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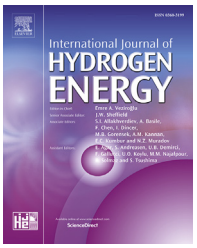

Experimental study on self-acceleration in expanding spherical hydrogen-air flames

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ABSTRACT

The development of cellularity for expanding spherical hydrogen-air flames at elevated pressure, owing to hydrodynamic and diffusional-thermal instabilities was experimentally investigated using high-speed schlieren images. The critical flame radii and critical Peclet numbers at which cracks begin to propagate and for the onset of flame acceleration were obtained. The dependency of Pe_{cl} on *Ma* for hydrogen-air flames was compared with that for other fuels. The results showed that cellular development depends on the intensity of the diffusional-thermal instability. The acceleration exponent and fractal excess for the acceleration regime of a hydrogen-air flame were evaluated. The values show that the transition regime and self-similar regime exist in the acceleration regime of expanding spherical hydrogen-air flames.

Introduction

During the propagation of laminar premixed flames, the flame front is wrinkled due to cellular instabilities such as hydrodynamic, diffusional-thermal, and body-force instabilities [1]. Hydrodynamic and diffusional-thermal instabilities are common issues in the cellular structure of premixed flames. Furthermore, it is well known that body-force instability is caused by difference in the densities of fluids, as observed in a ventilated tube. Darrieus and Landau independently analyzed the hydrodynamic instability in premixed flames [2,3]. Their result showed that the hydrodynamic instability in the premixed mixtures is caused by thermal expansion and that the flame is unstable for perturbations of any wavelength, that is, this instability appears for all flames. However, in real flames, the instability mechanism is affected by the diffusional-thermal instability owing to the non-equidiffusive effect. This can be estimated by the Lewis number, *Le*, that is defined as the ratio of the thermal diffusivity of the mixtures and mass diffusivity. $Le<1$ and $Le>1$ indicate unstable and stable flames, respectively. Furthermore, these instabilities in flames with small radii are suppressed by strong stretching, with positive stretching having a stabilizing effects. As the flame expands, instabilities are enhanced by the reduction of the stretching effect, and consequently, flames become cellular. The diffusional-thermal instability is dominant when the flame radius is small. However, as the flame radius increases, the hydrodynamic instability progressively dominates with a decrease in flame thickness. These instabilities cause the growth of a cellular structure on the surface, and this gives rise to self-acceleration.

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The onset of the instabilities, the development of cellular flames and self-acceleration have been extensively studied experimentally and theoretically. In the early stages of flame propagation, cracks produced by spark electrodes appear in the flame surface appear and propagate across the flame front; consequently, the flame shows a fully developed cellular structure, and its surface is curved by the cells [4–6]. Bradley described that two different critical Peclet numbers: one is the critical Peclet number $Pe_c = r_c/\delta$, where r_c is the flame radius at which cracks begin to propagate, δ is the laminar flame thickness of the mixture, and Pe_c values are close to those predicted by theoretical works [7,8], and the other is the critical Peclet number $Pe_{cl} = r_{cl}/\delta$, where r_{cl} is the flame radius for the transition. The cells grow and then cover the entire surface, leading to flame acceleration. This transition to cellularity at Pe_{cl} has been investigated experimentally [9–22]. r_{cl} and Pe_{cl} for various fuels were evaluated from experimental schlieren images [4–6,9–16] as well as from the relation between the experimental flame speed and the stretch rate [17–22]. The results show the relationship between Pe_{cl} and the equivalence ratio ϕ. It is indicated that the onset of flame acceleration depends on the intensity of diffusional-thermal instability. In particular, the dependency of Pe_{cl} on the Markstein number, $Ma = L/\delta$, where L is the Markstein length for methane-air, iso-octane-air, and propane-air explosions, is observed [6,18,20]. The increasing tendency of Pe_{cl} with Ma showed moderate agreement, although the empirical equations for various fuels were different. This difference might be attributable to the different definitions of the critical flame radius and the uncertainty of the Markstein length. In recent years, many studies have experimentally evaluated the critical point for the transition and this issue remains controversial.

