Laminar and unstable burning velocities and Markstein lengths of hydrogen–air mixtures at engine-like conditions

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Abstract

Hydrogen offers an attractive alternative to conventional fuels for use in spark ignition engines. It can be burned over a very wide range of equivalence ratios and with considerable exhaust gas recirculation. These help to minimise pumping losses through throttleless operation and oxides of nitrogen (NO_x) production through reduced temperature. Full understanding of hydrogen-fuelled engine operation requires data on the laminar burning rate of hydrogen–air residuals under a wide range of conditions. However, such data are sparse. The present work addresses this need for experimental data. Spherically expanding H_2–air flames were measured at a range of temperatures, pressures, and equivalence ratios and with varying concentrations of residuals of combustion. Unstretched burning velocities, u_l, and Markstein lengths, L_b, were determined from stable flames. At the higher pressures, hydrodynamic and diffusional-thermal instabilities caused the flames to be cellular from inception and prohibited the derivation of values of u_l and L_b. The effect of pressure on the burning rate was demonstrated to have opposing trends when comparing stoichiometric and lean mixtures. The present measurements were compared with those available in the literature, and discrepancies were attributed to neglect, in some works, the effects of stretch and instabilities. From the present measurements, the effects of pressure, temperature, and residual gas concentration on burning velocity are quantified for use in a first step towards a general correlation.
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Keywords: Hydrogen; Laminar burning velocity; Residuals; Engine

1. Introduction

Hydrogen is a very attractive alternative to traditional fossil fuels as an energy carrier due to its very clean combustion and the ease of manufacture. Because of its high flame speed, leading to near constant volume combustion, and wide flammability limits, a hydrogen-fuelled engine has the potential for high efficiency. The power output of such engines can be varied by changing the equivalence ratio to use very lean mixtures at low loads. Oxides of nitrogen are minimised, while maintaining adequate power, by varying the amount of EGR during stoichiometric operation [1]. In both cases, the throttle valve is not used, except maybe at idling, and pumping losses are minimised. Thus, hydrogen engines use a large range of equivalence ratios, and EGR concentrations can be very high with stoichiometric operation.

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Two of the authors have a history in experimental research on hydrogen engines (e.g., [2,3]). Although much knowledge has been gathered from engine tests, they have proved expensive both in money and time. Therefore, a mathematical model to simulate the combustion of hydrogen in spark ignition (SI) engines is being developed at Ghent [4]. This models the influence of the turbulence on the initially laminar flame propagation and assumes quasi-one-dimensional combustion. Such models rely on a known laminar burning velocity at the instantaneous cylinder pressure, temperature, and mixture composition, and they calculate the change in flame speed due to turbulence. A convenient way of obtaining the laminar burning velocity is by a laminar burning velocity correlation. However, the few data that exist on hydrogen–air laminar burning velocities at engine-like pressures and temperatures do not take stretch or cellularity effects into account, causing a large spread in the reported burning velocities [5–8]. Some unstretched burning velocities have been measured but were generally performed at atmospheric conditions [9–15]. Therefore, this paper presents and discusses measurements of the laminar burning velocity, and the effects of flame stretch rate on hydrogen–air and hydrogen–air residual mixtures. For conditions at which measurements of the laminar burning velocity are not possible due to fundamental flame instabilities, measurements of unstable burning velocities, obtained under initially quiescent conditions, are presented.

Using these data, the effects of pressure, temperature, and residual gas concentration on burning velocity are quantified for use in a tentative correlation.

2. Experimental apparatus and technique

A 380 mm diameter, spherical, stainless steel vessel (bomb) was employed which is capable of withstanding the temperatures and pressures generated from explosions with initial pressures of up to 1.5 MPa and initial temperatures of up to 600 K [16]. It has extensive optical access through three pairs of orthogonal windows of 150 mm diameter and is equipped with four fans driven by electric motors, used here only to ensure the reactants were well mixed. The fans were switched off prior to ignition allowing sufficient time for any mixture motion to decay. Mixtures were prepared in situ using the partial pressure method in which simulated residuals were synthesised from water and nitrogen and were injected into the bomb starting from 5% of vacuum, water first. The bomb was then filled to the desired pressure with high purity hydrogen and dry air from a cylinder. Following an explosion, the vessel was first flushed twice with dry air to remove any residual

products before a subsequent mixture was prepared. All other aspects of the equipment and experimental technique are given in [16,17].

Following central spark ignition, flame images were captured by schlieren cine' photography using a Phantom V4.1 digital camera at various resolutions and frame rates, depending on the burning rate of the mixture. For the slower flames, a frame rate of 1000 frames per second (fps) was used at the maximum available resolution of 512×512 pixels. Flame speeds, $S_n = dr/dt$, were then calculated from the mean flame radii, r, obtained from measurements of flame projected area. Because of the very high flame speeds obtained with hydrogen, 1000 fps proved to be too slow for the faster burning mixtures. Therefore, higher frame rates of up to 14,300 fps were achieved by capturing only a portion of the flame image at the full 512 pixel width but with a reduced vertical field of view of down to 32 pixels, which corresponded to a field of view of about 150 mm wide by 9.4 mm high. Because of the high flame speeds, the flames were almost spherical so there was very little loss in accuracy when using the reduced vertical field of view. Moreover, previous studies with other fuels showed essentially identical flame speeds at all radial locations [17].

The unstretched flame speed, S_s, unstretched laminar burning velocity, u_l, onset of instabilities, and the effect of flame stretch rate, α, embodied in the Markstein length were derived from flame speed using the methodology described in [16–18]. The total stretch rate on a stable, non-cellular, outwardly propagating flame is given by $\alpha = 2 \cdot S_n/r$ [18], and a linear relationship between this and S_n is quantified by a burned gas Markstein length, L_b, such that $S_s - S_n = L_b\alpha$. S_s is obtained as the intercept value of S_n at $\alpha = 0$ in the plot of S_n against α. The unstretched laminar burning velocity is then obtained from $u_l = S_s/(\rho_u/\rho_b)$, where ρ is the density, and the subscripts 'u' and 'b' refer to the unburned and equilibrated adiabatic products.

A problem arises with the above technique when a flame becomes unstable leading to a cellular flame structure. Under such conditions, the flame accelerates as the stretch rate reduces, and a linear relationship between S_n and α no longer applies. The methodology adopted in [17–19] was to extrapolate only the linear portion of the S_n against α curve to zero. This approach relies on there being a sufficiently large stable, linear, regime. Further, it has been shown that the onset of flame acceleration due to cellularity occurs at a critical Peclet number, $Pe_{cl} = r_{cl}/\delta_l$ [19], where r_{cl} is the radius at which cells start to induce flame acceleration, and δ_l is the laminar flame thickness. This increases linearly with Markstein number, $Ma_b = L_b/\delta_l$. Because the hydrogen flames used in the present work have a very thin reaction zone, the critical Peclet number is attained at small flame radii and, hence, only for mixtures at