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Quantitative research on gas explosion inhibition by water mist

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ABSTRACT

Water mist as an effective explosion inhibitor has wide application prospect to prevent and reduce gas explosion hazard. The quantitative study of gas explosion inhibition with water mist provides the groundwork for the design of gas explosion suppression system. In this paper, the influence of the initial droplet sizes and spraying concentrations on explosion inhibition were numerically studied in a 2D numerical model. Under the initial spraying concentrations in the range of ~1.5 kg/m^3, the inhibition effect of water mist on the explosion overpressure was not significant. The inhibition effect of water mist was mainly reflected in the suppression of the explosion flame temperature. When the initial droplet sizes were in the range of 50–150 μm, the flame length was obviously reduced. But when the initial droplet sizes were less than 50 μm or more than 150 μm, the inhibition to reduce flame length begin to weaken. The results of this study provide the theoretical basis of the suppression technology for gas explosion.

1. Introduction

Gas explosion accidents result in large directly and indirectly economic loss every year in China, which seriously limits the development of coal industry [1]. The key to solve this problem is to find a material which can control the gas explosion efficiently combining with suppressing explosion techniques to prevent the disaster occurrence. The active explosion suppression as one effective technology has been widely used in coal mine and other industry concourses [2–4]. Active suppression technologies are mainly by means of spraying inhibitor to suppress the scope and intensity of explosion to avoid excess pressure and temperature in limited spaces. The detectors are used to induct the initial explosion in order to inhibit the process of explosion and eliminate or weaken the harmful factors of explosion, that is, high temperature flame, shock wave and harmful gas. However, coal mine production system is usually too huge to make the explosion suppression device spread in all over the corner. The effective use range of each device is limited, which makes the explosion suppression to be greatly limited resulting in vicious gas explosion occasionally happening.

Due to the fine dispersity, high heat capacity and ease of evaporation, water mist has got widely used in building fire, ship fires and other fire types [5,6]. A number of researches have been conducted to develop the theory and technology of explosion suppression by water mist [7–9]. Liang and Zeng [10] used the SENKIN code of chemical kinetics package to analyze the mole fraction profiles of reactants, free radicals and catastrophic gases in the process of gas explosion suppression by water mist. Zhu et al. [11] developed an Eulerian–Lagrange model to study the extinguishing effect of ultra-fine water mist in total flooding experiment in confined space. The cooling and suffocation effects and the smaller average diameter of ultra-water mist were the main factors to extinguish fire. The effects of fine water mist on laminar flame speeds of propane-air mixtures are investigated both experimentally and numerically by Yoshida et al. [12]. The results showed that the large radial acceleration of the flow induced the mist droplet accumulation around the stagnation stream line, leading to the negative dependence of flame speed on stretch rate. Compared with the normal water mist, the gas explosion could be more effectively suppressed by the positively charged water mist [13]; the inhibition effect became stable with the increase of the nitrogen fraction in the ultrafine water mist [14]. However, the influence of spraying concentration on the changes in explosion flame structure and the relationship between the pressure rising and flame propagation have not been mentioned in the open literatures.

Feasibility study of explosion suppression by ultra fine water mist (diameter < 10 μm) has been discussed in literatures [15]. Sub-10-μm water drops were found to be an effective flame suppressant in a coflow cup burner flame [16]. The ultra fine water mist was able to successfully extinguish all pool fires [17]. The water mist (20 μm < diameter < 200 μm) having strong engineering application background, however, has been fewer studies made on its fire suppression mechanism [18]. Moreover, the secondary breakup process of water mist is researched insufficiently. In literatures, researches on premixed gas

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Nomenclature

a	Absorption coefficient (m^{-1})
a_p	Equivalent absorption coefficient (m^{-1})
A_d	Surface area of the droplet (m^2)
B	Breakup time constant
c_{p_g}	Heat capacity of gas product species (J/kg K)
c_{p_d}	Heat capacity of the droplet (J/kg K)
d	Orifice diameter of obstacle (m)
d_d	Droplet diameter (m)
D	Inner diameter of pipeline (m)
E_d	Equivalent emission of the droplets
F_D	Drag force (N)
F_x	Additional forces (N)
G	Incident radiation (rad)
h	Convective heat transfer coefficient (W/m^2 K)
h_{fg}	Latent heat (J/kg)
H_{lat}	Latent heat at reference conditions (J/kg)
H_{pyrol}	Heat of pyrolysis as volatiles are evolved (J/kg)
k_∞	Thermal conductivity of the gas (W/m K)
m_d	Mass of the droplet (kg)
$\dot{m}_d$	Mass flow rate of the droplets (kg/s)
$m_{d,in}$	Mass of the droplet on cell entry (kg)
$m_{d,out}$	Mass of the droplet on cell exit (kg)
Oh	Ohnesorge number
r	Newly-formed droplet radius (m)
r_0	Undisturbed droplet radius (m)
Re_d	Reynolds number based on the droplet diameter and the relative velocity($W/m^2 K^4$)
Δt	Time step (s)
T	Local temperature (K)
Ta	Taylor number
T_d	Droplet temperature (K)
$T_{d,in}$	Temperature of the droplet on cell entry (K)
$T_{d,init}$	Droplet initial temperature (K)
$T_{d,out}$	Temperature of the droplet on cell exit (K)
T_{ref}	Reference temperature for enthalpy (K)
T_∞	Local temperature of the continuous phase (K)
u	Gas phase velocity (m/s)
u'	A Gaussian distributed random velocity fluctuation (m/s)
$\bar{u}$	Mean fluid phase velocity (m/s)
u_d	Droplet velocity (m/s)
v	Relative velocity between the droplet and the gas phase (m/s)