It is known that a sufficiently large-scale flame wrinkled owing to cellular instabilities might become self-turbulization. Gostinsev et al. [23] evaluated large-scale flames and quantified self-similar propagation through the following power law:

$$r = r_{cl} + At^{\alpha} \quad (1)$$

where r is the flame radius; r_{cl}, the radius for the onset of self-turbulization; A, the constant for a given mixture; t, the time; and α, the acceleration exponent associated with the fractal excess $d = (\alpha\text{-}1)/\alpha$, based on which $\alpha = 1.5$. However, different values have been reported in other literature [24,25], and $\alpha = 1.5$ was only attained under limited conditions. Furthermore, the acceleration exponent for small-scale explosions varied over the range of $\alpha = 1.2$–1.5, because this exponent depends on the intensity of the diffusional-thermal instability as well as the enhancement of hydrodynamic instability [10,26]. The results of the acceleration exponent as evaluated from numerous theoretical and experimental studies remain inconclusive for practical applications from the viewpoint of industrial safety. Nevertheless, the acceleration exponent is very useful for evaluating the blast wave generated by deflagrations, because the prediction model for overpressure was suggested based on the self-similarity of a large-scale flame [27,28].

In view of the above considerations, the first objective of the present study is to estimate the critical Peclet numbers Pe_c at which the cracks begin to propagate and Pe_{cl} for the onset of acceleration in an expanding spherical hydrogen-air flame. In particular, we will evaluate the dependency of Pe_{cl} on Ma for a broad range of Ma values. The second objective is to provide further experimental information on the associated acceleration exponent and the fractal excess for hydrogen-air flames and thereby understand self-similar propagation. In this experimental investigation, a constant-pressure chamber is used to investigate the cellular structure and self-similar propagation of expanding spherical flames in hydrogen-air mixtures at elevated pressures.

Experimental and computational specifications

Fig. 1 shows that the experimental system consists of a high-pressure combustion chamber with total volume of 0.79 L, a high-speed schlieren photography system, and an ignition system. Experiments were conducted in a combustion

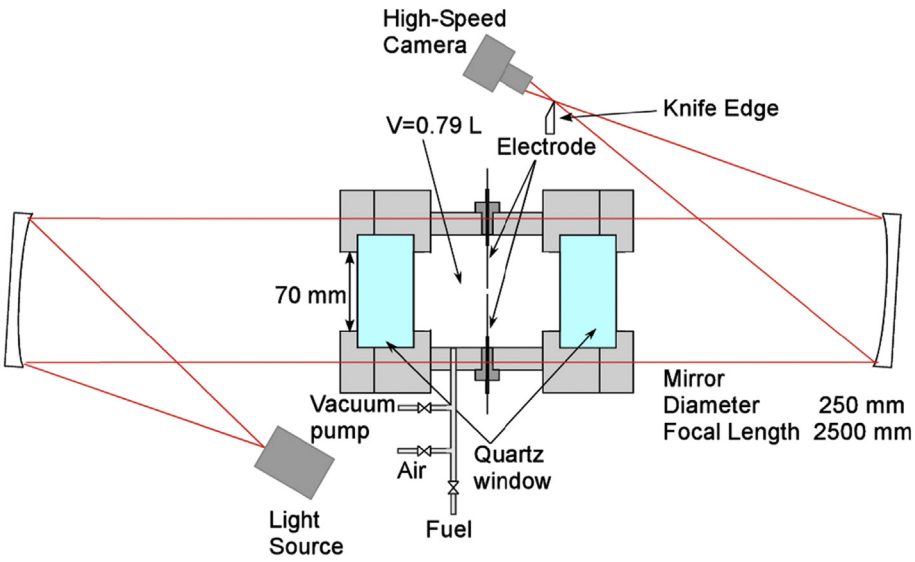

Fig. 1 – Schematic of experimental setup.

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