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A methodology to predict shock overpressure decay in a tunnel produced by a premixed methane/air explosion

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ABSTRACT

A methodology for estimating the blast wave overpressure decay in air produced by a gas explosion in a closed-ended tunnel is proposed based on numerical simulations. The influence of the tunnel wall roughness is taken into account in studying a methane/air mixture explosion and the subsequent propagation of the resulting shock wave in air. The pressure time-history is obtained at different axial locations in the tunnel outside the methane/air mixture. If the shock overpressure at two, or more locations, is known, the value at other locations can be determined according to a simple power law. The study demonstrates the accuracy of the proposed methodology to estimate the overpressure change with distance for shock waves in air produced by methane/air mixture explosions. The methodology is applied to experimental data in order to validate the approach.

1. Introduction

Gas explosions are major hazards in both the process industry (Proust, 2015) and underground coal mine (Zipf et al., 2013; Kundu et al., 2016). In order to effectively prevent losses from the explosion of methane/air mixtures, it is necessary to have some knowledge of the explosion process. In the case of an accidental explosion, the strength of the generated shock wave in air is a very important factor that has to be considered (Liu et al., 2004a,b). Therefore, the development of a shock propagation law for a methane/air explosion would be useful as the basis for blast-resistant design. Furthermore, this knowledge can also be used for the investigation of methane/air explosions.

Kindracki et al. (2007) carried out an experimental study investigating the influence of ignition position and obstacles on explosion development in a premixed methane/air mixture in an elongated explosion vessel. The pressure time-histories from two flush-mounted transducers were obtained for stoichiometric (9.5%), lean (7%) and rich (12%) methane/air mixtures. Pekalski et al. (2005) conducted experiments at standard and elevated initial pressure and temperature in a 20 L explosion vessel. In their work, the experimental results were compared to chemical equilibrium calculations. Four thermodynamic models, with different constraints on soot formation, were used to calculate the explosion equilibrium pressure. In experiments carried out in a closed spherical vessel with an internal diameter of 20 cm, for rich methane/air mixtures at initial pressures up to 30 bar and at ambient temperature, the results showed that lowering the position of the ignition source substantially in the vessel increases the explosion pressure (Van den Schoor et al., 2006); thereby implying that the central ignition is unsuitable to determine the explosion pressure for mixtures approaching the flammability limits.

Sacks et al. (2006) described a methodology to estimate the probability of ignition for methane/air mixtures. It provided a means to estimate the likelihood that an ignition could occur, and more importantly, allowed the calculation of "what-if" scenarios to investigate the effectiveness of engineering controls to reduce the hazard. The design of explosion isolation barriers is an important part of ascribing overall plant explosion protection. From a detailed understanding of flame propagation in a pipeline or duct, Moore et al. (2005) developed a model to calculate shock pressure change through a barrier. The efficacy of a barrier is critically dependent on both the selected hardware and the assumptions regarding explosion intensity and ignition location. The implicit residual risk of explosion isolation barrier designs can thus be assessed.

The development of a propagation-rule for a shock wave in a tunnel is important to predict the consequences of an explosion.

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Although at present extensive fundamental data are available to evaluate the explosion air shock wave parameters for condensed installation-state explosives, there are fewer data that can evaluate the air shock wave parameters for premixed methane/air in a tunnel.

TNT equivalency model uses pressure-distance curves to yield the peak pressure and has been used extensively to predict peak pressures from gas explosions. TNT is an ideal explosive material, and the unconfined blast wave decay-law is well established. The TNT equivalency method is based on the assumption that gas explosions in some way resemble those of high charge explosives, such as TNT. However, there are substantial differences between gas explosions and TNT (Lea, 2002). In addition, it is quite difficult to determine TNT equivalence for a methane/air mixture in a tunnel because the energy is distributed over a volume and the shock decay depends on the location of the explosion. The tunnel wall and the obstacles inside of the tunnel have significant influence upon the explosion propagation.

Numerical analysis has become one of the most effective ways to solve complex engineering problems (Tomizuka et al., 2013; Rosas et al., 2014). Computational Fluid Dynamics (CFD) models find numerical solutions to the partial differential equations governing the explosion process. The main drawbacks associated with the use of CFD are the limitations imposed by excessively long computational times. It seems unlikely that fully simulating a gas explosion in a real tunnel would be justified by concomitant improvements in explosion protection design. It is at least inconvenient to use. A detailed analysis of the blast effects of accidental explosions of methane should generally include studies of methane release and dispersion; an analysis of flame propagation, pressure build-up and blast generation in a complex three dimensional geometry; a study of the blast wave propagation and its effect on the surrounding objects. Because of the nature of the problems involved, this would generally require an application of 3D computational fluid dynamics simulations, which would be difficult or impossible to apply for all variety of the cases/applications. A simple approximate analytical tool should be useful in most cases (Dorofeev, 2007).

