Journal of Loss Prevention in the Process Industries 26 (2013) 236–244

Contents lists available at SciVerse ScienceDirect

Journal of Loss Prevention in the Process Industries

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

Numerical investigation and theoretical prediction of self-ignition characteristics of coarse coal stockpiles

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ARTICLE INFO

Article history:
Received 21 May 2012
Received in revised form
12 November 2012
Accepted 16 November 2012

Keywords:
Self-ignition
Coarse coal stockpile
Ignition time
Ignition location
Prediction model

ABSTRACT

Spontaneous combustion of coarse coal stockpiles in temporary coal storage yards was investigated numerically using COMSOL Multiphysics software. The main purposes of the numerical investigation were to identify the self-ignition characteristics of coarse coal stockpiles and formulate a theoretical model to predict the self-ignition time and locations of coarse coal piles. A mathematical model for self-ignition of coarse coal piles was developed and the process of spontaneous ignition of coarse coal stockpiles was simulated. The kinetic data of low-temperature oxidation reaction was obtained from the laboratory-scale experiments with bituminous coals taken from Jindi Coal Mine of Shanxi Province in China. The influence of moisture was ignored because the studied coal had low moisture content (mass concentration: 1.87%) and both coal and ambient environment were assumed to be saturated with moisture (or ambient environment was assumed to be dry). The effects of five variables (i.e. wind velocity, oxygen concentration, height, porosity, and side slope) on the spontaneous ignition in coarse coal piles were examined. Simultaneously, a theoretical prediction model was formulated in light of variable analyses and a great number of simulations.

Compared to self-ignition characteristics of fine-particle coal piles, several self-ignition characteristics of coarse coal piles were identified by numerical investigation. Wind-driven forced convection plays a predominant role in self-heating of coarse coal piles. As wind velocity increases, the self-ignition location in the pile migrates from the lower part which is close to the surface of the windward side to the upper part near to the surface of the leeward side. Wind velocity increase exerts the positive or the negative effect on self-heating, which depends on a critical wind velocity value to sustain balances of both the heat and the availability of oxygen in the coarse coal pile. The behavior of self-ignition is remarkably sensitive to both oxygen concentration and height, and a coarse coal stockpile will not ignite spontaneously as long as one of two critical variable values is satisfied: oxygen concentration of 5% or height of 3 m. The theoretical prediction model suggests when and where countermeasures should be made to prevent the self-ignition in the coal stockpile with engineering accuracy.

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1. Introduction

Spontaneous ignition of a coal stockpile refers to a physical and chemical process of thermal runaway, which is initiated as self-heating caused by exothermic oxidation reaction at low-temperature. If the heat produced by low-temperature reaction is not sufficiently dissipated to the surrounding environment by conduction or convection, the self-heating results in a net temperature increase in the coal pile and a higher rate of oxidation reaction (Kim & Sohn, 2012; Yuan & Smith, 2008, 2011; Zhang & Kuenzer, 2007; Zhang et al., 2007). When the temperature exceeds the threshold temperature (80–120 °C), the coal stockpile attains thermal runaway and then ignites spontaneously (Taraba & Michalec, 2011). Spontaneous ignition occurring in the process of coal storage leads to loss of the precious coal resources and the emission of greenhouse-relevant gases, such as carbon dioxide and methane, and other toxic gases, which threaten the health of local inhabitants. Statistics showed that more than 2100 coal stockpiles have been deposited in the Ukrainian coal industry (Pennig, 2003). More than 120 of these coal piles have ignited, which produced 15,000 tons of carbon dioxide and 5000 tons of carbon monoxide annually (Kuenzer & Stracher, 2012). Additionally, fires resulting from self-ignition of coal piles may damage infrastructure. Thus

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http://dx.doi.org/10.1016/j.jlp.2012.11.006

Nomenclature

A (s^{-1}) pre-exponential factor
c (mol m^{-3}) mole concentration of oxygen
C (J kg^{-1} K^{-1}) specific heat capacity
d (m) average diameter of overall particle
D (m^2 s^{-1}) diffusion coefficient
E (J mol^{-1}) activation energy
g (m s^{-2}) acceleration of gravity
ΔH (J mol^{-1} O_2) heat of oxidation reaction
k (mol m^{-3} s^{-1}) rate of oxidation reaction
P (N m^{-2}) pressure
ΔP (N m^{-3}) pressure gradient
R (J mol^{-1} K^{-1}) universal gas constant
t (s) time
T (K) temperature
u (m s^{-1}) horizontal component of gas velocity
v (m s^{-1}) vertical component of gas velocity
U (m s^{-1}) gas velocity
x (m) horizontal coordinate
y (m) vertical coordinate

Greek symbols
ε porosity
θ (deg) angle of side slope
κ (m^2) permeability
λ (W m^{-1} K^{-1}) thermal conductivity
μ (kg m^{-1} s^{-1}) viscosity
ρ (kg m^{-3}) density

Subscripts
0 initial value
a ambient
b buoyancy
g gas
i ignition
s solid
v gas velocity within the pile
max maximum

Superscripts
(a) average
(e) effective

spontaneous combustion of coal stockpiles is a serious economic, environmental and safety problem.

