Evolution of coal self-heating processes in longwall gob areas

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ABSTRACT

Understanding the evolution of coal self-heating in longwall mining gob areas is important for the mitigation of underground mine fires. The coal self-heating involves a chain of complex interactions between compositional gas and solid coal. These interactions are normally regulated by the dynamic gob configuration due to the extraction of coal. In this study, a fully coupled transient model of compositional gas flow and transport, and the heat transfer between solid coal and gas is developed to quantify the evolution of coal self-heating processes under the in-situ gob configuration. The modelled results were matched reasonably well with the field measurements of air temperatures and oxygen concentrations for a Chinese coal mine. The verified model was applied to conduct sensitivity studies of (1) ventilation flux; (2) ventilation resistance; and (3) advance rate of face. The main results of the sensitivity study reveal that (i) the high temperature zones are mainly distributed near the intake airway of gob; (ii) the higher ventilation flux or ventilation resistance leads to the higher self-heating temperature and the larger oxidation self-heating zone. Moreover, the self-heating zone migrates towards the much deeper gob area. Whereas, the higher advance rate of face results in the lower self-heating temperature and smaller self-heating zone. The simulated results can provide some suggestions for the prevention of coal spontaneous combustion in gobs.

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1. Introduction

Longwall mining is an extensive coal extraction process in a large area called a "panel", above which the formation layers fracture and separate due to stress release and form a fractured zone called a "gob" [1]. Longwall gobs have high-permeability fractures that form open pathways for gas transport. And the amount of coal accumulates in these areas, which may come from the unmined roof or floor coal, or from an overlying coal seam [2]. The residual coal of gob exposed to air undergoes oxidation reaction through a process of adsorption and chemisorption [3]. If the heat produced by the oxidation exothermic reaction is not dissipated as fast as it is accumulated, there will be an increase of temperature and a thermal runaway event can ensue [4,5]. It has been well known that the self-heating and spontaneous combustion of coal in gobs may pose a difficult, persistent and costly problem for coal

industries worldwide, usually causing significant economic losses, personal casualties, and environmental pollution [6,7]. In China's state-owned collieries, 56% of mines have been jeopardised by spontaneous combustion, and coal fires have been reported in 90–94% of coal mines. More than 60% of fires result from the spontaneous combustion of gobs and is not easy to detect by full-scale tests [8]. Statistical results showed that about 100–200 million tons of unmined coal per year in China are susceptible to fires, which would produce 2–3% of the world production of CO_2 as a result [9].

To prevent the incident of fire, it is essential to accurately predict the behaviour of coal self-heating which may involve a complex physico-chemical process [10]. An appropriate mathematic description could help understand and further explore the self-heating mechanisms of coal at the in-situ condition [11]. Extensive mathematical models have been proposed to predict self-heating tendencies of coal, including the one- to three-dimensional analyses and steady- to unsteady-state analyses [12–20]. However, the existing modelling studies are mainly focused on the coal stockpiles [12–17] and coal seams [18–20], less attention being paid to the self-heating in the mined-out longwall district of

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Nomenclature

K_P	bulking factor distribution function
a_0, a_1	bulking factor attenuation ratios (m^{-1})
d_0, d_1	specific spatial distances (m)
ξ_1	adjustment factor of distribution
H	caved zone height (m)
ε, k	gob porosity and permeability (m^2)
M	seam thickness (m)
d_p	particles diameter (m)
v_g	gas velocity vector (m/s)
Q_s	gas source or sink (kg/(m^3 s))
P	gob gas pressure (MPa)
ρ_g	mixture gas density (kg/m^3)
c_f	form-drag coefficient
u	advance rate of face (m/d)
M	gas dynamic viscosity (N s/m^2)
c_{O_2}	oxygen concentration (mol/m^3)
R	ventilation resistance (N s^2/m^8)
D_a	oxygen diffusion coefficient (m^2/s)
α_L	longitudinal dispersivity degree (m)
α_T	transverse dispersivity degree (m)

