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Interaction between gas explosion flame and deposited dust

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ABSTRACT

In order to study the patterns for local gas explosion inducing deposited dust combustion, the process of dust kicking-up and participating in gas explosion is numerically simulated. The pressure wave of local gas explosion kicks up deposited dust, then the flame triggers raised dust to burn and further spread. Coal dust participation can accelerate the methane-air flame propagation in the tube, which is shown by the increasing of flame propagating velocity, the flame temperature and the combustion duration. The temperature–time curves of complex flames display an apparent structure of double peaks, and the FWHMs (full width at half maxima) of temperatures vary at different deposited coal dust concentrations. The FWHM at 80 g/m^3 has no significant difference compared with the FWHM with no dust. Therefore, 80 g/m^3 can be esteemed as the lower limit for the secondary explosion (dust participating and methane/dust mixed-combusting). Furthermore, the effect of pressure wave velocity on dust kicking-up is studied. It is found that dust diffuses sufficiently when the pressure wave velocity lies in the range of 140 m/s–300 m/s.

1. Introduction

There are five major disasters in coal mines: gas, coal dust, water, fire and roof fall. Compared to water, fire and roof fall disasters, gas and coal dust explosions are more prone to occur for the fact that gas and dust are not only inflammable and explosive substance but also abundant in coal mines. The explosions of methane–air mixture and coal-dust–air mixture are sophisticated processes. The researches into the mixed system of combustible gas and combustible dust have shed light on the characteristic parameters including the minimum ignition energy of the mixture for gas and coal dust (Hassan et al., 2014; Li et al., 2013), the maximum explosion pressure (Chen et al., 1996; Rockwell and Rangwala, 2013; Xie et al., 2012), the maximum pressure rise rate parameters etc. (Ratzke et al., 2015; Tang et al., 2014; Liu et al., 2010).

Cashdollar (1996, 2000) conducted the ignition experiments on the methane and coal dust, the results from which showed that the lower explosive limit of mixture decreased as the ignition energy increased, and that the limit was closely linked with methane concentration, coal dust size and volatile content. Nagy et al. (1969) and Gieras et al. (2006) experimentally studied the flame structure and the explosion characteristics of coal dust and gas coexisting system. Torrent (1989) and Amyotte et al. (1991, 1993) experimentally evaluated the influence of methane on the character of coal dust explosion and found that the existence of methane could reduce the lower limit and the minimum ignition energy for coal dust explosion. In addition, large amounts of studies have focused on the numerical simulations of dust, methane and their mixtures. Takahashi and Watanabe (2010) numerically studied the diffusion of gas and coal dust explosion in open space and found that the expending cloud diameter of explosion increased with the amount and the sizes of obstacles. Kosinski (2007) studied shock wave interaction with a cloud of particles in a bending channel using the Eulerian–Lagrangian numerical method. Kobiera et al. (2007) investigated the effects of turbulence intensity and turbulence scale on the gas explosion process in a closed pipe using turbulent combustion modeling and derived the computation for fold flame burning rate. However, there still lacks effective methods to predict the participation mechanism of gas and coal dust combustion and there is no uniform turbulent model to outline the process of shock entraining deposited coal dust.

In the present paper, the numerical method is used to simulate coal dust explosion induced by gas explosion in a pipeline with a large aspect ratio. The objectives are to determine the characteristics of flame propagation and the variation rule of dust kicking-up occurring at dif-

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Nomenclature

A_ρ	The windward area of particles (m^2)
C_d	The drag coefficient
C_ψ	The dynamic shape factor, 1
$C_{1\varepsilon}$	The constant in the model, 1.44
$C_{2\varepsilon}$	The constant in the model, 1.92
E	The total energy (J)
F_d	The resistance acted on particles (N)
F_g	The gravity of particles (N)
F_f	The buoyancy acted on particles (N)
F_x	The force of Saffman lift (N)
G_k	The shear force caused by the fluctuation of turbulent kinetic energy rate (kg/s^3 m)
k	The turbulent kinetic energy (m^2/s^2)
k_{eff}	Thermal conductivity of gas mixture (W/m K)
m_p	The mass of particles (g)
u	The instantaneous value of the fluctuating gas flow velocity (m/s)
u_p	The velocity of particles (m/s)
$u_i u_j$	The sreamwise velocity (m/s)
Y_M	The contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate (kg/s^3 m)

