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Mining-induced void distribution and application in the hydro-thermal investigation and control of an underground coal fire: A case study

Shaofeng Wang[a,b,*], *Xibing Li*[a], *Deming Wang*[b]

[a] *School of Resources and Safety Engineering, Central South University, Changsha 410083, China*
[b] *Key Laboratory of Gas and Fire Control for Coal Mines of Ministry of Education, China University of Mining and Technology, Xuzhou 221008, China*

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ABSTRACT

Mining-induced voids are a necessary factor triggering underground coal fires that endanger the underground and atmospheric environment. On the other hand, voids provide channels for underground fluid and fire-fighting material migration. A series of void rate models were proposed to determine the three-dimensional heterogeneous distribution of the mining-induced voids in the disturbed strata. The void rate distribution map of horizontal voids presents a reversed "quadripod-type" shape in the strata plane, the void rate of vertical voids has a shape similar to two "basins" of different sizes and contrasting opening directions nested together, and the void rate of isotropic pores presents a "basin-type". It can be deduced from the distribution maps that were calculated by theoretical and numerical models that the voids present a "fractured dome" distribution and that the void rate gradually decreases from foot to crown of the dome. It was ascertained from the application of void rate models in the hydro-thermal investigation of an underground coal fire that the correlation between heat production and ground surface temperature presents a linear function, while that between outflow velocity and fire source temperature has a negative-exponential-power relationship. Additionally, a new Plan-Do-Check-Adjust cycle was established for the management of fire-fighting engineering, which includes the delineation of fire zones, the evaluation of fire behavior, the optimization of fire-fighting measures, the performance of the fire-fighting plan, and the assessment of control results to determine whether the fire-fighting plan should be reformulated or improved. After five control cycles lasting nine months, an approximately 115,200 m^2 fire zone was controlled.

1. Introduction

When coal is mined, the mined-out area in the coal seam appears. The overlying strata will cave, fracture and subside with the expansion of the mined-out area (Qian et al., 2010), while also the ground surface may crack and collapse (Li, 2014). In the above processes, the fracture and movement of strata produce many voids, including pores among the rubble, fractures in the strata, and fissures in the ground. The oxygen in the atmosphere and underground ventilation can interact with the crushed coal when passing through these voids. The coal temperature will increase if the heat that is released from coal oxidation is not sufficiently dissipated. When the temperature reaches the ignition point, the coal will start to burn,

* Corresponding author at: School of Resources and Safety Engineering, Central South University, Changsha 410083, China. Tel.: +86 18073369486.
E-mail address: wsfcumt@163.com (S. Wang).
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and this may cause an underground coal fire (UCF) over time (Zhang et al., 2008). The related oxygen permeability, which is determined by the void distribution in the mining-disturbed strata, is one of the key factors affecting the behavior of UCFs (Wolf and Bruining, 2007).

UCFs can be found all over the world, especially in China, the USA, India, Australia, and South Africa (Song et al., 2015; Kuenzer and Stracher, 2012; Engle et al., 2012; Pone et al., 2008; Zhang et al., 2008; Kuenzer et al., 2007b; Chatterjee, 2006; Gangopadhyay, 2006; Stracher, 2004; Stracher and Taylor, 2004; Heffern and Coates, 2004; Ellyett and Fleming, 1974). UCFs cause significant economic and environmental problems (Liang et al., 2014; Kuenzer and Stracher, 2012; van Dijk et al., 2011; Querol et al., 2008, 2011; Zhao et al., 2008; Kuenzer et al., 2007b; Stracher and Taylor, 2004; Finkelman, 2004). Economically, UCFs chronically consume large amounts of nonrenewable coal resources. Environmentally, UCFs bring a series of serious challenges such as atmospheric pollution, groundwater contamination, soil impoverishment, and vegetation deterioration. Furthermore, UCFs pose challenging obstacles to coal mining, as they threaten mining safety and infrastructure reliability, as well as local residents' health (Kuenzer et al., 2012; Wu and Liu, 2011). Fig. 1 shows the occurrences of coal fires from the surface or underground in the Antaibao Open Pit Mine, Shanxi, China.

