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Propagation characteristics of laminar spherical flames within homogeneous hydrogen-air mixtures

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ABSTRACT

Taking the laminar spherical flames propagate within homogenous hydrogen-air mixture as the studied object, the effects of initial conditions (including equivalence ratio, initial pressure, and initial temperature) on propagation characteristics are systematically investigated. During propagation, global stretch rate monotonously declines towards convergence, it first rises then declines with the increase of equivalence ratio (φ) from 0.5 to 4.0 and the maximal value is attained at $\varphi = 1.8$. With the declines of global stretch rate, the propagation speed within lean mixtures first declines and then rises, but it monotonously rises within stoichiometric and rich mixtures. Markstein length is sensitive to equivalence ratio and initial pressure rather than initial temperature. Unstretched laminar burning velocity isn't monotonously changed with the variation of equivalence ratio but it monotonously verifies with the variation of initial thermodynamic condition. Owing to the wane of stretch effects, flame develops towards unstable, the nexus between critical flame radius of cellularity behaviours and initial conditions are analysed based upon hydrodynamic and thermal-diffusive effects. In addition, the critical Peclet number is observed linear to equivalence ratio but less sensitive to initial ambient conditions.

1. Introduction

The 'On-Wheels' Era is in urgent need of alternative fuels for the sustainability, thus making investigations on fundamental combustion characteristics of such fuels has become a hot topic in the field of energy science. Due to its preeminent advantages in burning velocity and combustion products, hydrogen has been widely regarded as one promising alternative fuel [1–5] and has been tested in many energy conversion systems (for example, spark-ignition internal combustion engines, SI-ICEs) [6–10]. For a SI-ICE, the combustion performance is governed by the flame propagation process within cylinder [11,12], thus an in-depth understanding of hydrogen flame's propagation characteristics is necessary and essential to the further scientific applications, laminar burning velocity and intrinsic instabilities have been commonly regarded as two essential and crucial aspects among various fundamental combustion characteristics [13–15].

Laminar burning velocity is the factor reflects both combustion process and combustible mixtures' reactivity, thus it is usually employed to directly indicate combustion rate even validate chemical dynamics [16]. Therefore, many scholars have measured the laminar burning velocity of hydrogen-air premixed flames. Günther and Janisch [17], Liu and MacFarlane [18] respectively measured the laminar burning velocities of hydrogen-air mixtures in a flat flame and spherical flame at atmospheric pressure, Law et al. [19] did measurements on a Benson burner under atmospheric pressure with the dilution of hydrocarbon, Milton et al. [20] and Iijima et al. [21] respectively did measurements within a closed vessel based upon the curves of pressure evolution; however, all those reported results are absent from the effects of flame stretch. Koroll et al. [22] did measurements on double-kernel steam jet flames, Tse et al. [23] did measurements on spherical hydrogen-oxygen flames at elevated temperatures and pressures, Dahoe et al. [24] did measurements from the curves of pressure evolution, Know and Faeth [25]. discussed the relationship between stretch effects and laminar burning velocity in spherical hydrogen premixed flames with the dilution of methane under normal temperature; however, the related reports are analysed without the consideration of flames' intrinsic instability. Albeit Hu et al. [26], Pareja et al. [27], Dayma et al. [28], Yanz and Kuznetsov [29] respectively discussed both the effects of flame stretch and

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intrinsic instability in spherical hydrogen premixed flames by the methods of experimental and/or numerical, further detailed information on propagation characteristics (especially related to propagation speeds) are still needed to in-depth understandings.

Intrinsic instability is another utmost important factor effecting flames' detailed revolution, it is related to the obvious variation of flame's structure and consequently flame's propagation speed as Bradley reported [30]. Within the past decades, more and more scholars paid their attentions to hydrogen premixed flame's intrinsic instability: Aung et al. [31] studied the relationship between intrinsic instability and the destabilization process of hydrogen premixed flames; Sun et al. [13], Liu et al. [32], and Yang et al. [33] respectively analysed the effects of initial conditions (including equivalence ratio, thermodynamic parameters, even diluent fraction) on hydrogen premixed flames' intrinsic instabilities; however, quantificational relationship between initial conditions and intrinsic instabilities are still lack of for hydrogen premixed flames.

For providing more information on the propagation characteristics of hydrogen premixed flames, the present investigation focuses on both laminar burning velocity and intrinsic instabilities of laminar spherical flames within homogenous hydrogen-air mixtures. The effects of equivalence ratio and initial thermodynamic ambient parameters (including ambient pressure and ambient temperature) have been systematically investigated. The variations of seven essential and crucial indication parameters, including global stretch rate (α), Markstein length (L_b), unstretched laminar burning velocity (u_l), stretched laminar burning velocity (u_n), critical flame radius (R_{cr}) and critical Peclet number (Pe_{cr}) have been discussed and analysed. Owing to the unambiguous-defined flame stretch and the most similarity to actual flame within engines' cylinder [12], outwardly propagating spherical flame is employed as the model flame to the related investigation in the present paper.

