Combustion and Flame 171 (2016) 112–118

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Morphology and self-acceleration of expanding laminar flames with flame-front cellular instabilities

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ARTICLE INFO

Article history:
Received 23 February 2016
Revised 20 May 2016
Accepted 20 May 2016

Keywords:
Expanding flame
Hydrodynamic instability
Diffusional-thermal instability
Self-similar propagation

ABSTRACT

We report herein experimental observation and mechanistic interpretation of the evolution and self-acceleration of constant-pressure, spherically expanding $H_2/O_2/N_2$ flames, subjected to hydrodynamic and diffusional-thermal instabilities over a wide range of pressure, equivalence ratio and thermal expansion ratio. Results show the existence of three distinct stages of flame propagation affected by the development of the instability cells, namely smooth expansion, transition, and saturated states of cell development. The onset of the instabilities is primarily controlled by the diffusional-thermal instability, while characteristics of the subsequent transition to and maintenance of the saturated state is controlled by the hydrodynamic instability. The acceleration exponent for the fully developed saturated instability is found to be around 1.2–1.4, which is smaller than 1.5, the suggested value for self-turbulization.

1. Introduction

Propagating laminar flames are often subjected to various modes of flame-front instability arising from either intrinsic or external sources. Among the intrinsic instabilities, two of the most common modes are hydrodynamic and diffusional-thermal in nature, which induce cellular structure on the flame-front. The presence of these cells increases the flame surface area and as such could significantly augment the flame propagation speed as compared to that of the smooth flame. Furthermore, the extent of the augmentation could also continuously increase with evolution of the cells over an expanding flame, leading to the possibility of self-acceleration. Mechanistically, hydrodynamic instability sets in through sharp density change across the flame-front and characteristically occurs for either very large or very thin flames, while diffusional-thermal instability is controlled by the imbalance in the diffusivities of heat and the various species. The imbalance is usually characterized by the Lewis number, *Le*, defined as the ratio of the thermal diffusivity of the mixture to its controlling mass diffusivity, such that mixtures with $Le < 1$ favor the onset of the instability, while $Le > 1$ mixtures are stabilizing.

Because of their fundamental significance as well as practical importance as the primary modes of augmented flame propagation, especially within the high-pressure environments of IC engines for which the hydrodynamic instability can be substantially enhanced, there have been extensive studies on these two modes of instability. Among the experimental studies, both large-scale open flames [1–4] and confined flames in combustion vessels [5–9] have been employed. Theoretically, Sivashinsky [10–12], and Matalon and co-workers [13–16] have analyzed the critical conditions for the onset, cut-off limits, and growth rates of the instabilities using both linear and non-linear theories. Experimental investigation of the development of flame-front instability confronts considerable challenges because of the highly transient and multi-scale nature of the phenomena. For example, development of the large hydrodynamic cells in atmospheric flames requires large flame sizes, which not only requires experimentation in large open space, but the resulting large flame is also subjected to considerable buoyant distortion from spherical symmetry and as such renders it difficult to meaningfully define, say, the flame radius. Another potential difficulty, though not specifically addressed, is the need to identify the separate and coupled effects from the hydrodynamic and diffusional-thermal instabilities.

In the present study, we shall employ the well-vetted, dual-chamber, constant-pressure apparatus to conduct spark-ignited, expanding spherical flame experiments in enclosed environments of elevated pressure, which facilitate the development of hydrodynamic cells because of reduced flame thickness. In particular, we shall first suppress effects of diffusional-thermal instability by working with mixtures that are stoichiometric in composition and thereby are diffusionally neutral, and study the evolution dynamics of flames subjected only to hydrodynamic instability, at elevated

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http://dx.doi.org/10.1016/j.combustflame.2016.05.017
0010-2180/

Table 1
List of experimental conditions. ϕ: equivalence ratio; T_f: adiabatic flame temperature; P: pressure; X_{H_2}, X_{O_2}, X_{N_2}: mole fractions of H_2, O_2 and N_2 respectively; σ: thermal expansion ratio; Le_{eff}: effective Lewis number of the mixture. Initial temperature is 298(±2) K.

ϕ	T_f (K)	P(atm)	X_{H_2}	X_{O_2}	X_{N_2}	$\sigma(\pm 0.03)$	Le_{eff}
0.6	1600	5	0.1667	0.1389	0.6944	4.92	0.4
0.6	1700	1–5	0.1818	0.1515	0.6667	5.18	0.4
0.6	1800	1–5	0.1974	0.1645	0.6382	5.47	0.4
0.6	1900	5	0.2105	0.1754	0.6140	5.71	0.4
1.0	1600	5	0.1681	0.0840	0.7479	4.92	≈1
1.0	1700	1–10	0.1818	0.0909	0.7273	5.18	≈1
1.0	1800	1–10	0.1970	0.0985	0.7044	5.47	≈1
1.0	1900	5	0.2094	0.1047	0.6859	5.71	≈1
1.5	1600	5	0.2479	0.0826	0.6694	4.92	1.7
1.5	1700	1–10	0.2691	0.0897	0.6413	5.18	1.7
1.5	1800	1–10	0.2899	0.0966	0.6135	5.47	1.7
1.5	1900	5	0.3093	0.1031	0.5876	5.71	1.7

pressures. We shall then fold in the presence of diffusional-thermal instability by studying off-stoichiometric mixtures, and identify its separate and coupled effects on the development of the instability cells. The specific issues of interest are the parametric boundaries for the onset of the instabilities, the possible existence, nature and extent of self-acceleration, and an assessment of the possible attainment of the state of self-turbulization.

