Combustion and Flame 194 (2018) 419–425

Contents lists available at ScienceDirect

Combustion and Flame

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

Self-acceleration and global pulsation in hydrodynamically unstable expanding laminar flames

Jialong Huo[a], Abhishek Saha[b], Zhuyin Ren[a,*], Chung K. Law[a,b,**]

[a] Center for Combustion Energy, Tsinghua University, Beijing 100084, China
[b] Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544, USA

ARTICLE INFO

Article history:
Received 19 March 2018
Revised 11 May 2018
Accepted 22 May 2018

Keywords:
Self-acceleration
Hydrodynamic instability
Global pulsation
Expanding laminar flame

ABSTRACT

The cellularly unstable laminar flame is of fundamental and practical interest because of its intrinsic ability to accelerate without any external sources, as demonstrated previously for the spherically expanding flame. In this work, enriched physical insights and useful quantitative data on the subject phenomena are obtained by employing stoichiometric $H_2/O_2/N_2$ flames and focusing on the individual roles of pressure, P, and the burned flame temperature, T_b, on the flame speed acceleration. Specifically, we first demonstrate that the propagation speed of the self-accelerating cellularly unstable flames at various pressures, including the state of the critical radius at which the flame becomes unstable, can be collapsed by plotting the flame speed, normalized by the planar flame speed, versus the normalized radius, or the Peclet number. Furthermore, through experiments with reduced burned flame temperature achieved by increasing the amount of N_2 in air, the normalized flame speed with lower T_b is found to be larger than that with higher T_b. We have also found that instead of continuing with steady acceleration after its attainment, the unstable flames exhibit a global pulsatory acceleration mode in that stages of strong and weak acceleration are cyclically repeated. Mechanistically and confirming results from previous studies, while the flame is globally expanding, the local cascading process in the cellular structure could cause phases of faster and slower growth in the surface area. Such an intermittent local burning rate or flame speed consequently translates to oscillatory global propagation, even after global averaging, due to nonlinear coupling. The frequency and acceleration exponent of the pulsatory multi-stage acceleration are also determined, with the latter slightly smaller than the critical value of 1.5 suggested for self-turbulization.
© 2018 The Combustion Institute. Published by Elsevier Inc. All rights reserved.

1. Introduction

Cellular instabilities through either the Darrieus–Landau (DL), hydrodynamic instability or the diffusional-thermal (DT) instability wrinkle an otherwise smooth laminar flame-front, and consequently increase the total flame surface area and through it the global flame propagation speed. Such an increase is inherent to the internal structure of the (laminar) flame propagation without any external disturbance such as turbulence. Since the continuous evolution and increase in the number of cells and thus total surface area could induce acceleration of the wrinkled flame, even in the absence of confinement, this phenomenon has been referred to as *self-acceleration*. Indeed, it has been suggested that the continuous acceleration could even lead to self-turbulization of the laminar flame, and eventually to supersonic propagation as a possible mechanism of deflagration-to-detonation transition (DDT) [1]. As such, fundamental understanding of the evolution of the wrinkled flame through intrinsic flame-front instability leading to self-acceleration is an essential feature of flame dynamics.

Mechanistically, the DL instability occurs through sharp density gradient across the flame-front, and is facilitated either for large flame dimensions or at high pressures, under which the flame segments are much thinner than the hydrodynamic scale of the flow field. On the other hand, the DT cellular instability is controlled by the imbalance in the diffusivities of the thermal and species transport, whose influence can be conveniently measured through a global Lewis number (Le), defined as the ratio of an effective thermal diffusivity to an effective mass diffusivity between the deficient reactant and the inert, which usually exists in abundance. In particular, DT cellular instability is promoted for $Le < 1$ mixtures and is suppressed otherwise. There have been substantial theoretical advances on the study of cellular instabilities, for example in [2–7], involving both linear and nonlinear theories that lead to an-

* Corresponding author at: Center for Combustion Energy, Tsinghua University, Beijing 100084, China.
** Corresponding author at: Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544, USA.
E-mail addresses: zhuyinren@tsinghua.edu.cn (Z. Ren), cklaw@princeton.edu (C.K. Law).

https://doi.org/10.1016/j.combustflame.2018.05.025
0010-2180/© 2018 The Combustion Institute. Published by Elsevier Inc. All rights reserved.

alytical expressions for the various instability parameters, such as the onset, cut-off limit and growth rate of the instabilities. Corresponding experimental advances, however, have been relatively less, particularly on systematically acquired quantitative data. Furthermore, they have been performed either on large-scale, openly propagating atmospheric flames, which are invariably subjected to strong buoyancy and as such distortion from spherical symmetry [8,9], or on laboratory expanding spherical flames in closed vessels [10–16], which limit the flame size, the maximum operational pressure, as well as the inherent transiency of the chamber pressure if the chamber is of constant volume.

