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Characteristics of gas explosion flow fields in complex pipelines

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ABSTRACT

The explosion flow field in five straight pipes with different diameters and one bending pipe selected from a domestic coal mine are studied by the method of numerical simulation. And the results show that, both in the straight and bending pipes, the pressure wave and velocity wave are accelerated by the rising of reaction rate. As the explosion progressed, with the temperature reaching approximately 3000 K, only one pressure wave and one reaction rate wave were observed, while several velocity waves were found. The larger diameter presented the highest relative pressure as well as the largest velocity increase and subsequent decrease inside the tube. The bent pipes caused both turbulence and kinetic energy to increase, resulting in the acceleration of the reaction rate. The burning time was 7.4% shorter than the burning time observed for the straight pipe. Based on these results, designing one explosion resistance device, and in the practical engineering applications, it was to be proved to meet the security requirements fully.

1. Introduction

The gases, found in coal mines, are often flammable and toxic, including methane, carbon dioxide, carbon monoxide, nitrogen, sulfur dioxide and hydrogen sulfide, with methane typically present in the highest concentrations. To avoid methane accumulation and reduce accidental gas explosions, coal mine gases must be removed on a timely basis by appropriate ventilation. More than 70% of the coal mines in China, however, have gas removal systems that result in methane concentrations of approximately 5–16%, which is within the explosive range. Hence a spark, produced by impacts between metals or rocks during the removal process, has the potential to cause an explosion.

However, the research on the gases explosion law almost focus on the tunnel, or a closed container, and even the shape, size, and number of obstacles [1–4]. Phylaktou et al. [5] studied the gas explosion process in a container and found that the ignition location and the gas concentration have a great effect on the explosion intensity. The intensity of the explosion that was ignited at the bottom of the container was greater than when ignition occurred at the center of container. Additionally, when the gas concentration was in the vicinity of 10%, the maximum growth rate of the explosion pressure was observed. Maremonti et al. [6] simulated the explosion process in connected vessels and found that the pressure peak was far higher than that in a single vessel. Additionally, in different diameters of connected vessels the explosion intensities varied, which was mainly attributed to the different turbulence intensities. Salzano et al. [7], Fairweather et al. [8] studied the gas explosion propagation when placing obstacles in tubes. The results showed that the geometry sizes and number of grids used in simulations, and the obstacle size all had a great influence on the simulated flame propagation. Zhu [9,10] performed experimental trials in three different pipes (single bend, U-shaped and Z-shaped) and found that the explosion strength was significantly enhanced because of the turbulence induced by increasing the number of turns. Zhu [11] simulated the propagation of gas explosions along varying distances and found that the flame speed along a conduit can be divided into three stages: the diffusion stage, the rapid rising stage and the inertia stage.

All of the above literature involved detailed and systematic studies of the characteristics of gas explosions relevant to underground coal mines. However, compared with the roadway, the pipe in a standard gas removal system is relatively small in size and is sometimes bent. Thus, a gas explosion within gas removal system pipes is much more constrained, such that the explosive gas flows in a certain direction leading to some phenomena which are unique to piping explosions.

In this paper several different diameters of straight pipes and a horizontal, bent pipe–analogous to that commonly used in Chinese coal mines–are selected as the focus of the research. The distribution of temperature, pressure, flame propagation speed and the

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reaction rate inside the pipe, and the characteristics of transmission process transmission process are studied for in-pipe explosions. Furthermore, the impact of the structure and diameter of the pipe on the explosion flow field is also analyzed. The results have important theoretical and practical value for the design and layout of gas drainage pipelines and are useful for understanding the protection measures required to avoid explosions.

2. Mathematical modeling of compressible gases

The phenomena of gas expansion, pressure increases and a higher release rate of gas often occur during gas explosions. Thus, gases in explosions are compressible and the equation of state is described as ideal gases.

Mathematical models of compressible gases include equations governing the conservation of mass, momentum, energy, and turbulent kinetic energy. The RNG k–ε equation, which is derived from rigorous statistical techniques and considers the turbulent eddies, was selected as the turbulence model. The additional inclusion of the turbulent Prandtl number provides this model more credibility and accuracy than the standard k–ε model.

The combustion equation for the explosion is described by Eq. (1):

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{1}$$

When solving the conservation equations, the mass fraction of each component in the gas mixture is estimated by the convection–diffusion equation for that component, as shown in Eq. (2):

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \vec{v} Y_i) = -\nabla \vec{J}_i + R_i \tag{2}$$

where Y_i is the mass fraction of component; i, $\vec{v}$ is the net production rate of component; i, and R_i is the chemical reaction rate. J_i is the turbulent diffusion flux of i, and is calculated by Eq. (3):

$$\vec{J}_i = -\left(\rho D_{i,m} + \frac{\mu_t}{Sc_t}\right)\nabla Y_i \tag{3}$$

where Sc_t is the turbulent Schmidt number; $D_{i,m}$ is the diffusion coefficient of i in the mixture; μ_t is the eddy viscosity.