Greek letters

ε_d	Droplet emissivity
θ_R	Radiation temperature (K)
Λ	The maximum growth rate or the most unstable wave
ρ	Fluid density (kg/m^3)
ρ_d	Droplet density (kg/m^3)
σ	Stefan-Boltamann constant (5.67×10^8 $W/m^2 K^4$)
σ_d	Droplet surface tension
σ_s	Scattering coefficient (m^2/kg)
Ω	Corresponding wavelength ofΛ

explosion suppression by water mist were mostly under the condition that water mist had been mixed uniformly with premixed gas before the explosion [19–21]. But this condition is inconsistent with the explosion suppression by water mist in practical engineering. In mine production, the invalid or inadequate effects of explosion suppression by water mist are especially prominent, which is due to the limits of the triggering technology and the poor property of suppressant. Researches into the influence of water mist characteristics on the suppression effects are important to practical engineering. Therefore, the action mechanism between water mist and the explosion flame based on the practical engineering process is urgent to be studied.

In view of the high risk and input of explosive experimental research, and the interaction between water mist and explosive flame is difficult to observe, in this study, the CFD code was adopted which has been proven to be one of the most widely used tools to build fire models [22–24]. A two dimensional turbulent explosion mathematical model for combustible gas in pipeline was built in this study. The explosion flame propagation and the interaction between the water mist and the explosion flame was obtained in this study. The numerical simulation study of the transient process of gas explosion inhibition by water mist has been carried out to obtain the regulation of explosion suppression by water mist in the purpose of providing theoretical basis for the suppression technology in gas pipeline and the key parameters of engineering calculation.

2. Computational method

A finite element computational code for fluid dynamics was adopted to calculate the explosion inhibition propagation. The code solved the gas phase as a continuum by means of the time-averaged Navier-Stokes equations, while the dispersed phase was solved by tracking a large number of droplets through the calculated flow field. The turbulence flow was characterized by standard k-ε model. The finite-rate/eddy dissipation model was used to compute the chemical reactions. The detailed formulas of these models are listed in the Ref [25].

The droplet will absorb heat, when the droplet temperature is lower than its evaporation temperature. The heat balance equation is used to establish the relationship between droplet temperature and convection and radiation heat transfer to the droplet surface.

$$m_d c_{p_d} \frac{dT_d}{dt} = hA_d(T_\infty - T_d) + \varepsilon_d A_d \sigma(\theta_R^4 - T_d^4) \tag{1}$$

When the temperature of the droplet reaches the vaporization temperature, the evaporation occurs, and continues until the droplet reaches the boiling point. The droplet temperature is updated according to a heat balance that relates the sensible heat change in the droplet to the convective and latent heat transfer between the droplet and the continuous phase

$$m_d c_{p_d} \frac{dT_d}{dt} = hA_d(T_\infty - T_d) + \frac{dm_d}{dt} h_{fg} + \varepsilon_d A_d \sigma(\theta_R^4 - T_d^4) \tag{2}$$

When the droplet temperature reaches the boiling point, boiling rate equation is applied as

$$\frac{d(d_d)}{dt} = \frac{2}{\rho_d h_{fg}} \left(\frac{2k_\infty(1 + 0.23\sqrt{Re_d})}{d_d}(T_\infty - T_d) + \varepsilon_d A_d \sigma(\theta_R^4 - T_d^4) \right) \tag{3}$$

While the continuous phase always impacts the discrete phase, the effect of the discrete phase trajectories can also be incorporated on the continuum. This two-way coupling was accomplished by alternately solving the discrete and continuous phase equations. The interphase exchanges of heat, mass, and momentum between the particle and the continuous phase are given by

$$\text{Mass exchange } m = \frac{\Delta m_d}{m_{d,0}} \dot{m}_{d,0} \tag{4}$$

$$\text{Momentum exchange } M = \sum F_D(u_d - u)\dot{m}_d \Delta t \tag{5}$$

Thermal exchange

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