International Journal of Mining Science and Technology 25 (2015) 1037–1044

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

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

# Effects of atmospheric pressure fluctuations on hill-side coal fires and surface anomalies

Song Zeyang [a,*], Zhu Hongqing [b], Xu Jiyuan [b], Qin Xiaofeng [b]

[a] *Jiangsu Key Laboratory of Hazardous Chemicals Safety and Control, College of Safety Science and Engineering, Nanjing Tech University, Nanjing 210009, China*
[b] *Faculty of Resources and Safety Engineering, China University of Mining and Technology, Beijing 100083, China*

ARTICLE INFO

*Article history:*
Received 4 January 2015
Received in revised form 1 February 2015
Accepted 13 April 2015
Available online 4 November 2015

*Keywords:*
Coal fires
Oxygen consumption rate
Air leakage
Ventilation

ABSTRACT

This paper presents numerical studies on the effects of atmospheric pressure fluctuations on hill-side coal fires and their surface anomalies. Based on the single-particle reaction–diffusion model, a formula to estimate oxygen consumption rate at high temperature controlled by oxygen transport is proposed. Daily fluctuant atmospheric pressure was imposed on boundaries, including the abandoned gallery and cracks. Simulated results show that the effects of atmospheric pressure fluctuations on coal fires and surface anomalies depend on two factors: the fluctuant amplitude and the pressure difference between inlet(s) and outlet(s) of the air ventilation system. If the pressure difference is close to the fluctuant amplitude, atmospheric pressure fluctuations greatly enhance gas flow motion and temperatures of the combustion zone and outtake(s). If the pressure difference is much larger than the fluctuant amplitude, atmospheric pressure fluctuations exert no impact on underground coal fires and surface anomalies.

## 1. Introduction

Coal fires are fires in coal volumes, most frequently occurring in underground coal seams [1]. Most current coal fires are caused by mining activities, which exposes coal to air and then creates favorable conditions for coal self-ignition [1]. Coal fires occur in many countries, such as China, India, the USA, South Africa, Australia, Russia, and Indonesia [2–10]. They pose deleterious impacts on the environment, resource availability and safety, e.g. the emission of enormous amounts of greenhouse-relevant ($CO_2$ and $CH_4$) and toxic gases, perilous land subsidence, vegetation deterioration, and loss of precious coal resources [1,2,9,11]. Thus coal fires have drawn increasing public attention during recent years. A wide variety of investigations on coal fires have been conducted, including theoretical modeling and experiments [12–21], detection and monitoring studies [3,4,6,22], hazard assessment studies [1,2,7,8,11,23,24], and prevention studies [25,26].

Modeling and numerical studies of coal fires are promising approaches for obtaining a deep understanding of development. Huang et al. [12] developed a two-dimensional steady-state model of underground coal fires to analyze temperature and gas flow fields. However, the impacts of high temperature on the overlying rocks and permeability were ignored in this model and thermal energy released by coal fires was set as a constant. Later, Wolf and Bruining [13] established a two-dimensional quasi-steady state model to numerically analyze the interaction between coal fires and their roof rocks. Wessling et al. [14,15] formulated a two-dimensional unsteady-state model of underground coal fires and used the Rockflow software to simulate underground coal fires. Fuel (coal) consumption was considered in the model of underground coal fires. Meanwhile, the challenge of the varying timescales suffering from the concurrent processes of the kinetic reaction and oxygen transport was successfully addressed by the "operator-splitting" approach [14,15]. However, the heterogeneous permeability and characteristic structures of coal fire systems (such as cracks, rubble zones, and abandoned galleries) were ignored. Thus efforts made to improve coal fire models are still necessary.

Surface anomalies induced by coal fires including thermal surface anomalies and gas emissions from cracks or fissures are very important indexes for interpreting the development of subsurface coal fires. Zhang et al. [18,19] investigated the thermal characteristics of coal fires and the relationship between thermal surface anomalies and solar heating patterns. Wessling et al. [16] utilized two approaches i.e., *in-situ* temperature mapping and numerical simulation to analyze thermal surface anomalies. The simulated results showed that the overall thermal energy flux away from

---

[*] Corresponding author. Tel.: +86 18261948384.
*E-mail address:* songzeyang03@126.com (Z. Song).

http://dx.doi.org/10.1016/j.ijmst.2015.09.024
2095-2686/

the burning coal seam into the surrounding bedrock was about 30-times higher than the flux through the surface [16]. Ide and Orr [7] estimated $CO_2$ emission and coal consumption rates using the exhaust gas velocity from a fissure.

Atmospheric pressure fluctuates daily with temperature variations. Atmospheric pressure fluctuations impact the air/gas motion and the development of underground coal fires. Irregular variations of gas motion and thermal surface anomaly caused by atmospheric pressure fluctuations bring great difficulties in interpreting the extent of subsurface coal fires. Therefore, it is significant to analyze the effects of atmospheric pressure fluctuations on coal fires and surface anomalies. Wessling [14] numerically studied the effects of atmospheric pressure fluctuations on the temperature and oxygen concentration. These numerical investigations showed that responses of temperature and oxygen concentration to atmospheric pressure fluctuations were irregular and complicated [14]. Despite of complexity of the responses, Wessling [14] concluded that atmospheric pressure variations seemed to be insignificant for the overall combustion process; take temperature for example, an increase of only 6 K was produced by atmospheric pressure fluctuations. However, these investigations were limited by the short time span investigated ($\sim$20 days).