We shall now first present the experimental and computational specifications of the present investigation, which is followed by the presentation and discussion of the various experimental components aiming to provide insight and answer to the above issues of interest.

2. Methodology

2.1. Experimental details

Details of the constant-pressure, dual-chambered apparatus, in which a mixture of fuel, oxidizer and inert is filled at required concentration ratio and pressure, and then centrally ignited producing a spherically expanding flames, are described in Refs. [17,18]. Mixtures of hydrogen, oxygen and nitrogen were used. The experimental conditions, listed in Table 1, are so chosen that they cover a wide range of the parametric space, including the equivalence ratio ϕ(various H_2/O_2 ratios), adiabatic flame temperature T_f (various N_2/O_2 ratios), and pressure P. The evolution of the flame-front morphology was recorded by a high-speed Schlieren image system, with the highest sampling rate of 15 kHz at 600pix × 600pix, yielding the instantaneous flame radius $R(t)$, defined as $R = \sqrt{A/\pi}$, where A is the area of the 2D-projection of the flame, and the subsequent instantaneous flame speed, based on the burned mixture, as $S_b(t) = dR/dt$. Details of the image processing are in Ref. [8]. To avoid the effects of ignition and chamber confinement, data processing was limited to flames with radii between 5mm and 20 mm, the latter being 30% of the chamber size.

2.2. Computational specifications

The fundamental parameters, namely the (downstream) laminar flame speed ($S_{b,0}$), flame thickness (δ), adiabatic flame temperature (T_f), and thermal expansion ratio (σ) for the planner laminar flame at the experimental conditions were calculated by simulating the 1D planar flame using the Chemkin-Pro Software and the H_2/O_2 kinetics model of Burke et al. [19]. The Lewis number is given by $Le = Le_{H_2} < 1$, ≈ 1, and $= Le_{O_2} > 1$ for lean, stoichiometric, and rich mixtures, respectively. Flame thickness (δ) was calculated based on temperature profile using the relationship, $\delta = (T_f - T_0)/(dT/dx)_{max}$, where T_0 is the initial temperature and $(dT/dx)_{max}$ the maximum temperature gradient. The laminar flame speed ($S_{b,0}$) and flame thickness (δ) values for the experimental conditions are listed in the Appendix.

3. Flame-front evolution and self-acceleration

3.1. Evolution dynamics of hydrodynamic instability

We first study the evolution dynamics for flames affected mainly by hydrodynamic instability, accomplished by suppressing the diffusional-thermal instability by working with stoichiometric mixtures ($T_f = 1800$ K) whose Le is close to unity. The intensity of the hydrodynamic instability is varied by changing the system pressure, and thereby the flame thickness. The measured downstream flame speeds of the burned mixture, S_b, at different radii and pressures are plotted in Fig. 1(a) and clearly show substantial increase in the flame speed as the flame expands. Figure 1(I–IV) also shows that, for the same flame radius, flames at higher pressures are highly wrinkled and hence more cellularly unstable.

Figure 1(a) further shows that at the lower pressure of 1 atm, S_b barely exhibits any acceleration, while at 2.5 atm, S_b starts to accelerate significantly after reaching a certain radius. At the higher pressure of 5 atm, the flame exhibits three stages: starting with a relative constant flame speed, followed by large acceleration, and then mild acceleration. Furthermore, at the highest pressure of 10 atm, only the latter two stages are observed as upon ignition the flame immediately starts propagation with large acceleration and then settles to mild acceleration.

To conduct a rational interpretation of the data shown in Fig. 1(a), we first recognize that there are three factors affecting the burning rate of the flame with increasing pressure, namely the increase in the density and thereby the amount of mass needed to be processed by the propagating flame, the increase in the chemical reactivity with increasing concentration and hence pressure, and the increase in the surface area due to the flame-front wrinkling. To systematically investigate the influence due to these three factors, and eventually isolate the influence due to the instability effect, we first note that since the fundamental parameter indicating the burning rate of a flame is the density-weighted flame speed instead of the flame speed itself, Fig. 1(b) plots this quantity, the mass burning rate ($\rho_b S_b$), which then clearly shows that the flame indeed has larger mass burning rate at higher pressures, as should be. This density-weighting effect has been amply demonstrated for laminar flames, with the understanding that the laminar burning rate, namely the density-weighted flame speed, is the proper rate parameter indicating the efficiency with which a flame consumes the reactive mixture.

To (largely) eliminate the influence of increased chemical reactivity, we plot in Fig. 1(c) the normalized flame speed $\overline{S_b} = S_b/S_{b,0}$, where $S_{b,0}$ is the unstretched, laminar flame speed, so that effects