2. Experimental and computational specifications

2.1. Experimental apparatus and procedure

The experiments are conducted within a closed combustion vessel whose inner chamber is designed into a spherical space with a volume of 2.744 litters. Upon the vessel, one pair of quartz windows (with an effective diameter of 100 mm) are mounted for providing optical access, one pair of tungsten-copper electrodes (associated with a 12 V ignition coil) are mounted for realizing the ignition, three independent gas circuits are mounted for discharging reactants and products of combustion, sets of heating coils (covered by thermal insulation layers, linked with temperature control system) are mounted for heating the mixtures, two pressure transmitters (DPA01M-P with a range of −100.0~+100.0 kPa, and DPA10M-P with a range of −0.001~+0.999 MPa) are mounted to monitoring the static pressure within the vessel during the discharging, and one piezoelectric pressure transducer (Kistler 6052-C) is mounted to recording the pressure evolution near the inner wall during the combustion. Off the vessel, a Z-shape arranged Schlieren system and a high-speed digital camera are employed for capturing the images of propagating flame during the combustion. In the present investigation, the employed hydrogen is pure hydrogen with a purity of 99.995%, synthetic air (synthetized by high purity oxygen and high purity nitrogen with a volume ratio of 21:79) is employed as the oxidation reaction in order to avoid the dilution effects of other gases (such as argon, carbon dioxide, water vapour, etc.) in the air on the fundamental combustion characteristics of hydrogen-air mixtures. Details of the experimental setup have been shown in Fig. 1.

Procedurally, pumping the vessel into vacuum for the provision of reactant mixtures, hydrogen gas and synthetic air are successively charged into the vessel to form desired mixture based upon Dalton's law of partial pressures. For studying the effects of initial ambient temperature on the propagation characteristics of hydrogen-air premixed flame, different initial ambient temperature should be realized. Within the heating process, the heating coils are energized by electricity to heat the vessel's wall, and the mixture within the vessel are correspondingly heated by wall heat transfer, the whole heating process is monitored and automatically controlled by heating control system. Once the initial ambient temperature has reached the target setting, a quarter of an hour is needed to make the mixture homogenous and motionless [34,35] (it should to be noted that an absolute motionless of mixture never can be realized, the motionless here mainly refers to the dissipation of turbulence induced by discharging process and heating process), and then the mixture is ignited to form the flame kernel. After a set of experiment, the vessel is vented for removing high-pressure exhaust gas, then flushed twice with synthetic air for removing any residual combustion products, and finally again pumped into vacuum for next set of experiment. Within the present article, fuel concentration is denoted by equivalence ratio (φ, defined as the ratio of actual fuel-air ratio to stoichiometric fuel-air ratio, varies from 0.5 to 4.0), initial ambient condition is denoted by initial pressure (P_{int}, varies from 0.1 MPa to 0.5 MPa) and initial temperature (T_{int}, varies from 300 K to 450 K).

2.2. Global stretch rate, Markstein length, and laminar burning velocity

To outwardly propagating spherical premixed flames, its propagation speed (S_n) can be directly derived from the flame images, as

$$S_n = \mathrm{d}R/\mathrm{d}t \tag{1}$$

where R is instantaneous flame radius and can be measured from the images, t is elapsing time from spark-ignition. For avoiding the influences of ignition spark, just the flames whose sizes are more than 5 mm are employed [36].

The stretch effect on flame front is commonly indicated by global stretch rate (α, defined as the Lagrangian time derivative of the logarithm of surface area), as [36].

$$\alpha = \mathrm{d}(\ln A)/\mathrm{d}t = (1/A)\cdot(\mathrm{d}A/\mathrm{d}t) \tag{2}$$

where A is the area of flame front's projection.

Furthermore, α has a linear relationship to unstretched flame propagation speed (S_l) within the early period of flame propagation (during which the flame is highly smooth and stable) [36], as

$$\alpha\cdot L_b = S_n - S_l \tag{3}$$

where L_b (a parameter can be obtained from the slope of S_n–α curve) is the Markstein length (of burned gases). Still within this period, the pressure of the field flame propagates keeps a constant value of P_{int}, and unstretched laminar burning velocity (u_l) can be obtained as

$$u_l = S_l/\sigma = S_l/(\rho_u/\rho_b) = S_l\cdot\rho_b/\rho_u \tag{4}$$

where σ is the density ratio across the flame-front, ρ_u is the density of unburned gas, ρ_b is the density of burned gas, the both densities can be calculated by the chemical equilibrium program GASEQ.

Actually, flame thickness also plays influence on propagation characteristics of premixed flames. Taking the mentioned consideration, stretched laminar burning velocity (u_n) can be defined as