In this study, a systematic experimental investigation on flame-front instability in expanding spherical flames has been performed for a substantially larger observation range together with sharper images and faster recording rates, obtainable in a newly constructed dual-chamber, constant-pressure, spherical flame chamber. Furthermore, in order to sharpen the scope of the present investigation, we have focused on the role of the hydrodynamic instability only, by working with diffusional neutral ($Le \approx 1$), stoichiometric H_2 flames, especially at elevated pressures. Such conditions would suppress the DT instability while enhance the DL instability. Consequently, we have further quantified the initiation and the subsequent transition of smooth flames to full-fledged cellular flames. We have also observed the phenomenon of global pulsation of the propagation speed, arising from the nonlinear averaging of the local variation in geometry of the cellular flame fronts, and the related local burning rates. In this regard we note that a global pulsation phenomenon has been reported in large-scale flames of *meters* in dimension at ambient pressure for propane flames and hydrogen flames [17,18], with the increase of the flame velocity following a pattern of self-similar oscillatory growth, caused by the periodic growth and saturation of a narrow range of length scales following each generation of cell formation. Worthwhile as they are, it was nevertheless noted that buoyancy [19] and radiation [20] effects could be significant in such large-scale flames, especially for the fact that buoyant flow could also impart its own periodicity into the phenomena. Furthermore, since both propane/air and hydrogen/air mixtures exhibit strong preferential diffusion effects, the potential intermingling of hydrodynamic and diffusional-thermal cells could cause considerable uncertainty in the interpretation of the results. Such potential complications are avoided in the present investigation by working with the near-equidiffusive, high-pressure, small and fast-burning flames that not only promote stronger hydrodynamic instability [21] but they also minimize and indeed practically eliminate the omnipresent buoyancy effects. It is also noted that such a global pulsation phenomenon was implicitly embedded in the plots of some previous simulations [22–26], although its significance and mechanistic origin were not recognized until the recent DNS work of [27]. We are therefore pleased to report our experimental investigation of this potentially important phenomenon, with well-controlled system parameters, yielding results of high physical and quantitative fidelity needed for further studies.

In the following, we shall sequentially present the experimental details of the investigation, the experimental results and related discussions.

2. Experimental setup and conditions

The experiments were performed in a constant-pressure, dual-chamber vessel, with the inner chamber diameter of 250 mm and the maximum observable flame radius of 50 mm, which is substantially larger than those of previous chambers with reported maximum flame radius up to 25 mm [12–15]. Details of this apparatus and the experimental procedure are described in Ref. [28]. The combustible pre-mixture in the inner chamber was centrally spark-ignited, resulting in an outwardly expanding flame, whose evolution and morphology were captured using high-speed Schlieren imaging recorded with a digital camera (Photron Fastcam SA-Z) at 20,000 frames per second (fps) and 1024×1024 pixel^2 resolution. The measured instantaneous flame radius, $R_f(t)$, defined as $R_f = \sqrt{A_f/\pi}$, where A_f is the area of the 2D-projection of the flame, was subsequently used to calculate the instantaneous flame speed of the burned mixture, as $S_b = dR_f/dt$. To minimize/eliminate ignition and confinement effects, we have only used experimental data within the range of 5 mm $\leq R_f \leq$ 50 mm. It is noted that large flame radius and high temporal resolution of the images are critical in capturing some of the features of the cellularly unstable flames reported in the sequel.

Since we are interested in the evolution of hydrodynamic cellular instability, we have studied only diffusionally neutral ($Le \approx 1$) flames, obtained by using stoichiometric ($\phi = 1$) hydrogen flames, whose effective Le is close to unity. Furthermore, recognizing that the intensity of the hydrodynamic instability is influenced by the pressure, P, and the burned flame temperature, T_b, the individual effects of P and T_b on flame-front instability are investigated with the experimental conditions in Group 1 and Group 2, respectively, in Table 1. For the conditions in Group 1, air is used as the oxidizer

Table 1
Experimental conditions and fundamental parameters (P: pressure; ϕ: equivalence ratio; T_b: flame temperature; σ: expansion ratio; $S_u{}^0$ and $S_b{}^0$: planar laminar flame speed of the unburned and burned side respectively; δ_f: planar laminar flame thickness; X_i: mole fractions of species i, $i = H_2$, O_2, N_2). The initial temperature of the unburnt mixtures, T_u, is 298 K.

Experimental conditions Group 1

Mixture	P (atm)	T_b (K)	σ	$S_u{}^0$ (cm/s)	$S_b{}^0$ (cm/s)	δ_f (mm)
H_2/air	1	2361	7.92	212.2	1552	0.351
	1.5	2391	8.02	211.1	1456	0.211
	2	2402	8.06	208.2	1442	0.143
	3	2413	8.10	200.9	1397	0.087
	4	2396	8.04	191.5	1313	0.067
	5	2427	8.14	186.0	1298	0.052

Experimental conditions Group 2

Mixture	P (atm)	X_{H_2}	X_{O_2}	X_{N_2}	T_b (K)	σ	$S_u{}^0$ (cm/s)	$S_b{}^0$ (cm/s)	δ_f (mm)
$H_2/O_2/N_2$	3	0.212	0.106	0.683	1900	6.38	75.1	431	0.147
		0.227	0.113	0.660	2000	6.71	96.5	575	0.126
		0.242	0.121	0.637	2100	7.05	121	753	0.115
		0.258	0.129	0.613	2200	7.38	149	960	0.107
		0.275	0.137	0.588	2300	7.72	179	1197	0.093
		0.296	0.148	0.556	2400	8.10	200.9	1397	0.087

Download English Version:

https://daneshyari.com/en/article/6593510

Download Persian Version:

https://daneshyari.com/article/6593510

Daneshyari.com