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Turbulent burning velocity of hydrogen–air premixed propagating flames at elevated pressures

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ABSTRACT

Lewis number represents the thermo-diffusive effects on laminar flames. That of hydrogen–air mixture varies extensively with the equivalence ratio due to the high molecular diffusivity of hydrogen. In this study, the influences of pressure and thermo-diffusive effects on spherically propagating premixed hydrogen–air turbulent flames were studied using a constant volume fan-stirred combustion vessel. It was noted that the ratio of the turbulent to unstretched laminar burning velocity increased with decreasing equivalence ratio and increasing mixture pressure. Turbulent burning velocity was dominated by three factors: (1) purely hydrodynamic factor, turbulence Reynolds number, (2) relative turbulence intensity to reaction speed, the ratio of turbulence intensity to unstretched laminar burning velocity, and (3) sensitivity of the flame to the stretch due to the thermo-diffusive effects, Lewis and Markstein numbers. A turbulent burning velocity correlation in terms of Reynolds and Lewis numbers is presented.

1. Introduction

Hydrogen is an alternative fuel for internal combustion engines because of its less emissions properties of unburned hydrocarbon, carbon monoxide, carbon dioxide, and particulates [1]. Lean mixture operation is possible because hydrogen has a wider flammable range and larger burning velocity than other common fuels. It can yield a higher thermal efficiency of hydrogen engines due to the reduction of the pumping loss. Emission levels of NO_x may be also reduced by lean combustion [1,2].

At the same time, however, characteristic features of hydrogen also tend to cause some problems such as preignition [1,2], the onset of knock [2,3]. In order to overcome these problems, it is important to understand the properties of hydrogen flame.

In addition to hydrogen, various types of fuel containing hydrogen have been also investigated in order to improve the performance of engines [4], to use biomass as fuel [5], or to increase the safety of hydrogen by hydrocarbon substitution [6]. A small amount of hydrogen addition introduced changes in the flame characteristics [4]. Thus, this study investigated the fundamental aspects of hydrogen flames from the following viewpoints.

Internal combustion engines are operated at elevated pressures. However, only a few fundamental studies on combustion of hydrogen and hydrocarbons have been carried out at elevated pressures [7–14]. To date, these studies have

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indicated that flames at elevated pressures have rather different behaviour [8–14] to the corresponding flames observed at atmospheric pressure.

Studies of burning velocity at elevated pressure such as those by Bradley et al. [8], Gu et al. [9], and Faeth et al. [10,11] have reported that consideration of the influence of flame stretch via aerodynamic strain and/or the flame curvature on laminar flames is important to establish reliable laminar burning velocity measurements. The response of the laminar burning velocity of a flame to stretch has been characterised by a Markstein number [15], which has proven to be sensitive to mixture strength and pressure [8–11,14,16,17].

Bradley et al. [18] and Law et al. [13] have reported the transition to cellular flame structures at smaller flame radii for higher pressures for outwardly propagating spherical flames. Hence, the flame instability proved to be influenced by increasing mixture pressure. Experimental observations of laminar and turbulent combustion using burner-stabilized flames by Kobayashi et al. [12,19,20] showed that local flame structures were finer and more convoluted at elevated pressures.

Turbulent burning velocities have also been investigated at elevated pressures [14,21,22]. Increased turbulent burning velocities (relative to the unstretched laminar burning velocity) were reported for those mixtures most sensitive to flame instability. Hence, turbulence may well influence local flame stretch and affect the burning velocity with increasing mixture pressure.

In this study, the laminar and turbulent burning velocities were investigated for outwardly propagating hydrogen–air flames in an optically accessed combustion vessel, for initial pressures in the range of 0.10–0.50 MPa. The Lewis number of hydrogen–air mixture varies widely with the equivalence ratio compared to common hydrocarbons in laboratories such as methane and propane. Lean flames with small Lewis numbers were observed quite unstable. Unstretched laminar burning velocities and Markstein numbers could not be determined from those explosions carried out at laminar conditions. They were obtained by the numerical simulation using detailed reaction-kinetic mechanism.

