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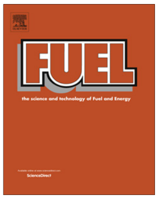

Experimental study of minimum ignition energy of methane/air mixtures at elevated temperatures and pressures

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HIGHLIGHTS

- The minimum ignition energy of methane/air mixtures at elevated temperatures and pressures are studied experimentally.
- The MIE has a linear relationship with $1/P^2$ and a nearly linear relationship with $1/T$.
- The fitting formula based on experimental results can accurately predict the MIE at elevated pressures and temperatures.
- Our experimental results are compared with the ignition prediction model previously used by Coronel et al.

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ABSTRACT

The minimum ignition energy (MIE) is an important parameter when describing explosion characteristics. While the minimum ignition energy of methane has been studied by many researchers, little information is available for elevated temperatures and elevated pressures. In our study, firstly, the minimum ignition energy of methane/air mixtures was measured for different temperatures (30–150 °C) and different pressures (0.1–0.9 MPa). Then, our experimental results were compared with the ignition prediction model previously used by Coronel et al. Results indicate that in our experimental setup, the sensitive electrode gap is 1 mm and the sensitive methane equivalence ratio is 1. With increasing pressure or temperature, the MIE decreases. The MIE has a high order linear relationship with $1/P^2$, but an approximately linear relationship with $1/T$. With increasing temperature, the influence of pressure on the MIE becomes smaller. In addition, with increasing pressure, the effect of the temperature on the MIE also decreases. The fitting formula for the MIE at elevated temperatures and pressures is able to predict the MIE accurately. The prediction model used by Coronel et al. is valid for predicting the minimum ignition energy of methane at various initial pressures. Overall, the calculated results by prediction model are about 1.5 times as large as the experimental values, which is acceptable when predicting the MIE of methane at elevated pressures.

1. Introduction

The minimum ignition energy is defined as the minimum energy that a successful ignition of a combustible gas requires. MIE can reflect the explosion sensitivity of the combustible gases and is usually considered to be one of the key parameters to predict explosion [1,2]. During the last few years, the MIEs of combustible gases have been determined by many researchers both experimentally and via numeric simulation. Han et al. [2,3] studied the spark ignition characteristic of a hydrogen/air mixture as well as a methane/air mixture using detailed chemical kinetics. Kondo et al. [4] calculated the minimum ignition energy of combustible gases using two formulas. After comparing the theoretical with the experimental data, they found that the calculated results contain a large error. Janes et al. [5] measured the minimum ignition energy of a dust cloud using the Mike 3 and Hartmann setup. They discovered the effect of the explosion setup on the MIE. Ono et al. [6] studied the effects of humidity and spark duration on the MIE of hydrogen/air mixtures. Coronel et al. [7] studied the MIE of lean H_2–N_2O mixtures using an experimental method. They considered the influence of both nitrogen and initial pressures.

In recent years, many researchers studied the MIE using a statistical method. They thought the success of ignition in an ignition energy range was a probabilistic event. Eckhoff et al. [8] studied the minimum ignition energy of propane/air mixtures experimentally based on the statistical method. They found that the classical

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minimum ignition values for combustible gases, as published by Lewis and Von Elbe, are very conservative. Wahner et al. [1] tested the MIE for hydrogen, ethane and propane using logistic regression. Bane et al. [9] developed a very low-energy capacitive spark ignition system to test the spark energies of lean hydrogen–oxygen–argon mixtures. The experimental results were analyzed using statistical tools to obtain probability distributions for ignition as a function of spark energy. Then Bane et al. [10] studied the spark ignition energy in a gaseous kerosene–air mixture, experimentally, using the same spark ignition system. The kerosene results were compared with the previous study for traditional hydrogen-based surrogate mixtures as well as two hexane–air mixtures and the statistical nature of spark ignition were discussed.

Based on the studies above, we find that the existing studies of the MIE mainly focus on standard conditions, i.e. room temperature and atmospheric pressure, no matter which method they use. The factors that affect the MIE mainly include the explosion apparatus, the ignition electrodes, the ignition voltage and storage capacitor, and the composition of the combustible gases. On the other hand, the influence of the initial temperature and pressure on the MIE has never been studied. Generally, the MIE of gases decreases with increasing initial temperature and pressure. Unfortunately, the dependent of the MIE on the initial temperature and pressure are not known. In addition, the MIE data at elevated temperatures and pressures were never obtained.

For these reasons, we designed an experimental setup to measure the minimum ignition energy for combustible gases at elevated temperatures and elevated pressures. The minimum ignition energy of methane/air mixtures were measured across a wide temperature range (30–150 °C) as well as pressure range (0.1–0.9 MPa). We believe that the results are of both scientific and commercial significance.