In this study, the overpressure distribution characteristics for a shock wave produced by a methane/air mixture explosion in a tunnel were investigated using numerical simulation. Based on the results of the simulation, a new empirical model for predicting overpressure of methane-air explosion in a tunnel was obtained.

2. Computational code and governing equations

The commercial finite-element CFD code AutoReaGas, suitable for gas explosion and blast problems, was used to carry out the numerical simulation. In the calculation, the EULER algorithm was chosen. The heat is supplied by the combustion, which is modeled by a simple one-step conversion process of non-reacted methane/air mixture into combustion products. This is mathematically formulated as a conservation equation for the fuel mass fraction.

$$\frac{\partial}{\partial t}\left(\rho m_{\text{fu}}\right)+\frac{\partial}{\partial x_j}\left(\rho u_j m_{\text{fu}}\right)=\frac{\partial}{\partial x_j}\left(\Gamma_{\text{fu}}\frac{\partial m_{\text{fu}}}{\partial x_j}\right)+R_{\text{fu}} \quad (1)$$

where t is time, x_j is the coordinate in the j direction, ρ is the density, m_{fu} is the unburnt fuel mass fraction, u_j is the velocity, R_{fu} is the volumetric combustion rate of the unburnt fuel, and Γ_{fu} is the turbulent flow dissipation coefficient characteristic for the unburnt fuel. The combustion rate, R_{fu}, to be included in the mass conservation equation, is computed as

$$R_{\text{fu}}=C_t\rho\frac{S_t^2}{\Gamma_{\text{fu}}}R_{\min} \quad (2)$$

where $R_{\min}$ is the minimum mass fraction among those of fuel, oxygen and products. Mass fractions of the fuel, oxygen and products change every moment, and the combustion rate is limited by the minimum mass fraction among the three components. C_{t} is a dimensionless turbulent combustion modeling constant, which represents the main adjustable parameter. The turbulent combustion rate can be controlled by the specification of the value of parameter C_{t} whose value is set on the basis of previous sensitivity analyses (Popat et al., 1996; Salzano et al., 2002; Tufano et al., 1988; Zhang et al., 2015). For applications in a long confined space, the use of a value of 100 for the parameter of C_t was recommended, and the satisfactory correspondence is established for a wide range of experiments. Therefore, in this paper, a value of 100 is used. The turbulent burning speed (S_t) is calculated via an empirical relationship correlating the laminar burning velocity, turbulence parameters and mixture properties as follows

$$S_t=1.8u_t^{0.412}L_t^{0.196}S_l^{0.784}\nu^{-0.196} \quad (3)$$

where u_t is the turbulence intensity, L_t is the turbulent macroscale, S_l is the laminar burning velocity, and ν is the kinematic viscosity of the unburned mixture.

The computation domain was divided into two parts, consisting of the blast (shock propagation in air) and explosive (methane/air flame propagation) parts.

3. Simulation results and analysis

The geometry modeled was a 500 m straight tunnel with cross-section area of 9 m^2 (3 m × 3 m), with one end closed. A uniform 11% methane in air mixture filled 39 m of the closed-end of the tunnel. The mass of methane was 27.6 kg, and the volume of methane/air mixture in the tunnel was 351 m^3. A weak ignition source was located at the closed-end of the tunnel. Two cases were investigated: smooth tunnel walls and tunnel walls with supports. In the second case, 60 mm square supports, equally spaced at 3 m, were placed next to the side and top walls, as shown in Figs. 1 and 2.

The computational domain was composed of cubes with 8 nodes, and the mesh size used was 0.05 m. The mesh was uniform along the entire length of the tunnel, including the sections filled with methane/air and air. The total number of mesh points was 36 million. Sub-grid model has been used in numerical simulation on gas explosion (Maxwell et al., 2015). Sub-grid objects were taken into account by a sub-grid representation. The capacity of present computers sets severe limitations to the grid size. Therefore, sub-grid objects should be taken into account by a sub-grid

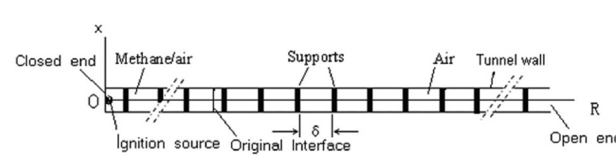

Fig. 1. Schematic showing the top-view of the tunnel.