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Experimental investigation of spherical-flame acceleration in lean hydrogen-air mixtures

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ABSTRACT

Large-scale experiments examining spherical-flame acceleration in lean hydrogen-air mixtures were performed in a 64 m^3 constant-pressure enclosure. Equivalence ratios ranging from 0.33 to 0.57 were examined using detailed front tracking for flame diameters up to 1.2 m through the use of a Background Oriented Schlieren (BOS) technique. From these measurements, the critical radii for onset of instability for these mixtures, on the order of 2–3 cm, were obtained. In addition, the laminar burning velocity and rate of flame acceleration as a function of radius were also measured.

Introduction

As the prevalence of hydrogen use throughout industry has increased, the potential for a large accidental release of hydrogen has become a greater concern. Due to the high reactivity of the fuel, and its wide detonability range, mitigation techniques such as ventilation, or limitations on the total quantity stored, are commonly used to reduce the hazard in buildings and enclosures. Nevertheless, there are many situations where these methods cannot maintain concentrations below the lower flammability limit during an accidental release and lean hydrogen-air mixtures may form. Flames in these lean hydrogen-air mixtures are particularly sensitive to the formation of hydrodynamic instabilities, which significantly accelerate the flames. As the laminar burning velocity alone is traditionally used to characterize the baseline reactivity of a fuel, the development of flame instabilities are not usually taken into account. Models that do not account for the development of flame instabilities will significantly underpredict the flame propagation velocity, rate of heat release, and pressures that develop during an explosion. To improve the performance of these models, there is great interest in characterizing the behavior of lean hydrogen-air mixtures and properly account for the development of flame instabilities.

The primary hydrodynamic instability that forms in all flames is generated by the Darrieus–Landau instability [1,2], which has been extensively observed throughout studies of spherical-flame propagation [3–6]. Even in the absence of initial turbulence, spherical flames will spontaneously form cellular structures, resulting in flame acceleration due to an increase in flame surface area. For a given mixture, the radius at which these cells form is a material property, which is commonly normalized by flame thickness and expressed as a critical Peclet number [7,8].

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The increase in flame surface area, and the overall magnitude of acceleration, depends on the amplitude and wavelength of the structures that form. Previous studies have found that these flames accelerate indefinitely as the flame grows in radius, resulting in propagation velocities that increase as a power law with time [9]. In atmospheric-pressure propane-air flames, it has been observed that the flame velocity increases by a factor of 1.5 by the time the flame radius has grown to between three to four times the critical radius [10]. This effect is of particular importance within the context of industrial safety, where the peak flame velocity is the primary factor that determines the pressures that develop. This effect is considerably more severe in lean hydrogen-air mixtures, which have significantly smaller critical radii and result in significantly higher velocities at the same physical radius.

In the work of Gostintsev et al. [9,11], it was suggested that the sustained acceleration is a result of ongoing cell splitting, which generates fractal structures of the flame surface. In a previous study examining propane-air mixtures [10], oscillatory flame acceleration was observed with frequency intervals consistent with the concept of cell splitting and the formation of fractal structures. Based on these results, the original power law relation of Gostintsev et al. [9] was reformulated and the following relationship between propagation velocity and flame radius was obtained [10]:

$$u/u_L = (R/R_0)^{\beta}. \tag{1}$$

where u_L is the laminar flame propagation velocity of the mixture, R_0 is the critical radius of onset of instability, and β is a fractal excess that can be obtained experimentally. This result suggests that the critical radius is an integral parameter in characterizing the overall mixture reactivity in general and, specifically, in determining the overall propagation velocity of a spherical flame at a given radius.

The objective of this study is to examine the rate of spherical-flame acceleration for lean atmospheric-pressure hydrogen-air flames in a large-scale enclosure. This includes performing detailed front tracking to capture the flame radius as a function of time for flames up to 1.2 m in diameter, and to characterize the critical radius and fractal excess of lean hydrogen-air mixtures. In addition, other phenomena seen in past studies, such as oscillatory flame acceleration [10] and the possibility of multiple regimes of flame acceleration [6] will also be examined.

Experimental setup

The experiments were performed in a 64 m^3 vented enclosure with dimensions of $4.6 \times 4.6 \times 3.0$ m^3, as shown in Fig. 1, with a single 5.4 m^2 vent to maintain a constant internal pressure during flame propagation. The overall experimental setup used in this study follows closely that of a previous study [10], where a full description of the test setup and instrumentation can be found. Ignition was supplied by an automotive ignition system using two 50 μm tungsten wires as electrodes and the overall ignition energy was estimated to be less than 100 mJ. A thin polypropylene sheet was used to contain the initial mixtures during filling and mixing. The sheet was pre-cut to the size of the vent and held in place by a rigid frame using pneumatic clamps that were released 1 s prior to ignition.

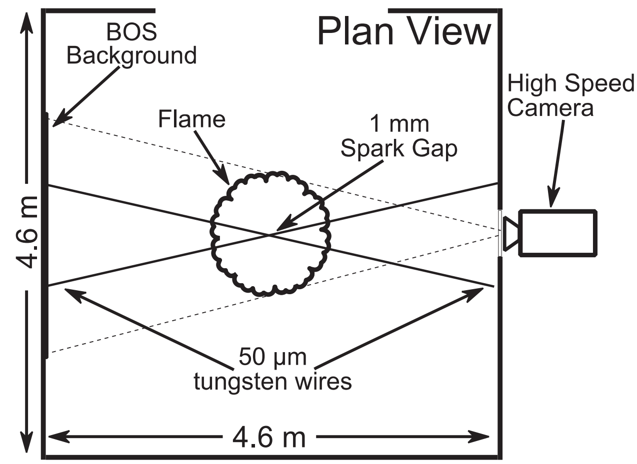

Fig. 1 – Schematic of the enclosure and ignition configuration.

A range of hydrogen-air concentrations were examined with equivalence ratios, ϕ, ranging from $\phi = 0.33 - 0.57$ (12.3–19.2% hydrogen in air by volume). This range of concentrations was selected to limit the effect of buoyancy, for the lean limit, and ensuring that the maximum pressures that develop within the enclosure were below its design strength, for the upper concentration limit. The initial mixtures were prepared by injecting research grade hydrogen from a port at the center of the floor of the enclosure. Four large diameter mixing fans in a counter-flow arrangement were used to produce a uniform composition throughout the enclosure. The fans were stopped five minutes prior to ignition to ensure a quiescent initial mixture, with turbulent fluctuations $u' \ll 0.05$ m/s. The initial concentration was continuously monitored prior to ignition using an Illinois Systems P710 paramagnetic oxygen analyzer. Overall experimental uncertainty in mixture equivalence ratio was estimated to be within $\phi \pm 0.015$.

As the hydrogen-air flames did not emit sufficient radiation in the visible spectrum to allow for direct tracking of the propagation of the flame, a Background Oriented Schlieren (BOS) technique was used. The background images were captured using a Vision Research Phantom Flex high speed camera for flame diameters up to 1.2 m. The flame propagation velocity was calculated from flame radii extracted from 1600×1600 pixel images captured at a rate of 2000 frames per second and the onset of cellular instability was extracted from the image sequence using the procedure described in the previous study [10]. Due to the smaller critical radii produced in lean hydrogen-air flames, however, the smoothing algorithm was reduced to a second order Savitzky-Golay filter with a window size of 5 ms to better capture the initial flame propagation.

Background Oriented Schlieren technique

The Background Oriented Schlieren (BOS) technique [12] allows for the generation of schlieren images without the need