The influences of the turbulence intensity, mixture pressure, and Markstein number on turbulent flame propagation were investigated. A turbulent burning velocity correlation for application to elevated pressures is proposed in terms of the Reynolds and Lewis numbers and ratio of turbulence intensity to unstretched laminar burning velocity.

2. Experimental apparatus and procedures

Experiments were carried out using the constant volume bomb apparatus outlined schematically in Fig. 1. The combustion vessel is comprised of three 265 mm diameter cylinders, which intersect orthogonally. The total volume of the chamber is approximately 35,000 cm^3 or equivalent to that of a sphere with a diameter of 40.6 cm. The vessel has been designed to withstand the maximum pressure of 10 MPa expected for explosions carried out with an initial pressure of up to 1.0 MPa.

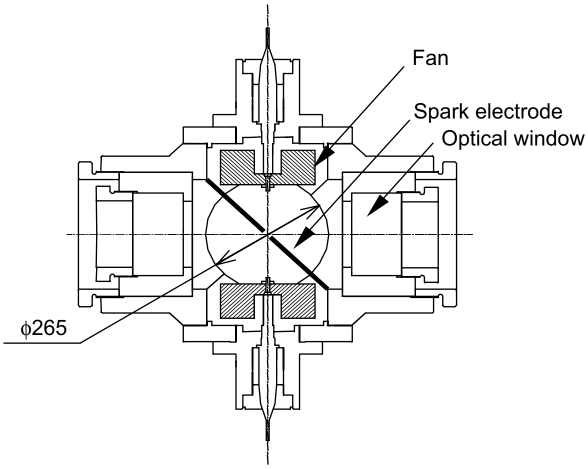

Fig. 1 – Schematic figure of combustion chamber.

Combustible hydrogen–air mixture quantities were prepared in the vessel according to the required partial pressures of hydrogen and air. In the present study, the equivalence ratio, φ was 0.4, 0.6, 0.8, and 1.0. Explosions were carried out with initial mixture pressures, P_i of 0.10, 0.25, and 0.50 MPa. The initial temperature of the mixture was kept 300 K for all experiments.

The two fans (mounted at the top and bottom of the vessel and driven by electric motors) were operated after mixture preparation to ensure proper mixing. In the laminar combustion experiments, mixture was ignited 1 min after the two fans were stopped and mixture flow in the vessel decayed completely.

In the turbulent combustion experiments, the fans were operated during explosions. Relationships between the fan shaft rotational speed, turbulence intensity, u', and longitudinal integral length scale, L_f have been conducted previously using Particle Image Velocimetry (PIV). Turbulence intensities of 0.80 and 1.59 m/s were adopted. The integral length scale proved to be 10.3 mm and was independent of all examined initial pressures and rotational fan speeds.

Mixture was ignited by the electric spark at the center of the chamber. The spark electrodes had a diameter of 1.8 mm and the spark gap was set to 3 mm, the spark energy was 1.4 J. Flame propagation was observed using schlieren photography via two 160 mm diameter windows mounted oppositely. Explosions were recorded using a Phantom v4.1 high-speed digital camera operated at 1000–25000 f/s with 512×512–256×32 pixel image resolution, respectively.

Laminar and turbulent burning velocities have been obtained from flame radius [8,14,21,22]. With an initial pressure of 0.10 MPa, the maximum pressure rise in which the entire flame front is visible (flame radius of less than 80 mm) is 0.05 MPa. Hence, measurements were considered to have been completed at the adopted approximate initial pressure and temperature.

At least three explosions were carried out at each condition. Experimental scatter of measured burning velocities was within a range of 5–10% of average value at most conditions, and it exceeded 15% at some conditions. As shown in the