In this paper, we attempt to model hill-side coal fires and numerically analyze long-term effects of atmospheric pressure fluctuations on hill-side coal fires and surface anomalies – this gives insight into diurnal fluctuations and interpretations of thermal anomalies and exhausts. The structure of this paper is organized as follows: in Section 2, we represent physical and kinetic models for hill-side coal fires and propose a formula to estimate the rate of oxygen depletion at high temperature based on the single-particle reaction–diffusion model proposed by Krishnaswamy et al. [27]. In Section 3, a geo-metric model of hill-side coal fires is developed and details of the numerical simulations are represented. Section 4 investigates the effects of atmospheric pressure fluctuations on hill-side coal fires and surface anomalies, and analyzes the factors determining these effects. Main conclusions are drawn in Section 5.

## 2. Modeling hill-side coal fires

### 2.1. Physical model

Hill-side coal fires are common in valleys like QueerGou hill-side coal fires in Xinjiang Uygur Autonomous Region, China. A three-dimensional schematic diagram of a hill-side coal fire is shown in Fig. 1a. Because of overburden pressure and mechanical failure induced by volume loss of the coal seam, overlying rocks tend to subside. The subsidence becomes more serious as the coal fire propagates along the coal seam. During this progress fissures may be formed. When overlying rocks subside to a certain extent, they will collapse and cracks will appear at the ground surface. In addition, high temperatures caused by coal fires can accelerate subsidence or collapse because of thermo-mechanical stresses. These mechanical failure processes form different porous zones such as the rubble zone, overburden zone and even cracks. The permeability of these zones is different from each other and higher than intact zones. Heterogeneous permeability of different porous zones is considered in this paper. The mechanical processes of subsidence and crack formation and the interaction between coal fires and their overlying rocks are outside the scope of this paper. These specific investigations have been presented elsewhere [13,17]. An abandoned gallery is involved in the hill-side coal fire model because air leakage from the abandoned gallery has great influences on coal fires [21], and is closely related to effects of atmospheric pressure fluctuations. In order to simplify computational calculations, wind and moisture are not taken into account.

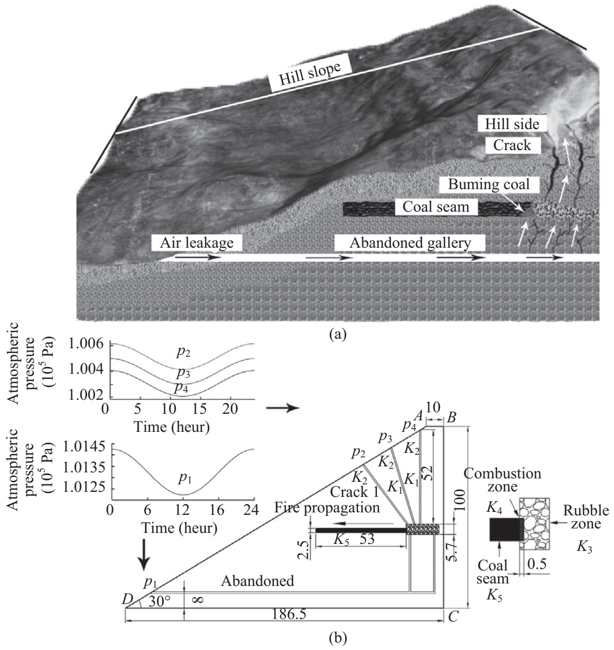

Fig. 1. Hill-side coal fire model (a) 3-D schematic diagram of a hill-side coal fire; (b) geometric model for simulating hill-side coal fires.

### 2.2. Atmospheric pressure fluctuation

The atmospheric pressure fluctuates daily, which approximately reaches a maximum in the middle of the night and a minimum at noon. The fluctuant atmospheric pressure can be represented by a cosine function [28]:

$$p = P_{\text{atm}} + P_0 \cos(wt) \tag{1}$$

where $P$ is fluctuant atmospheric pressure, Pa; $P_{\text{atm}}$ is standard atmosphere, Pa; $P_0$ is the amplitude of fluctuant pressure and $w$ is the frequency in 1/s, defined as

$$w = \frac{2\pi}{86,400} \tag{2}$$

In addition, as shown in Fig. 1, because of height differences among the abandoned gallery and cracks, atmospheric pressure differences should be taken into account:

$$\Delta p = p_1 - p_i = \rho g (z_i - z_1) \quad i = 2, 3, 4 \tag{3}$$

where $p_1(z_1)$ is the atmospheric pressure (height) of the abandoned gallery and $p_i(z_i)$ $(i = 2,3,4)$ denotes the atmospheric pressure (height) of the crack.

### 2.3. Kinetic reaction model

#### 2.3.1. Paradoxical relationship between kinetic reaction and oxygen transport at high temperature

To illustrate the relationships among temperature, kinetic reaction and oxygen transport, we briefly introduce the temperature-dependent timescales of kinetic reaction and oxygen transport. The timescale is reversely proportional to the rate, namely, a longer timescale indicates a slower rate. According to Wessling's research [15,16], the timescale formulations of kinetic reaction and oxygen transport can be written as