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Proceedings of the Combustion Institute xxx (2014) xxx–xxx

Proceedings of the Combustion Institute

www.elsevier.com/locate/proci

Experimental investigation of Darrieus–Landau instability effects on turbulent premixed flames

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Abstract

The turbulent propagation speed of a premixed flame can be significantly enhanced by the onset of Darrieus–Landau (DL) instability within the wrinkled and corrugated flamelet regimes of turbulent combustion. Previous studies have revealed the existence of clearly distinct regimes of turbulent propagation, depending on the presence of DL instabilities or lack thereof, named here as super- and subcritical respectively, characterized by different scaling laws for the turbulent flame speed.

In this study we present experimental turbulent flame speed measurements for propane/air mixtures at atmospheric pressure, variable equivalence ratio at Lewis numbers greater than one obtained within a Bunsen geometry with particle image velocimetry diagnostics. By varying the equivalence ratio we act on the cut-off wavelength and can thus control DL instability. A classification of observed flames into sub/supercritical regimes is achieved through the characterization of their morphology in terms of flame curvature statistics. Numerical low-Mach number simulations of weakly turbulent two-dimensional methane/air slot burner flames are also performed both in the presence or absence of DL instability and are observed to exhibit similar morphological properties.

We show that experimental normalized turbulent propane flame speeds S_T/S_L are subject to two distinct scaling laws, as a function of the normalized turbulence intensity U_{rms}/S_L, depending on the sub/supercritical nature of the propagation regime. We also conjecture, based on the experimental results, that at higher values of turbulence intensity a transition occurs whereby the effects of DL instability become shadowed by the dominant effect of turbulence.

Keywords: Premixed turbulent flames; Bunsen flames; Darrieus–Landau instability; Turbulent propagation speed; Flame curvature

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1. Introduction

The search for a universal scaling law for the turbulent propagation speed of premixed flames is still debated and systematically complicated by the wide scatter of experimental results, often

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http://dx.doi.org/10.1016/j.proci.2014.07.060

Please cite this article in press as: G. Troiani et al., *Proc. Combust. Inst.* (2014), http://dx.doi.org/10.1016/j.proci.2014.07.060

due to the strong dependence from experimental conditions [1–3], and by a general disagreement with proposed theories.

In the context of flame–turbulence interaction, the presence of intrinsic Darrieus–Landau (DL) hydrodynamic instabilities, especially when the incident turbulence is weak, were recognized as an important factor influencing the propagating characteristics of flames [4–6]. A number of experimental studies were performed [7–13] with emphasis on the role of DL instability. Although no final quantitative agreement yet exists on such role [1], there is mounting evidence that the bifurcative transition to DL instability greatly influences turbulent flame morphology and dynamics, hinting at the existence of a multiplicity of scaling laws for the turbulent propagation speed.

In a laminar scenario [14,15] a planar flame transitions, upon onset of DL instability, to a typical large scale cusp-like corrugated conformation steadily propagating at a speed substantially greater than the unstretched laminar flame speed S_L. Recently, in a series of numerical studies by Creta and Matalon [16–19], it was found that in a turbulent scenario a similar dichotomy persists. Thus, an originally laminar and stable planar flame will remain statistically planar, defining a *subcritical* turbulent mode (or regime) of propagation, whereas an unstable flame in the presence of turbulence will exhibit a more complex corrugation, with sharp cusps protruding into the burnt mixture, hence defining a *supercritical* turbulent mode in which DL effects are dominant. For each mode of propagation, such studies highlighted the presence of clearly distinct scaling laws for the turbulent speed S_T, expressed in the form $S_T/S_L \sim (U_{rms}/S_L)^n$, with U_{rms} the intensity of the turbulent field in terms of the r.m.s. of velocity fluctuations. In particular, indicating the two modes with subscripts *sub, sup* it was observed that (*i*) $(S_T/S_L)_{sup} > (S_T/S_L)_{sub}$ owing to increased flame corrugation leading to a DL-enhancement of the turbulent speed, (*ii*) scaling exponents are subject to $n_{sup} < n_{sub}$ indicating that the supercritical mode is less sensitive to turbulence, and (*iii*) DL effects are overpowered by the increasing wrinkling at high turbulent intensities, with the scaling exponent n reverting back to values similar to subcritical behavior.

A rather similar scenario was recently proposed by Chaudhuri [20] where a limiting condition was identified at which turbulence suppresses the effects of DL instability. If, however, DL instabilities can develop in weaker turbulence, then two distinct scaling laws for the turbulence speed, derived through spectral closure techniques and self similarity arguments, indeed emerge.

In this work we present experimental evidence for the above general dual behavior for turbulent flame speed, induced by the presence or absence of intrinsic DL instabilities. We adopt a $D = 18$ mm diameter propane–air Bunsen flame at atmospheric pressure and variable equivalence ratio ϕ and variable inflow turbulence intensity equipped with particle image velocimetry (PIV) diagnostics. Results are supported by two dimensional low-Mach number direct numerical simulations of methane–air turbulent Bunsen flames, performed to investigate the morphological differences between subcritical and supercritical modes of propagation.

2. Determination of stability limits

We defined super/subcritical turbulent regimes as flame propagation modes characterized respectively by the presence or absence of DL instability. Figure 1 displays Mie scattering images of propane–air Bunsen flames, subject of the present investigation, qualitatively illustrating the morphological differences of such propagative modes. We note smooth convex/concave wrinkling in the subcritical regime as opposed to sharp cusp-like protrusions towards the burnt mixture typical of DL corrugation which characterizes the supercritical regime. A general guideline is thus needed to discriminate between such regimes and possibly control their onset as a function of the independent parameters available in the context of an experimental setting.

Given a characteristic hydrodynamic length L, representative of the transverse dimension of the flame or device producing it, a planar laminar flame can become unstable to disturbances of long wavelength λ if stabilizing effects, of thermal diffusive nature, are insufficient to the extent of decreasing the critical (cut-off) disturbance wavelength λ_c below L so that $\lambda_c < \lambda < L$. Increasing the pressure or driving the mixture composition towards stoichiometric conditions can indeed reduce the flame thickness and thus the Markstein length, which is of the same order, and which in turn decreases λ_c thus promoting instabilities. In the context of the hydrodynamic theory of premixed flames the linear stability analysis of a planar flame yields asymptotic dispersion relations [21–23] in the form of truncated series expansions in powers of the transverse wavenumber $k = 2\pi/\lambda$, expressing the disturbance growth rate $\omega(k)$. As shown in [14], simplified Markstein-type flame models can yield a closed form dispersion relation yielding similar qualitative results. Such models generally retain corrective diffusive effects only in the flame speed expression $S_f = S_L - \mathscr{L}\mathbb{K}$, where S_f is defined as the speed relative to the unburnt mixture and where $\mathscr{L}$ is the Markstein length and $\mathbb{K}$ is the flame stretch. The closed form dispersion relation yields a cut-off disturbance wavelength, defined at $\omega = 0$ (see bold continuous and dashed lines in Fig. 2), which

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