most serious area subjected to coal fires in China and even the worldwide, which has total of 39 burning areas with coverage of 6.056 million m^2 and the coal loss is amounted to 7.7695 million tons, followed by Rujigou coalfield in Ninxia and Wuda area in Inner Mongolia (Kuenzer et al.,

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Nomenclature

E	Young's modulus of coal (MPa)
E_s	Young's modulus of coal grains (MPa)
K	Bulk modulus of coal (MPa)
K_s	Bulk modulus of coal grains (MPa)
f_i	Body force in *i*-direction (kg/m^3)
u_i	Displacement in *i*-direction (m)
ε_V	Volumetric strain of coal
G	Shear modulus of coal (MPa)
υ	Poisson's ratio of coal
V_{sg}	Mobility of absorbed gas content
T	Temperature of coal (K)
T_{ar}	Reference temperature (K)
τ	Diffusion time of matrix methane (day)
$\boldsymbol{v}$	Darcy velocity of gas (m/s)
M	Gas molecular weight (kg/mol)
R	Molar gas constant (J/(mol K))
ϕ	Coal porosity
k	Coal permeability (m^2)
p	Gas pressure (MPa)
c_1	Pressure coefficient (MPa^{-1})
c_2	Temperature coefficient (K^{-1})
m_b	Absorbed gas content in matrix (kg/m^3)
α_T	Thermal expansion coefficient of coal grains (K^{-1})
M	Gas dynamic viscosity of gas ($N\ s/m^2$)
ρ_s	Density of coal (kg/m^3)
ρ_a	Methane Density at standard condition (kg/m^3)
ε_s	Gas adsorption/desorption induced volumetric strain
D	Gas diffusion coefficient (m^2/s)
ε_L	Volumetric strain at infinite pore pressure
K	Heat conductivity coefficient (J/(m s K))
c_p	Specific heat capacity (J/(kg K))
κ_{eff}	Effective heat conductivity coefficient (J/(m s K))
$(\rho c_p)_{eff}$	Effective heat capacity coefficient (J/(kg K))
W_{O_2}	Coal-oxidation reaction rate ($mol/(m^3\ s)$)
Q_T	Coal-oxidation reaction heat ($kJ/(m^3\ s)$)
Q_H	Thermal energy release rate (kJ/mol)
P_L	CH_4 Langmuir pressure constant (MPa)
V_L	CH_4 Langmuir volume constant (m^3/kg)
c_{O_2}	Concentration of oxygen (mol/m^3)
E_a	Activation energy (kJ/mol)
A	Pre-exponential factor (s^{-1})
Subscript	
0	Initial value of the variable
m	The matrix system of coal
f	The fracture system of coal or gas phase
s	Solid phase

2007; Wessling et al., 2008b), whose annual loss amounts of coal burned are estimated to be 0.3 and 0.2 million tons, respectively.

Advances in our understanding of coal–oxygen interactions for self-heating have provided some effective measures to retard or suppress underground mine fires. The evolution of self-heating processes in underground coal seams is a chain of physico-chemical reactions, which is labeled as “coupled processes” implying that one reaction process affects the initiation and progress of another (Xia et al., 2014b,c; Zhu et al., 2011). This coal–oxygen reaction chain is linked together through dominant mechanisms, including compositional gas flow and diffusion, reaction kinetics, energy transport and coal deformation (Song and Kuenzer, 2014; Xia et al., 2014a; Zhu et al., 2011). The individual reaction process, in the absence of full consideration of cross couplings, forms the basis of well-known disciplines such as hydrology, chemistry, elasticity and heat transfer (Liu et al., 2011). Huang et al. (2001) developed a two-dimensional steady model by using natural convection theory in porous media to simulate gas flow and temperature profiles caused by underground coal fires. Klika et al. (2004) analyzed the partial burning of three bituminous coal seams by the numerical solution of the nonlinear initial-boundary value problem for a heat equation. Wolf and Bruining (2007) developed a two-dimensional model by combining geo-mechanical and reactive flow effects to study the interactions between underground coal fires and their roof rocks. Wessling et al. (2008a,b) proposed a hydro-thermo-chemical model to investigate the self-heating mechanisms of coal seams, but rock mechanical deformation was not considered in their model. In our latest research (Xia et al., 2014a), a fully coupled hydro-thermo-mechanical model, involving complex interactions among geo-mechanical effects, oxygen transport and flow, and energy transport, was proposed to quantitatively predict the time and locations of spontaneous combustion of underground coal seams.

However, self-heating process of coal is usually accompanied by the desorption and release of adsorbed methane, which may cause gas explosion accidents under favorable conditions (Karacan et al., 2007; Xia et al., 2014a,c; Zhou, 2012). The coal seam, characterized by a typical dual-porosity system containing a micro-porous matrix surrounded by macro-porous cleats/fractures, is both the source and the reservoir for coalbed methane (Pan and Connell, 2012; Wang et al., 2013; Xia et al., 2014b). According to recent statistical results of 299 pairs of China's state-owned collieries (Zhou, 2012; Zhou et al., 2013a,b), 32.3% of the mines are of high methane content and combustible coal mines, and the symbiosis disasters associated with coal-gas combustion are more frequent and serious with the increase of mining depth. For example, because of borehole leakage triggering a chain of coal–oxygen reactions, a large amount of CO with the maximum concentration of 551 ppm were extracted during the methane drainage of a high methane content and combustible coal seam in the Pingdingshan Mining Co., Ltd. of Henan Province in China, resulting in more than 400 coal seam boreholes mandatory shutoff.

Although a certain extent of success has been achieved using the previous models to explain and match the experimental or in-situ data, the impacts of gas desorption and release processes within the methane-rich coal on self-heating are not considered, namely, the self-heating evolution within methane-rich coal is not well understood by previous models. Zhu et al. (2011) developed a coupled model of coal deformation, gas transport and thermal transport to examine the complex coal–gas interactions under variable temperatures, but the reaction kinetics of coal self-heating are not considered in their model. The conceptual model of self-heating processes within the methane-rich coal can be seen from Fig. 1 that outside air firstly flows into the coal fractures under gas pressure and is subsequently mixed with the desorption methane from the matrix. Once oxygen molecules in the mixed gases are in contact with coal particles, the oxygen adsorption and coal-oxidation reaction occur immediately. When the heat generated by the coal oxidation is not adequately dissipated, the reaction becomes self-accelerating until a fire may ensue. In addition, the self-heating process within the methane-rich coal is also accompanied by the coal matrix shrinkage due to methane desorption and coal matrix swelling caused by coal-oxidation heat; the net influences of these dual competing mechanisms determine the evolution of coal permeability.

In this work, we extend our previous hydro-thermo-mechanical model of coal self-heating (Xia et al., 2014a) by combining coal deformation (gas-desorption induced coal shrinking and self-heating induced coal swelling), methane diffusion from matrix, and compositional gas flow in fractures, coal–oxygen reaction kinetics, and thermal transport mechanisms together to further characterize self-heating evolution of underground methane-rich coal seams. Furthermore, the self-heating susceptibilities associated with extrinsic and intrinsic factors, incorporating methane desorption diffusion time, coal permeability, differential pressure of leakage, coal-oxidation reaction heat