Journal of Hazardous Materials 278 (2014) 520–528

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

High methane natural gas/air explosion characteristics in confined vessel

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HIGHLIGHTS

- The effect of methane fraction on pressure evolution during natural gas combustion is examined.
- Increasing pressure will increase the explosion pressure and the maximum rate of pressure rise.
- Increasing pressure will decrease the combustion duration.
- An empirical correlation for the combustion phasing is proposed.

ARTICLE INFO

Article history:
Received 26 March 2014
Received in revised form 8 June 2014
Accepted 20 June 2014
Available online 28 June 2014

Keywords:
High methane concentration natural gas
Explosion characteristics
Combustion phasing
Dilution

ABSTRACT

The explosion characteristics of high methane fraction natural gas were investigated in a constant volume combustion vessel at different initial conditions. Results show that with the increase of initial pressure, the peak explosion pressure, the maximum rate of pressure rise increase due to a higher amount (mass) of flammable mixture, which delivers an increased amount of heat. The increased total flame duration and flame development time result as a consequence of the higher amount of flammable mixture. With the increase of the initial temperature, the peak explosion pressures decrease, but the pressure increase during combustion is accelerated, which indicates a faster flame speed and heat release rate. The maximum value of the explosion pressure, the maximum rate of pressure rise, the minimum total combustion duration and the minimum flame development time is observed when the equivalence ratio of the mixture is 1.1. Additionally, for higher methane fraction natural gas, the explosion pressure and the maximum rate of pressure rise are slightly decreased, while the combustion duration is postponed. The combustion phasing is empirically correlated with the experimental parameters with good fitting performance. Furthermore, the addition of dilute gas significantly reduces the explosion pressure, the maximum rate of pressure rise and postpones the flame development and this flame retarding effect of carbon dioxide is stronger than that of nitrogen.

1. Introduction

Depletion of fossil fuels and the urgent requirement of reducing environmental pollutions caused by combustion have recently driven the studies on the combustion characteristics of alternative fuels. Natural gas is thought to be one of the best alternative fuels and it has been widely used in city bus and taxi engines in China. Natural gas is a mixture of light hydrocarbons such as methane, ethane, propane, etc. Components of natural gas from different production sites may vary but the primary component is methane [1]. There are several advantages for the application of natural gas in the internal combustion engines; engines can operate under high compression ratio because of high fuel octane number [2]. Natural gas is the clean energy and has the lowest C/H ratio among all the hydrocarbons thus allowing the reduction emission of CO_2 [2–5]. Moreover, most of the technology developed for the internal combustion engines can be easily applied to burn natural gas as engine fuel.

Previously, extensive investigations have been carried out to evaluate the fundamental combustion characteristics of natural gas. Gu et al. [6] and Liao et al. [7] measured the laminar burning velocity of methane and natural gas mixed with air at different

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http://dx.doi.org/10.1016/j.jhazmat.2014.06.047
0304-3894/

