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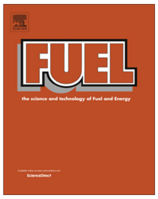

Study on the flame propagation and gas explosion in propane/air mixtures

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HIGHLIGHTS

- Laminar burning velocity and Markstein length were studied in a 1.16 m^3 vessel.
- The variations laminar flame parameters with methane addition have been studied.
- The flame instability and the critical radii of instability onset were studied.
- In propane/air flame with an equivalence ratio near 1.8, two explosions take places.

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ABSTRACT

The characteristics of flame propagations and gas explosions in propane/air mixtures were studied in a 1.16 m^3 explosion chamber with two quartz glass windows of 250 mm diameter. The outward propagations of the spherical flame were recorded by the Schlieren system and high speed motion analysis system. The pressure and temperature histories of the explosion process were measured by pressure sensors and platinum–rhodium thermal couples of 0.02 mm diameter mounted on the wall of the experimental chamber. The instabilities of the propane air flame with different equivalence ratio flame were observed and the critical radii of flame instability onset were obtained. The laminar burning velocities of propane air mixture were obtained by analyzing the experimental results of Schlieren system by using outwardly propagating spherical method. The variation of laminar burning velocity with equivalence ratio was studied. Pressure and temperature responses of the gas explosion were obtained and analyzed. The variations of the maximum overpressure and the maximum temperature with equivalence ratio were obtained and discussed. In propane/air mixture with an equivalence ratio near 1.8, two explosions take places.

1. Introduction

Propane has a long history of being used as a domestic, agricultural, industrial, and commercial fuel. It has also been used in the petrochemical industry as a raw material to make plastics and other items. Propane is also being increasingly used as a vehicle fuel. It is the third most popular vehicle fuel after gasoline and diesel. An advantage of propane for use in cars is that it can be liquefied at a moderate pressure. This allows fast refill times, affordable fuel tank construction, and ranges comparable to (though still less than) gasoline. Meanwhile, it is noticeably cleaner (both in handling and in combustion), and results in less engine wear (due to carbon deposits) without diluting engine oil (often extending oil-change intervals). Propane is still the most common alternative transportation fuel in use today.

The laminar burning velocity is an intrinsic property of flammable mixtures and an important parameter for the propagation and stabilization of laminar flames. Knowledge of laminar burning velocity is required in various applied research fields, such as the design of explosion vessels and active suppression and/or relief devices for confined explosions, the modeling of turbulent combustion, and the optimization of internal combustion engines. In basic research, the laminar burning velocity is a key parameter for validating models of combustion wave propagation that take into account the detailed chemical kinetics. Therefore, accurate determination of laminar burning velocity is of great interest. Various methods have been used for the determination of burning velocities under a wide range of initial conditions: constant-pressure or constant-volume methods, and making use of steady or unsteady flames. Among them, the method based on the study

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of unsteady flame propagation in a closed spherical vessel with central ignition may be considered a versatile and accurate method, especially when synchronous records of pressure and flame radius during explosion propagation are available. The method provides transient values of burning velocity, which refer to a steadily compressed unburned gas, and must be carefully corrected for stretch effects when applied to an extended period of flame propagation in a closed vessel [1,2]. The possibility of determining burning velocity over an extended range of unburned gas pressures and temperatures (using several sets of data or just one single $p(t)$ record) is a great advantage of this method [3,4]; however, the advanced mathematical treatment limits its current use. An easier approach is to restrict the examination of closed-vessel flame propagation to just the early stage, when temperature gradients in both the unburned and burned gas are not so large and can be neglected.

In the work reported herein, the flame propagation and explosion in propane/air mixtures have been studied in a 1.16 m^3 vessel with central ignition. The burning velocities of the mixtures have been evaluated in terms of the flame-front trajectory and pressure history, respectively. Flame temperatures have been measured by a fine-wire thermocouple. The experimental values of burning velocity and temperature of propane/air flames have also been compared with computed values obtained from a detailed kinetic modeling of propane/air 1-D laminar, premixed, free flames.

The motivation of this paper is to get combustion and explosion parameters of propane air mixtures accurately. In outwardly propagating spherical flame method, the flame propagation speed is affected by compression effects. And the explosion parameters are affected by the heat absorption of vessel wall. The influences of compression on flame propagation and heat absorption of wall on explosion can be minimized by using a relatively large vessel. So the vessel of 1.16 m^3 was used in present study.

2. Experimental set-up and procedure

A schematic diagram of the experimental set-up is shown in Fig. 1. It consists of an explosion test chamber, a Schlieren photo measurement system, a pressure measurement system, and a temperature measurement system.