2. Experimental

2.1. Experimental apparatus

A schematic diagram of the experimental setup is shown in Fig. 1. It includes the gas cylinders, the explosion vessel, the heating system, the ignition system, the vacuum-pumping system and a data acquisition system. The explosion vessel is a vertical stainless steel cylinder with a height of 400 mm, an inner diameter of 140 mm, and a wall thickness of 18 mm. The pressure rating of the vessel is 15 MPa, which is much higher than the explosion pressure at all temperatures and pressures used in this experiment. The explosion vessel is placed in a heating box, which is equipped with an automatic temperature control function. The initial temperature of the combustible gas can be tested by a fast response thermocouple (Nanmac E Graduation S) located near the center of the vessel.

The combustible gas was composed using the partial pressure method. Each component is added to the explosion vessel in series by regulating the needle valve. In this experiment, methane was first added into the vessel until it reached the desired partial pressure. Then nitrogen and oxygen were added, one after the other. For the purpose of acquiring the accurate concentration of the prepared combustible mixture, a gas chromatograph was used for the analysis prior to the ignition. The initial pressure was recorded by a precision pressure gauge with an accuracy of 0.02.

Both the explosion pressure and temperature curve were recorded using a piezo-electric pressure transducer (Dytran 2200V5) at a sampling rate of 500 kHz and a fast response thermocouple (Nanmac E Graduation S), respectively. In this study, an explosion is considered successful when the pressure increases by more than 5% of the initial pressure. This is consistent with the BS-EN-1839-2003 standard.

In the traditional MIE test, the ignition energy can be calculated easily using both the capacitance in which energy is stored and the high voltage, using Eq. (1). However, the MIE calculated with Eq. (1) is usually higher than the true value because of the circuit resistance and stray capacitance. The ignition circuit used in our study is shown in Fig. 2. The capacitor is charged first by turning on switch 1 and turning off switch 2. Then, the capacitor is discharged by turning off switch 1, and turning on switch 2. At the same time, a spark is triggered between the two electrodes in the explosion vessel. The current probe is used to test the current flowing through the electrodes during spark duration while the voltage probe is used to measure the voltage between the two electrodes. The current–time curve and voltage–time curve were recorded with an oscilloscope. Typical current and voltage versus time

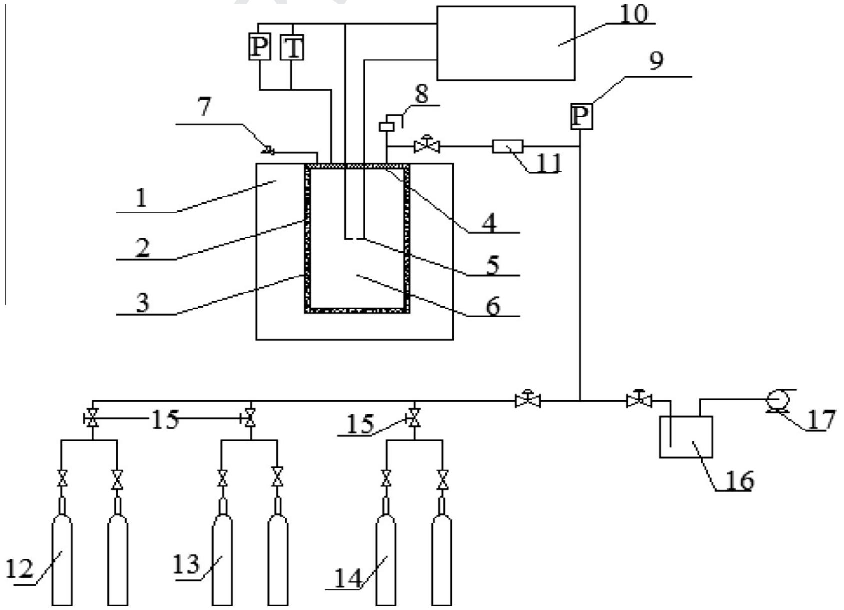

Fig. 1. Experimental setup. 1 – Heating box, 2 – Inner wall of the heating box, 3 – Aluminum powder, 4 – Insulating layer, 5 – Ignition electrode, 6 – Explosion vessel, 7 – Sampling valve, 8 – Safety valve, 9 – Precision pressure gauge, 10 – Data acquisition system, 11 – Flame arrester, 12 – Methane gas cylinders, 13 – Oxygen gas cylinders, 14 – Nitrogen gas cylinders, 15 – Needle valve, 16 – Vacuum vessel, and 17 – Vacuum pump.

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