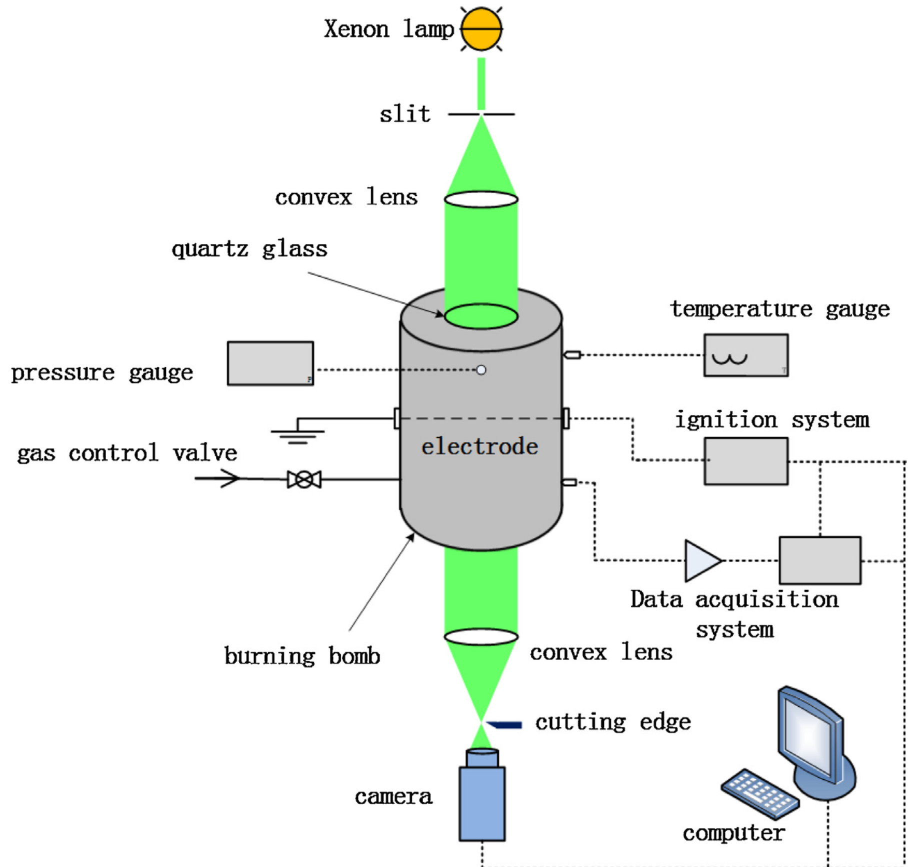

Fig. 1. Experimental setup.

equivalence ratios and investigated the flame instability at high pressures. Huang et al. [8] and Hu et al. [9] studied the laminar burning characteristics of hydrogen enriched natural gas. They obtained the stretched flame propagation speed and the burning velocity. Cho et al. [10] reviewed the spark ignition natural gas engines. They highlighted some indexes such as emissions, combustion efficiency, and strategies to get stable combustion of the natural gas engines. Slavinskaya et al. [11] developed a kinetic mechanism to predict the emission of methane–ethane flame, especially the poly-aromatic hydrocarbons (PAH). However, there are some problems of the application of natural gas. One of the problems for utilizing natural gas is the disasters about combustion such as ignition and explosion [12–14]. The dominant damages of the fire resulting by leakage are the heat release from the sustained fire and collapse of buildings because of the explosion [15]. But there has been little study focusing on the explosion characteristics of natural gas. Another problem is about purification. Purification is difficult and expensive. But the research about the influence of other non-methane gases such as ethane is very little.

The explosion pressure (P_{max}), the rate of pressure rise (dP/dt), and the time when P_{max} reaches (t_R) (also defined as the combustion duration) [16] are the most important parameters of explosion in appraising the risk of the application of natural gas [17,18]. They are also important for the transportation and storage of natural gas. The parameters such as P_{max}, dP/dt and t_R are very sensitive to initial pressure, initial temperature, equivalence ratio, and the fuel compositions. The dilute gas also has significant influence on those parameters because it reduces the flame temperature due to increased average mixture specific heat. Theoretically, constant volume adiabatic equilibrium pressure (P_e) for given mixture composition is the maximum pressure that the system can thermodynamically achieve [19]. However, the explosion pressure (P_{max}) measured in confined vessel is expected to be significantly lower than the adiabatic equilibrium pressure (P_e). The main reason is the heat loss resulted by the thermal conduction, convection and radiation [19]. Razus et al. [20] have observed the influence of initial temperature and pressure on the explosion characteristics in a spherical vessel. They found that the $(dP/dt)_{max}$ and the deflagration indices were linear functions of initial pressure, when the initial temperature and the fuel/oxygen were constant. And when the initial pressure and the composition were constant, the $(dP/dt)_{max}$ and the deflagration indices were influenced by the initial temperature.

The objectives of this work are the following. Firstly, the influence of the initial conditions such as pressures, temperatures, equivalence ratios, dilution ratios and different types of dilute gases on the explosion characteristics of high methane natural gas including the explosion pressure, the pressure rise rate, the combustion duration will be investigated. Additionally, some natural gas companies in China are trying to produce high methane concentration natural gas (up to 99.9% in volume) because of high octane number of methane, though this purification process is extremely expensive. Thus our second objective is to see to what extend the explosion pressures are affected by the variation of methane concentration. Finally, the peak pressure and the combustion phasing of these high methane concentration natural gas mixtures will be studied so as to provide some fundamental data for natural gas engine timing control.

2. Experimental setup and procedures

Fig. 1 is the sketch of the experimental system. It includes the constant volume combustion vessel, the ignition system, the heating system and the data acquisition system. The diameter of the stainless steel cylinder combustion vessel is 180 mm and the length