τ	tortuosity factor of porous media
A	pre-exponential factor (s^{-1})
E	apparent activation energy (kJ/mol)
R_g	molar gas constant (J/(mol K))
c_p	specific heat capacity (J/(kg K))
κ	heat conduction coefficient (J/(m s K))
Q	workface ventilation flux (m^3/min)
Q_1	coal oxidation reaction heat (kJ/mol)
Q_T	heat sources or sinks (J/(m^3 s))
a_{sg}	specific porous media surface area (m^{-1})
h_{sg}	interfacial heat transfer coefficient (J/(m^2 s K))
H_1	residual coal thickness (m)
T_w	temperature of gob roof and floor (K)
T	temperature (K)
n	apparent order of reaction

Subscripts

s	solid phase
g	gas phase

underground coal mines [21,22]. Besides, in previous simulations on the coal self-heating of gob, the realistic physical configuration of gob, involving ventilation parameters, residual coal thickness, longwall face advance, and dynamic evolution of the permeability and caved zone height, are not fully considered. Saghafi and Carras developed a two-dimensional CFD (Computational Fluid Dynamics) modeling of self-heating in an underground coal mine with a U-ventilation system, which could only be applied to the stationary longwall face [23]. Using the CFD modelling, Yuan and Smith conducted three-dimensional numerical simulations on the self-heating process of coal in gobs where the impact of the ventilation system with a stationary longwall face was investigated [24,25]. Later, they studied the case for an advancing longwall face [26]. However, the face advance was defined by on a series of discrete movements rather than a continuous motion. Li et al. proposed a two-dimensional unsteady model of self-heating through the compositional gas flow and energy transport, but failed to consider the effects of continuous retreat mining advance and subsequent dynamic evolutions of the permeability on the self-heating of gob [27]. Recently, Taraba et al. used a three-dimensional single-phase model with a continuously advancing longwall face to characterise the oxidation process of coal in the gob, but the non-equilibrium heat transfer between the air and solid phases is not yet considered [22,28]. Based on this brief review above, it is concluded that previous studies have not addressed the full interactions among non-Darcy compositional gas flow and transport, and heat transport both in the solid phase and the gas phase under the in-situ gob configuration. The collective impacts of these interactions on the evolution of coal self-heating processes in a gob area are not well understood. This knowledge gap defines the objective of this study.

In our latest research [19], a fully coupled hydro-thermo-mechanical model, involving complex interactions between geomechanical effects, compositional gas flow and transport, and energy transport, was proposed and implemented into a finite element (FE) model to quantitatively predict the time and locations of spontaneous combustion of underground coal seams. In this study, the fully-coupled model was modified to fully consider the non-equilibrium nature of heat transfer between the solid phase and the gas phase under the in-situ gob and mining conditions.

2. Formulation of coal self-heating processes

2.1. Gas flow equation

Considering the dynamic evolution of the caved zone height which imposes important constraints on the flow field of gob, one can obtain the mass balance equation of gas at the steady state [27,29]:

$$\nabla \cdot (H \cdot \boldsymbol{v_g}) = Q_s \tag{1}$$

where $\boldsymbol{v_g}$ is the velocity vector, H the caved zone height, and Q_s the gas source or sink.

Taking the flow configuration of fluid in porous media into account, the non-Darcy Forchheimer equation of gas flow is adopted [30]:

$$-\nabla p = \frac{\mu}{k} \boldsymbol{v_g} + \frac{c_f \rho_g}{\sqrt{k}} \boldsymbol{v_g} |\boldsymbol{v_g}| \tag{2}$$

where p is the gas pressure, k the permeability of gob, μ the dynamic viscosity of gas, $|\boldsymbol{v_g}|$ the modulus of velocity vector, ρ_g the mixture gas density, and c_f a dimensionless form-drag coefficient defined as [31]:

$$c_f = \frac{1.75}{\sqrt{150\varepsilon^3}} \tag{3}$$

Eq. (2) can be rewritten as the form of Darcy's law

$$\boldsymbol{v_g} = -\frac{k}{\mu} \delta \nabla p, \tag{4}$$

where the Darcy correction coefficient δ is defined as

$$\delta = \frac{1}{1 + \frac{\sqrt{k}}{\mu} c_f \rho_g |\boldsymbol{v_g}|} \tag{5}$$

Substituting Eqs. (4) and (5) into Eq. (1) yields the flow governing equation

$$\nabla \cdot \left[-\frac{kH}{\mu + c_f \rho_g \sqrt{k} |\boldsymbol{v_g}|} \nabla p \right] = Q_s \tag{6}$$