Greeks

α_k	The inverse effective Prandtl numbers for k
α_ε	The inverse effective Prandtl numbers for ε
$(\tau_{ij})_{eff}$	Deviatoric stress tensor (W/m K)
μ_{eff}	The total flow viscosity in flow (Pa s)
ε	The turbulent dissipation rate (m^2/s^3)
ζ	A random number between −1 and 1

ferent deposited dust concentrations. In addition, an experiment was conducted under similar conditions in order to observe the characteristics of hybrid coal dust and methane flame in the tube.

2. Theory and modeling

Eulerian–Lagrangian techniques were adopted in numerical simulations for two-phase combustion as they are very realistic from the physical point of view and some actual physical phenomena can be considered, such as collisions (Chang and Kailasanath, 2003; Kosinski and Hoffmann, 2005; Kosinski et al., 2005; Lu et al., 2005; Ilea et al., 2008). In this paper, the Eulerian–Lagrangian modeling technique is employed to study the mechanisms of dust kicking-up and the state change in the process of two-phase explosion. This means that the gas phase behavior is modeled in an Eulerian frame of reference and that the motion of the particle phase is resolved in a Lagrangian one.

2.1. *Basic assumptions*

Gas and coal-dust explosion is a fast and complex process, thus in order to simplify the simulation process while ensuring the accuracy and reliability of numerical simulations, some reasonable assumptions are first made for certain conditions (Ajrash et al., 2017; Wu et al., 2016).

(1) It is assumed that the tube is at normal temperature and atmospheric pressure, and that the oxygen content of the air is normal.
(2) Methane is the main component of gas, so the chemical reactions of other components in the gas are left out of consideration. Furthermore, methane and oxygen are presumed to react irreversibly in a single step.
(3) It is assumed that the pulverized coal particles are spherical particles, and that they will start to burn if the reaction conditions are met.

2.2. *Governing equations*

In the study reported here, the RNG k–ε model is used for the continuous phase; the discrete phase model (DPM) is adopted for the solid phase.

Analyzing gas explosion with high Mach number and high pressure-gradient flow field numerically requires a model with high calculating speed and accuracy. The RNG k–ε model for continuous phase is as follows (Yakhot and Orszag, 1986; Choudhury, 1993):

Continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{2.1}$$

Momentum equation

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}\left(\rho u_i u_j + p\right) = \frac{\partial}{\partial x_j}\left[\tau_{ijeff}\right] \tag{2.2}$$

Energy equation

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i}\left[u_j(\rho\varepsilon + p)\right] = \frac{\partial}{\partial x_j}\left[u_i\left(\tau_{ij}\right)_{eff}\right] + \frac{\partial}{\partial x_j}\left[k_{eff}\left(\frac{\partial T}{\partial x_j}\right) + \sum h_s J_s\right] \tag{2.3}$$

Component equation

$$\frac{\partial}{\partial t}(\rho f_s) + \frac{\partial}{\partial x_i}[\rho u\, {}_i f_s] = \frac{\partial}{\partial x_j}\left(D_{eff}\frac{\partial f}{\partial x_j}\right) - \omega_s \tag{2.4}$$

k equation

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\alpha_k \mu_{eff}\frac{\partial k}{\partial x_j}\right) + G_k - \rho\varepsilon - Y_M \tag{2.5}$$

ε equation

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho u_i \varepsilon) = \frac{\partial}{\partial x_j}\left(\alpha_\varepsilon \mu_{eff}\frac{\partial \varepsilon}{\partial x_j}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}G_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} - R_\varepsilon \tag{2.6}$$

The following model predicts the trajectory of a discrete phase particle by integrating the force balance on the particle written in a Lagrangian reference frame. Based on the classical Newton's second law, force balance equation of dust particle phase is:

$$m_p\frac{du_p}{dt} = \sum F = F_d + F_g + F_f + F_x \tag{2.7}$$