Extensive investigations were carried out to gain a deep understanding of this complex process, which could mainly involve mathematical models (Brooks & Glasser, 1986; Chen, 1992; Salinger, Aris, & Derby, 1994), numerical studies (Akgun & Essenhigh, 2001; Kim & Sohn, 2012), experimental observations (Fierro et al., 2001; Sensogut & Ozdeniz, 2005), preventive methods (Fierro et al., 2001; Kim & Sohn, 2012; Krajčiová, Jelemenský, Kiša, & Markoš, 2004; Sipilä et al., 2012) and theoretical predictions (Akgun & Essenhigh, 2001; Ejlali, Mee, Hooman, & Beamish, 2011; Krajčiová et al., 2004). However, the subject of this paper is confined to numerical investigation of the influences of factors (variables) on the spontaneous combustion and to theoretical prediction. The effects of some factors (variables) including the characteristics of coal (coal reactivity, particle size, and moisture content) (Akgun & Arisoy, 1994; Akgun & Essenhigh, 2001; Chen, 1992, 1994; Ejlali et al., 2011; Krajčiová et al., 2004; Krishnaswamy, Agarwal, & Gunn, 1996), the characteristics of pile (height, bed porosity and side slope) (Akgun & Essenhigh, 2001; Arisoy & Akgun, 2000; Ejlali et al., 2011; Fierro et al., 2001, 1999; Krishnaswamy et al., 1996) and meteorological conditions (sun radiation, intensity and direction of wind, oxygen concentration, temperature and humidity) (Akgun & Essenhigh, 2001; Brooks & Glasser, 1986; Ejlali et al., 2011; Fierro et al., 2001, 1999; Krajčiová et al., 2004; Krishnaswamy et al., 1996; Moghtaderi, Dlugogorski, & Kennedy, 2000; Sensogut & Ozdeniz, 2005) on self-ignition of coal piles have been studied in detail. Additionally, several theoretical models have been formulated to predict the critical parameter values under which a coal stockpile fails to ignite spontaneously (Akgun & Essenhigh, 2001), the time of spontaneous combustion (Akgun & Essenhigh, 2001; Ejlali et al., 2011) and the maximum temperature in the stockpile (Ejlali et al., 2011). But, most of these investigations focused on fine-particle coal piles. Diameters of fine-particle coals are about a few millimeters (Sipilä et al., 2012), and gas flow within the fine-particle coal pile follows the Darcy's law. But diameters of coarse coals are much greater than those of fine-particle coals, ranging from 3 to 20 cm, which indicates that the gas flow within the coarse coal pile is inappropriate to be governed by Darcy's law because of high Darcy's parameter and Reynolds number. In practice, due to difficulty in transportation and lack of crushers, coarse coal stockpiles, which are more prone to spontaneous combustion than fine-particle coal piles, are also widely laid in temporary coal storage yards in China. Up to now, few studies have been carried out to gain insight into self-ignition process of a coarse coal stockpile. In another aspect, although the investigated theoretical prediction models could provide some important information with respect to spontaneous combustion in a coal stockpile, the location of self-ignition, one of the most significant parameters, cannot be predicted from these models. Therefore, it is necessary to study the self-ignition characteristics of coarse coal piles and formulate a theoretical model to predict both the time and the locations of self-ignition in coarse coal piles.

In this paper, numerical investigation was carried out to study the characteristics of coarse coal stockpiles. Although moisture plays an important role in the process of self-heating, the effect of moisture is ignored because the studied coal, collected from Jindi Coal Mine located in Shanxi Province of China, has low moisture content (mass concentration: 1.87%) and ambient environment is dry because of dry meteorological condition and little rain. A mathematical model for spontaneous combustion in coarse coal stockpiles was formulated. Then a number of simulations were performed using COMSOL Multiphysics software to evaluate the influences of five variables including wind velocity, oxygen concentration, height, porosity and side slope on the self-ignition in coarse coal piles. Finally, a theoretical model to predict the time and the locations of self-ignition in coarse coal stockpiles was formulated on the basis of the variable analyses and a large number of simulations. Although the focus of this particular work is on the coarse coal stockpiles, the approach is also applicable to other similar situations such as coal gangue dumps and gob areas of coal mines.

2. Mathematical model

Due to the small size of diameters of fine-particle coals (about a few millimeters) (Sipilä et al., 2012), the behavior of gas flow within the fine-particle coal pile can be described by Darcy's law (Akgun & Essenhigh, 2001; Brooks & Glasser, 1986; Krishnaswamy et al., 1996; Moghtaderi et al., 2000; Salinger et al., 1994). However, diameters of coarse coals are much larger than those of fine-particle coals, ranging from 3 to 20 cm. Thus it is more effective

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