Fire Safety Journal 87 (2017) 49–56

Contents lists available at ScienceDirect

Fire Safety Journal

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

Prediction of coal mine goaf self-heating with fluid dynamics in porous media

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ARTICLE INFO

Keywords:
Coal mine
Self-heating
Goaf porosity
Temperature distribution
Porous media

ABSTRACT

Coal mine goaf self-heating due to exothermic coal oxidation has been recognized as a major threat to coal mine safety. To evaluate the risk of the coal mine goaf self-heating hazard, both gas distribution characteristics in goaf and heat transfer mechanisms in porous media must be studied. However, due to the difficulty of determining goaf permeability and the complexity of the overlaying strata caving characteristics, it is a considerable challenge to determine the thermal-fluid field coupling. Based on the volumetric average method in porous media, this work develops three numerical models for solving fluid dynamics and heat transfer in both longwall face and goaf. The Brinkman-Forchheimer-extended Darcy model is introduced to describe inertia and frictional forces in fluid phase exerted by solid phase. Temperature profile is highly dependent on and affects coal oxidation rate; therefore, governing equations for energy and oxygen mass equilibrium must be coupled. A two-dimensional goaf permeability distribution model is established based on different caving conditions in goafs. Three scenarios are simulated and validated by field and experimental data, and it is observed that these models are capable of predicting gas flow pattern and temperature distribution.

1. Introduction

Goaf self-heating due to exothermic coal oxidation is a major threat to coal mine safety. If heat liberated by coal oxidation is not dissipated properly, it may lead to open flame or even trigger a catastrophic explosion if sufficient combustible gas is present. Available statistics [1] indicate that approximately 17% of the 87 reported fires in US underground coal mines from 1990 to 1999 were caused by spontaneous combustion. In China, the incident rate is much higher, and 56% of all underground coal mines are liable to spontaneous combustion.

Most spontaneous combustion incidents occur in goafs [2], which are cavities filled with residual coal and rock fragments after the coal seams are mined out. Coal oxidation may still occur even if only a few air channels are connected to the goafs, as they may provide sufficient oxygen. Heat generated by coal oxidation can result in significant temperature rise in goaf if airflow is too slow to dissipate the heat adequately. Numerous measures can be used to mitigate spontaneous combustion risk, such as balancing ventilation pressure, injecting grout or nitrogen into goaf, or directly cooling down. However, the measures' effect will be quite limited if the gas distribution and thermal conditions inside goaf remain unknown. Theoretically, either field measurement or numerical modelling can be employed to investigate the gas distribution and thermal conditions in goaf. However, due to the inaccessibility of goaf, numerical modelling is preferable.

The gas and temperature distributions in goaf are often derived numerically in literature. Since the goaf can be regarded as a type of naturally porous media, porous thermal-fluid dynamics can be applied. Huang et al. [3] developed a two-dimensional model to simulate flow pattern and temperature distribution in permeable zones with consideration of spontaneous combustion. Wolf and Bruining [4] proposed a more detailed model for flow, temperature and oxygen concentration distributions for coal fires under shallow cover. In this model, goaf was divided into six domains with varied permeabilities. However, the first two models that employed Darcy's law of single-phase flow to depict flow pattern in porous media had a major flaw, i.e., the viscous shear stress and inertial force were ignored. Therefore, the accuracy of these two models can hardly meet engineering requirements.

More accurate results can be achieved using computational fluid dynamics (CFD) modelling. Wendt and Balusu et al. [5,6] studied the flow pattern in a longwall goaf with bleederless ventilation by CFD modelling, considering the varied permeability in the goaf. Yuan et al. [7] employed CFD modelling to study flows in goaf for both bleeder and bleederless ventilation configurations by treating flows in porous media as laminar flows and fully turbulent flow in the maingate and tailgate.

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http://dx.doi.org/10.1016/j.firesaf.2016.12.002
Received 25 April 2016; Received in revised form 15 November 2016; Accepted 3 December 2016

Nomenclature

a_0	Initial specific surface area of the coal (m^2/m^3coal)
C	Inertial coefficient (dimensionless)
c_p	Specific heat capacity (kJ/(kg °C))
D	Diffusion coefficient of oxygen in air (m^2/s)
E	Activation energy (kJ/mol)
g	Gravitational acceleration (m/s^2)
H	Sagging of the lowest uncaved strata (m)
h_f	Extracted seam thickness (m)
h_i	Height of the caved strata (m)
$\Delta_r H$	Heat release rate or enthalpy of the reaction in coal oxidation (J/mol)
K	Permeability (m^2)
K_A	Bulking factor (dimensionless)
K_{eq}	Equilibrium constant, which is a function of temperature
l/L	Length or width (m)
l_f	Width of the working face (m)
m	the partial order of reaction with respect to product (dimensionless)
n	the partial order of reaction with respect to Oxygen (dimensionless)
q_r	Heat source (from surrounding rock and a coal cutter) (W/m^3)
R	Universal gas constant (J/(mol K))
r_s	Chemical reaction rate per unit area ($mol/(m^3\ s)$)
r_V	Chemical reaction rate per unit volume ($mol/(m^2\ s)$)
r_0	Pre-exponential factor ($mol/(m^3\ s)$)
T	Temperature (°C)
u, v	Filter velocity components (m/s)
x, y	Cartesian coordinates (m)

