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Effects of hydrogen on combustion characteristics of methane in air

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ABSTRACT

The explosion process of multi-component gas mixture is extremely complex and may cause serious disaster effects. The safety issue concerning explosion of multi-component gas mixture is urgent to be investigated on account of its wide range of applications. In current work, series of experiments were performed in a 20 L spherical explosion vessel at initial conditions of 1 atm and 293 K, involving methane–hydrogen/air mixtures. The proportion of hydrogen in fuels varied from 0% to 100%. It was observed that peak temperature is always behind the peak pressure in arrival time whatever the fuel equivalence is. Experimental values of peak overpressure are lower than adiabatic ones due to heat loss. It was also founded that the hydrogen addition can raise explosion pressure and temperature in experiment but slightly decrease that in adiabatic condition, and both the increase in experiment and the decrease in adiabatic show a linear correlation versus the proportion of hydrogen. Hence the deviation between the experimental results and the adiabatic results decreases as the hydrogen proportion rises. Moreover, the positive effect of hydrogen addition on $(dp/dt)_{max}$ is very slight at low hydrogen proportion, while the effect becomes much more pronounced at higher hydrogen contents, showing an exponential growth. For each fuel composition throughout all experiments, the peak overpressure, peak temperature and $(dp/dt)_{max}$ concerning fuel equivalence ratios of 0.6, 1 and 1.5 follow a same rule: $\Phi = 1$ is the highest, followed by $\Phi = 1.5$ and $\Phi = 0.6$. Finally, the MIEs of gaseous methane–hydrogen/air mixtures at a fuel equivalence ratio of 1.5 were measured as a function of hydrogen proportion. It shows a sharp decrease as the fraction of hydrogen in fuel rises, from 118 mJ for methane–air to 0.12 mJ for hydrogen–air. It is also observed that the MIE of multi-component gas mixtures can be approximately figured as the linear weighted sum of the MIE of each component; the weighting factor is respectively the volume fraction of each component. This can be considered as a universal method to obtain the MIE for a specific multi-component gas.

Introduction

Explosions involving multi-component gas, such as mine gas, city gas and petroleum gas, occur frequently, cause severe consequence and threaten the security of person and property. What outstanding is the gas explosion accident in coal mine [1]. Generally, coal mine gas consists mainly of methane, and normally contains small amount of hydrogen in consequence of the thermal metamorphism of coal, mine fires and

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explosions [2]. The presence of a small amount of hydrogen will be able to improve the explosion sensitivity, enhance the explosion power and raise the disaster hazard in gas explosion [3] owing to its characteristics of high flame reactivity, wide explosion range, low minimum ignition energy and high explosion risk [4]. Therefore, the safety issues of multi-component gas in coal mine deserve enough attention to prevent loss from gas explosion in mines.

On the other hand, the development of clean alternative fuel, hydrogen–hydrocarbon mixtures, has attracted more and more attention in engine community because primary fossil fuels have a number of problems related to environmental issues and energy security on account of their combustion products, such as CO, CO_2, NO_x and hydrocarbons [5,6]. For the safe use of hydrogen–methane fuel, it seems worthwhile to investigate the characteristics of hydrogen–-methane mixture explosion behaviors.

The peak overpressure and the maximum rate of pressure rise, $(dP/dt)_{max}$, are both the most important safety parameters for the hazard assessment of an explosion process and the design of process vessel [7–9]. The minimum ignition energy (MIE) is also essential for safe and reliable operation. MIE expresses the ignition sensitivity of one specific combustible gas. The danger degree of an accident possibly caused by a hidden trouble is mainly dependent on the minimum ignition energy (MIE) of the gaseous mixture. Taking measures to control ignition source is the most economic and rational way to prevent a gas explosion. All these explosion parameters of multi-component gas depend strongly on the proportion of each fuel component and the concentration of mixture [10,11].