Experiments were performed in a 1.16 m^3 explosion chamber, which could withstand an internal pressure of 50 bar, as shown in Fig. 1. It consisted of a cylinder section of inner diameter 1300 mm and length 764 mm, and two semi-ellipsoid surfaces; the total axial length of the experimental chamber was 1438 mm. The vessel was equipped with several ports for gas feed and evacuation valves, and for mounting pressure sensors, thermocouples, and the ignition electrodes. Two high-strength quartz windows of diameter 250 mm were mounted on opposite side walls of the cylinder section for optical access. The fuel/air mixtures were ignited by an electrical spark ignition device, the electrical energy of which ranged from 0.2 mJ to 2.5 J. The spark energy was measured by monitoring the current through the spark and the voltage across the spark gap, and the energy of the spark used for ignition of the fuel/air mixture in the present study was 5 mJ. A Schlieren image system and a high-speed digital camera operating at 8400 frames per second were used to record the movement of the flame front during the flame propagation process. The pressure histories were measured by Kistler pressure sensors connected to a pressure adapter and the temperature histories were measured by homemade thin-wire thermocouples and thermocouple adapters. A data acquisition system was used to record the pressure and temperature histories during the flame propagation. Before each test, the combustion vessel was evacuated and the mixture was prepared by introducing each component according to its corresponding partial pressure for the specified equivalence ratio. An equilibration time of 300 min was allowed to ensure thorough mixing and to avoid any influence from the wall. The mixture was then ignited by the centrally located electrodes. The ignition of the fuel/air mixture, the triggering of the high-speed camera, and the data acquisition system were all controlled by the control unit. Once the combustion was completed, the combustion vessel was flushed by the venting system to avoid any influence of the residual gas on the next experiment. The quoted purity of the propane used in the study was 99.995%.

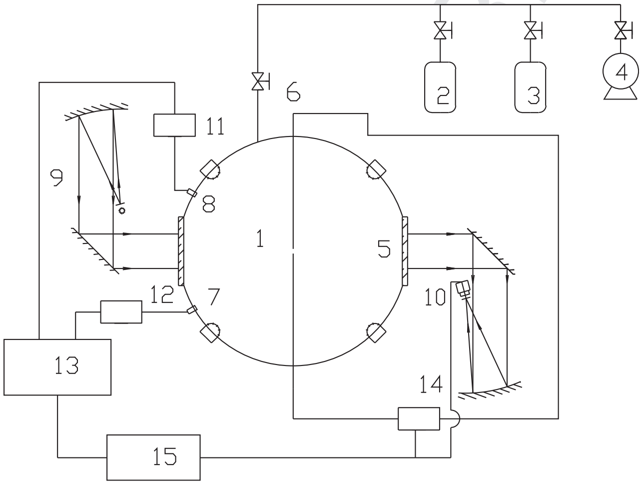

Fig. 1. Schematic diagram of the experimental set-up. 1 explosion chamber, 2 propane, 3 air, 4 vacuum pump, 5 quartz glass window, 6 electrode, 7 pressure sensor, 8 thermocouple, 9 Schlieren system, 10 high-speed motion analysis system, 11 thermocouple adapter, 12 pressure sensor adapter, 13 data acquisition system, 14 electric spark ignitor, 15 control unit.

3. Laminar burning velocity evaluation method

3.1. Determination of laminar burning velocity by the expanding spherical flame method

As described above, the flame propagation sequence was imaged by Schlieren photography and recorded using a high-speed digital camera. For the outwardly propagating flame, the propagation speed can be expressed [5] as:

$$S_b = \frac{dr_b}{dt} \tag{1}$$

where r is the flame radius in the Schlieren photo and t is the time.

Flame stretch rate, α, represents the rate of expansion of the flame area (A) [6,7]. In a quiescent mixture, it is defined as:

$$\alpha = \frac{1}{A}\frac{dA}{dt} = \frac{2}{r}\frac{dr_b}{dt} \tag{2}$$

According to asymptotic analysis [8,9], in the early stage of flame propagation, when there is little increase in pressure and low stretch rate, the local flame propagation rate S_b is linearly related to the flame stretch rate α by the law:

$$S_b = S_b^0 - L_b\alpha \tag{3}$$

where S_b^0 is the propagation speed of the unstretched flame and L_b is the Markstein length of the burned gas. The unstretched propagation speed can be obtained as the intercept value at $\alpha = 0$ in a plot of flame propagation speed S_b against stretch rate α. The Markstein length of the burned gas is calculated from the slope of an S_b–α fitting curve.

Integrating Eq. (3) with respect to time yields:

$$r + 2L_b \ln(r) = S_b^0 t + \text{constant} \tag{4}$$

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