The mass transfer and diffusion of components also cause the transmission of enthalpy. There are five components in the gas explosion. Four versions of Eq. (2) were required to be solved, with N_2 being selected as the fifth component, as this generated the smallest error value.

The eddy dissipation model was used to describe the interaction of the turbulence with the chemical reaction. The chemical reaction rate was controlled by k–ε and the mixing time scale of large eddies. The reaction rate was determined as the lesser of the results from Eqs. (4) and (5).

$$R_i = \upsilon'_i M_{w,i} A \rho \frac{\varepsilon}{k} \min\left(\frac{Y_R}{\upsilon'_R M_{w,R}}\right) \tag{4}$$

$$R_i = \upsilon'_i M_{w,i} A B \rho \frac{\varepsilon}{k} \frac{\sum p Y_p}{\sum_i^N \upsilon''_i M_{w,i}} \tag{5}$$

where v'_i is the stoichiometric coefficient for reactant i, v''_i is the stoichiometric coefficient for product i, υ'_R is the stoichiometric coefficient of a particular reactant; k is the turbulence kinetic energy, ε is the turbulent dissipation rate, N is the total number of reactants and products in the chemical reaction, and in this paper, $N = 5$, Y_P is mass fraction of any product species, Y_R is the mass fraction of a particular reactant, $M_{w,i}$ is the molecular weight of material k/ε, $M_{w,R}$ is the molecular weight of a particular reactant, and A and B are empirical constants set as 4.0 and 0.5, respectively.

3. Calculation conditions

3.1. Physical model and mesh generation

To calculate the conditions of the explosion and gas combustion, two types of pipe are considered: horizontal straight pipe and horizontal bent pipe. Five diameters of horizontal straight pipe were analyzed—100, 200, 250, 300 and 500 mm—each of length 25 m. The bent pipe was selected to represent a Chinese coal mine. Its structure is shown in Fig. 1 where from left to right the bending angles are 90°, 120°, 120° and 150°, and each bending length is 5 m, the diameter of the bent pipe is 300 mm, the total length is 25 m. Both of the models are divided into quadrilateral grids, the grids length of a side is 25 mm, and the number of total grids for the straight pipes is 4000, 8000, 10,000, 12,000, and 20,000 respectively, for the bending pipe, the grids number is 20,000.

3.2. Gas composition and ignition conditions

When the concentration of methane in the gas is between 8% and 10% the explosion intensity is the greatest. Therefore, the volume fraction of the methane gas was set to approximately 10% at a temperature of 15 °C, and the pressure is atmospheric pressure. The fire source was semicircular, with diameter of 0.1 m and was set at the end of pipe. Because methane burns completely and consumes all of the oxygen present, only carbon dioxide, water and nitrogen are found inside the fire source. The initial gas composition inside the pipe is shown in Table 1.

3.3. Boundary conditions

The mass-flow-inlet and the pressure-outlet were set at the left and right side of the pipe, respectively. The initial mass fraction of methane was 10% and the outlet pressure was set to atmospheric. The type of inlet-wall on both sides of pipe was non-slipping and adiabatic. For the horizontal straight pipe, there were six monitoring points near the wall, positioned 1, 5, 10, 15, 20 and 24 m from the inlet, to monitor changes in temperature, pressure, reaction rate and flame propagation speed.

4. Results and discussion

4.1. Verification of simulation results

A 30 m pipe of 500 mm diameter was used for verification experiments. Measurements of flame speed were recorded by 10 flame transducers positioned along the pipe, as shown schematically in Fig. 2. Over the span of 0–20 m from the left end of the pipe, a sensor was installed every 3 m, while sensors were positioned at 4 m intervals along the remainder of the pipe. Air was initially pumped out of the pipe to create a vacuum, after which methane was introduced to obtain a concentration of methane in the test gases of approximately 10%. One kind of ignition called KCLO3-C is used to ignite, whose initiation impulse is 6–8 A^2 ms

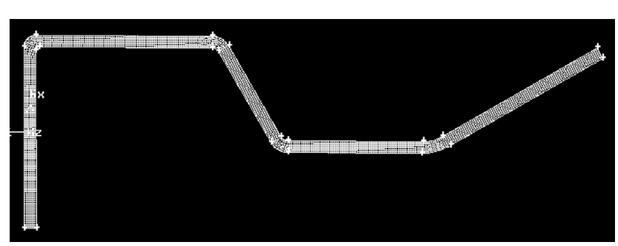

Fig. 1. Meshing of the bent pipe.