Greek letters

α	Oxygen concentration (mol/m^3)
β	Coefficient of thermal expansion (1/K)
ε	Mass ratio of coal in the solid mixture (-)
δ	Porosity (dimensionless)
λ	Heat conduction coefficient ($W/(m^2\ °C)$)
ψ	Stream function (m^3/s)
ω	Vorticity (1/s)
ρ	Density (kg/m^3)
v_f	Viscosity (m^2/s)

Subscripts

f	Fluid
p	Product
r	Rock
s	Solid
v	Void

In these works, the critical velocity zone was identified based on convective heat loss during post processing, however, temperature distribution was still unclear as energy equations were not solved. The propensity for self-heating was supposed to be high whereas flow velocities is less than a critical value. Yuan and Smith [8] included energy conservation equations to advance the studies of temperature distribution in longwall goaf. It should be noted that the assumption of laminar flow is not valid for the entire goaf; flow patterns inside a goaf are very complicated. It is widely accepted that airflow close to the working face and in the airways is fully turbulent while airflow in the deep goaf zone is laminar, and a transitional flow exists between the working face and deep goaf zone.

To solve gas flow patterns, the porosity and permeability of the goaf must be predetermined. According to Wolf and Bruining [4], temperature and oxygen concentration profiles depend on the permeability distribution of related area. The porosity and permeability of a goaf are often varied rather than constant as simplified by Skotniczny [9]. To be more specific, the area right behind the working face is more permeable because of the support of longwall chocks and less caving. In the centre of a goaf, the collapsed rock fragments reduce the void ratio and permeability significantly.

Generally, there are two categories of models describing porosity and permeability distributions. The first category is the one-dimensional analytical distribution model, in which the porosity gradient only occurs along the central line of the goaf. Szlazak [10] and Sevcik [11] assumed that the permeability decreases linearly from the working face to deep goaf and then remains constant in other directions. Other researchers [12–14] linked the variation of goaf permeability to stress redistribution caused by rock caving, and reported an exponential relationship between permeability and stress along the central line of the goaf. The second category of the porosity model gives discontinuous permeability distributions in two or three dimensions. Brunner [15] divided a goaf into numerous rectangular zones in two dimensions and directly assigned an approximate permeability value to each zone. A similar approach was employed by Van [16], who regarded a goaf as a permeable bulking medium in three dimensions. Although this approach is simple, there are unrealistic gaps in permeability value across boundaries between zones. Hence, a more sophisticated model for goaf porosity and permeability distribution is required.

Numerical modelling can provide an insight of the goaf conditions, but often a few assumptions are made in building the model, so conclusions drawn from numerical solution must be validated with experimental and field measured data. To our best knowledge, few literatures have reported the validation of goaf numerical modelling, due in part to the difficulty of undertaking field measurement and defining boundary conditions.

The above literature review reveals that an accurate momentum model that can incorporate with viscous shear stress and inertial effect is crucial to describe goaf gas flows. Compared to the commonly used linear Darcy model in coal mine goafs, Brinkman-Forchheimer-extended Darcy model can improve the simulation of drag forces in a porous medium. A one-dimensional analytical porosity distribution model or discontinuous porosity in two or three dimensions may cause significant computational errors. In goaf thermal-fluid patterns research, it is necessary to validate the reported numerical models.

2. Mathematical models

2.1. Governing equations

Instead of observing the actual microstructure in porous media, most porous fluid dynamics models regard the porous media as a continuous medium composed of evenly distributed solid and fluid phases. Thus, only averaged thermal-fluid parameters are of core interest and the volumetric average method is widely adopted [17].

Because the length and width of a goaf are much longer than the height, a two-dimensional model in goaf will be adequate to capture important details. Fig. 1 is a two-dimensional schematic including working face and goaf. The goaf is modelled as two-dimensional porous media composed of rock fragments and residual coal, while the working face is assumed to be a pure fluid region. Since fluid can be thought of as an equivalently porous media with zero content solid phase, porosity can be taken as unit, and governing equations for pure fluid will not be highlighted in the following sections.