The paper is aimed at investigating the explosion parameters (peak overpressure, temperature, maximum rate of pressure rise and the minimum ignition energy) in a 20 L vessel, involving a wide range of compositions for methane–hydrogen mixtures at fuel-lean, stoichiometric and fuel-rich conditions and gives a universal calculation method of MIE for methane–hydrogen mixtures at any composition.

Experimental apparatus and procedures

General

The volume percentage of hydrogen in fuel mixtures (X) is

$$X = \frac{V_{H_2}}{V_{H_2} + V_{CH_4}} \tag{1}$$

where V_{H_2} and V_{CH_4} are the volume of hydrogen and methane respectively. Hydrogen volume fraction in the fuel varies from 0% (pure methane in fuel) to 100% (pure hydrogen in fuel).

The fuel equivalence ratio (Φ) is

$$\Phi = \frac{(F/A)}{(F/A)_{stoic}} \tag{2}$$

where (F/A) refers to the fuel–air ratio and $(F/A)_{stoic}$ is the stoichiometric value of (F/A). $\Phi < 1$ is for lean fuel, $\Phi = 1$ is for stoichiometric fuel and $\Phi > 1$ is for rich fuel.

Experimental tests were performed in a 20 L closed spherical vessel with central ignition for explosions of hydrogen–methane mixtures at three fuel equivalence ratios (Φ). The experimental apparatus consists of an explosion vessel, an electric ignition system and a data acquisition system, as shown in Fig. 1. The initial temperature and pressure for all experiments were 293 K and 1 atm. In the experimental vessel, ignition was achieved by means of an inductive–capacitive spark produced between stainless steel electrodes with rounded tips, separated by a spark gap of 1 mm, along with the data acquisition system and the determination of ignition energy. All the experimental apparatus were described in previous work [12] in detail. Purities of methane and hydrogen in the study are 99.99% and 99.99%.

Experimental procedure

When preparing gas mixtures, each component (methane, hydrogen and air) gas is introduced into the vessel according to its corresponding partial pressure for the specified equivalence ratio. After the gas mixtures are prepared, the stirrer inside the vessel is turned on to stir for 2 min. Subsequently let these mixtures standing for 5 min to allow the mixtures to be homogeneous and quiescent before ignition. Once the combustion is completed, the combustion vessel is vacuumed and flushed with dry air for three times to avoid the influence of the residual gas on next experiment. Table 1 gives the mixture compositions adopted in the explosion test.

Numerical method

A finite element computational code for fluid dynamics, suitable for gas explosion and blast problems, was adopted to calculate the adiabatic, premixed, confined gas explosion propagation. The code solves Navier–Stokes partial differential equations numerically by means of the finite volume formulation [13].

The turbulent flow field is modeled by a two-parameter (k-ε) model [14], which uses conservation equations for the turbulence kinetic energy, k, and its dissipation rate, ε.

The heat addition is supplied by combustion reaction which is considered as a simple single-step conversion from

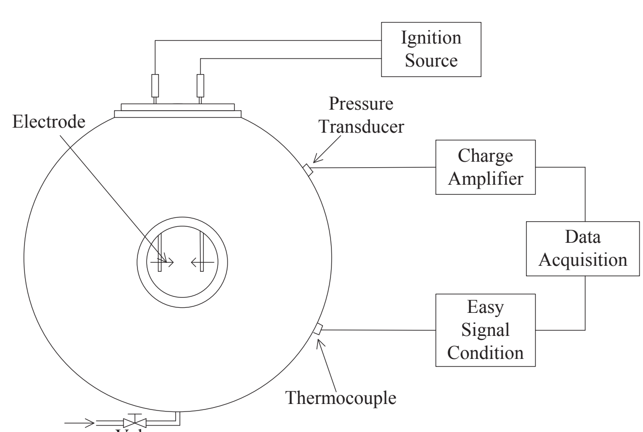

Fig. 1 – Spherical vessel and experimental set-up.