UCF constitutes a complex system involving thermal, hydraulic, chemical, and mechanical processes (Wessling, 2007; Kessels and Wessling, 2005; Huang et al., 2001). The factors influencing these processes can be categorized into three groups: coal and rock properties, seam and strata properties and external conditions (Song et al., 2014a,b; Wolf and Bruining, 2007). Among these factors, mining activities creating ventilation voids or pathways are the most common factors triggering coal fires (Song and Kuenzer, 2014). Within the thermodynamic system of UCFs, the mining-induced voids in the disturbed strata are passageways for oxygen supply, smoke emission and heat dissipation. Therefore, these voids are important factors influencing coal oxidation and heating. Finally, these voids determine the concentration distribution of species, flow velocity and temperature distribution (Wang et al., 2014a,b; Ide et al., 2010; Zeng et al., 2010; Cao et al., 2009; Wessling et al., 2008; Zhang et al., 2008; Wolf and Bruining, 2007; Huang et al., 2001). Some distribution models of permeability or porosity have been built to investigate the characteristics of coal fires (Li et al., 2012; Zeng et al., 2010; Yuan and Smith, 2008; Huang et al., 2001; Li et al., 2000), flow of fire-fighting media (Shi, 2010), and migration of oxygen gas and coalbed methane (CBM) (Guo et al., 2012; Song et al., 2011; Liang et al., 2009; Whittles et al., 2006; Ren and Edwards, 2000). Although these models are very valuable, there are difficulties in obtaining a clear understanding of heat and mass transfer in the UCFs because of complex and concealed transportation pathways, namely voids that are induced by coal mining or combustion (Wessling et al., 2008).

The detection and monitoring of UCFs is frequently performed by analyzing ground-surface data, such as the surface fissure distribution, temperature anomalies, gas flow and gas compositional measurements (Shao et al., 2014; Kuenzer and Stracher, 2012; Kuenzer et al., 2008; Schaumann, 2008; Kuenzer et al., 2007a, 2007b; Zhang and Kuenzer, 2007; Litschke, 2005). However, the underground fire behavior and the relationship between surface features and underground parameters are vague due to a lack in the understanding of the complex pathways that are used to transfer heat and mass (Wessling et al., 2008). Some experiments have explored the underground characteristics of coal fires (Zhang et al., 2007), but small-scale experiments have difficulties in scaling the results to realistic large-scale conditions (Yuan and Smith, 2008). Meanwhile, large-scale experiments are very expense and time-consuming (Xia et al., 2014). As a substitute for experimental study, mathematical modeling and numerical simulation have been used to investigate the occurrence and development mechanisms under the realistic conditions of UCFs (Xia et al., 2014; Yuan and Smith, 2008; Wessling et al., 2008; Huang et al., 2001). For these studies, the distribution of the void rate (VR) which represents the volume fraction of voids in the rock mass in an UCF should be an indispensable input parameter. However, a very limited number of studies have investigated this parameter. The Kozeny-Carman equation was proposed to define a positive correlation between porosity and hydraulic conductivity in porous media, which revealed that porosity may have an important control over

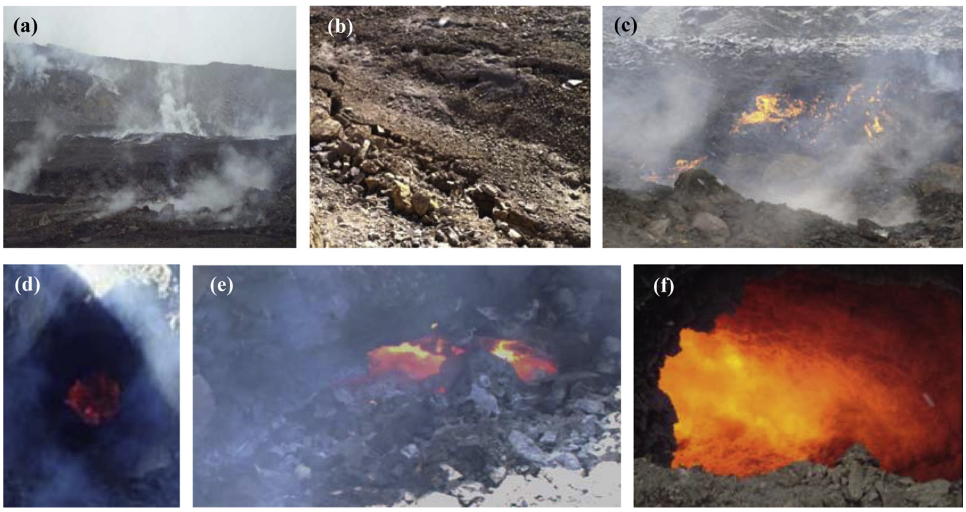

Fig. 1 – Occurrences of underground coal fires in the Antaibao Open Pit Mine, Shanxi Province. (a) Smoke containing toxic and harmful gases emitted from underground coal fires; (b) surface fissures and vents; (c) exposed fires due to the excavation of the overburden; (d) a borehole in which underground burning coal can be observed; (e) a collapsed roadway in which coal is violently burning; (f) a huge ball of flame spouting from an exposed hole.