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Laminar burning velocities, Markstein lengths, and flame thickness of liquefied petroleum gas with hydrogen enrichment

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ABSTRACT

In this paper, experimental data of laminar burning velocity, Markstein length, and flame thickness of LPG flames with various percentages of hydrogen (H_2) enrichments have been presented. The experiments were conducted under the conditions of 0.1 MPa, 300 K in a constant volume chamber. The tested equivalence ratios of air/fuel mixture range from 0.6 to 1.5, and the examined LPG contains 10%–90% of hydrogen in volume. Experimental results show that hydrogen addition significantly increase the laminar burning velocity of LPG, and the accelerating effectiveness is substantial when the percentage of hydrogen is larger than 60%. Effect of hydrogen addition on diffusion thermal instability, as indicated by Markstein length, was analyzed at various equivalence ratios. Hydrogen addition decreases the flame thickness. Equivalence ratio has more dominating effect on flame thickness than hydrogen does. For the fuel with 10% LPG and 90% hydrogen, the flame thickness values are close for all equivalence ratios.
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Introduction

Liquefied petroleum gas (LPG) consists mainly of butane and propane. As one of the main energy sources used for domestic and commercial applications, LPG has the advantages such as stable flame, high heating value, and low processing cost. Although LPG is a relatively clean fuel with low ash and sulfur contents, it still emits a large amount of carbon dioxide (CO_2) and unburned hydrocarbon (HC) during combustion, which are causing serious environmental problems. Besides, the CO_2/HC emissions, the narrow flammability range of LPG is also an unfavorable factor, and significantly limits application of LPG. Hydrogen, another well known clean fuel, has zero CO_2/CO emission and wide flammability range. However, hydrogen flame can be rather unstable during operation because of its extremely light weight and special combustion characteristics. Also, because of its low density and light molar weight, hydrogen has very low volumetric heating value. It seems that LPG and hydrogen are complementary with each other on emissions, flame stability, and heating value. LPG with hydrogen addition may be helpful in extending flammability

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Nomenclature			
$H_2\%$	volumetric percentage of hydrogen in fuel mixture, %	λ	thermal conductivity of unburned gas, cal m^{-1} K^{-1} s^{-1}
V_{air}	volume of air, m^3	r_{sch}	schlieren front radius, m
V_{fuel}	volume of fuel, m^3	α	flame stretch rate, s^{-1}
S_n	stretched laminar flame speed, m/s	S_l	unstretched laminar flame speed, m s^{-1}
r_u	cold flame front radius, m	L_b	burned gas Markstein length, mm
ρ_b	burned gas density, kg m^{-3}	u_l	unstretched laminar burning velocity, cm s^{-1}
ρ_u	unburned gas density, kg m^{-3}	δ_l	laminar flame thickness, mm
		C_p	specific heat of unburned gas, cal kg^{-1} K^{-1}
		Ma	Markstein Number

range and reducing CO_2/HC emissions. Furthermore, adding hydrogen in LPG may stabilize the flame and improve volumetric burning velocity of the fuel. Thus, the mixture of LPG and hydrogen may be a potential solution for high energy, low emission, and extended stable flames.

Laminar burning velocity (LBV) is a fundamental property of fuel. It is determined by the kinetics of chemical reaction and the molecular heat and mass transport [1]. LBV is also an important parameter in validating the chemical kinetics [3] and combustion characteristics of a fuel, and hence it is an important parameter in predicting performance and emission of a fuel for any combustion systems [2]. The LPG–H_2 mixture studied in this paper is a unique and complicated fuel mixture containing butane, propane, and hydrogen. Although there are extensive researches on LBVs of hydrogen, propane, and butane individually [3–16], few LBV data are accessible for the mixture of these three fuels.

Markstein length is another important property of fuel, which is related to the diffusional-thermal instability of flame, while flame thickness and density ratio are related to the hydrodynamic instability of flame. By analyzing Markstein length, flame thickness, and density ratio of a LPG-hydrogen flame, the optimal ratio of LPG and hydrogen for a safe and stable flame could be determined [8].

There are several methods to measure the LBV, such as conical flame method, soap bubble method, counterflow burner method, and constant volume combustion bomb method [2,17]. The constant volume combustion bomb method uses the spherically propagating flame, which has simple flame geometry, low thermal conduction heat loss, and low friction with the vessel wall [1]. There are some other advantages of using the constant volume combustion bomb, it can measure the LBV at high-pressure with less consumption of fuel and easy controllable initial conditions and mixture compositions [3]. In this study, a constant volume combustion bomb was used, and the initial conditions were set as 0.1 MPa and 300 K. The measured data in this study can be used to study the application of LPG–H_2 mixture, and provide useful information for the related studies.

Experimental setup

In this study, experiments were conducted using a constant volume combustion bomb. As shown in Fig. 1, the system consists of a combustion bomb, a gas control system, an ignition system, a lighting system, and data acquisition system. The combustion bomb is of cylindrical shape. Two pressure-resisting quartz windows were installed on the two sides of the combustion bomb to allow the combustion process optically accessible. Electrodes were located in the centerline of the combustion bomb to ignite the mixture. The gas control system includes gas valves, a manometer, and a vacuum pump. The vacuum pump was used to evacuate the

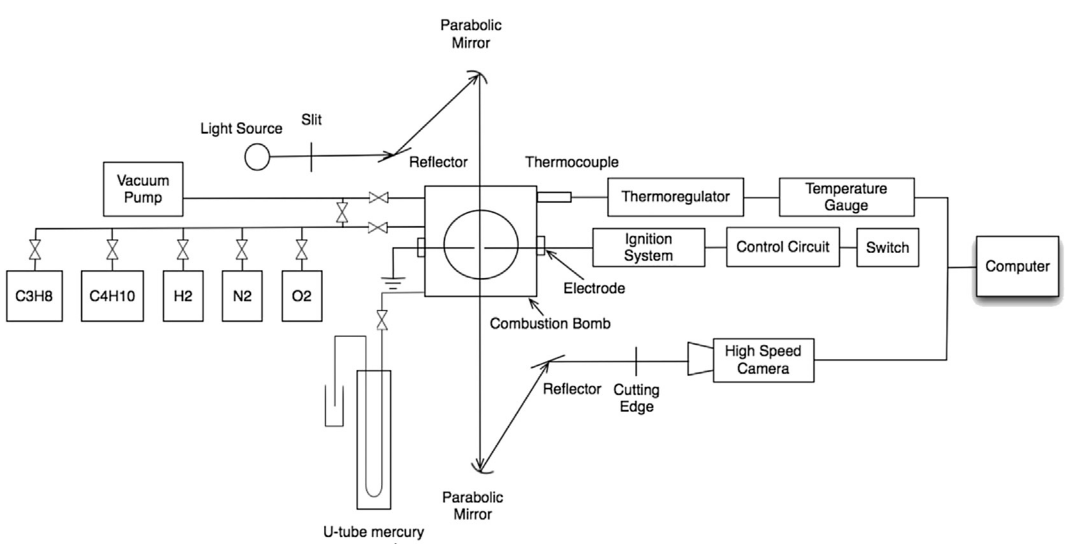

Fig. 1 – Experimental system.

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