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Effect of unsteady stretching on the flame local dynamics☆

F. Zhang, T. Zirwes, P. Habisreuther, H. Bockhorn*

Engler-Bunte-Institute, Division of Combustion Technology, Karlsruhe Institute of Technology, Engler-Bunte-Ring 1, Karlsruhe 76131, Germany

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ABSTRACT

Numerical simulations employing detailed reaction kinetics and transport have been applied to calculate steady-state and harmonically excited laminar hydrogen–air flames with equivalence ratios ranging from fuel-lean to fuel-rich mixtures. The objective is to gain a basic understanding of the influence of unsteady flow stretching on the flame's response. The flame displacement speed and consumption speed have been evaluated, together with stretch, curvature and strain. In the steady-state simulations, a quasi-linear correlation has been obtained for the flame speeds with stretch for a moderate range, which confirms the applicability of the asymptotic relation for small stretch. In the case of unsteady flow conditions, a phase shift is observed between the oscillations of the fluid flow and the flame surface position, indicating a delayed response of the flame to changing flow conditions. The corresponding delay time or relaxation time is found to be depending on the turnover time of the flow oscillations. The flame response in terms of displacement from its steady state location is shown to be dampened at higher excitation frequencies and for flames with large flame transit times τ_{L0}. Due to the delayed response, the local consumption speeds at different phase angles show different dependences on flame stretch. This discrepancy is large for flames in flows excited with lower frequencies as well as equivalence ratios with smaller flame transit times. Also, a larger variation of consumption speeds from different phase angles over flame stretch has been observed for regions with positive stretch, because the internal structure of the flame is altered, leading locally to smaller flame transit times. This explains the large scattering of flame propagation statistics in turbulent combustion, where the flow is characterized by a cascade of interacting vortices with different turnover frequencies. The unsteady effect is quantitatively analysed by comparing the characteristic times of the flame and the flow. In this way, an extension of the Markstein regression has been provided based on the simulation results, giving Ma as a function of the Damköhler number defined by $Da = \tau_{flow}/\tau_{L0} = S_{L0}/\delta_{L0}/f$. Evaluating the consumption speed for different phases during a turnover period of the oscillations and averaging over the period results in a correlation of the averaged Markstein number with the Damköhler number.

1. Introduction

Flame speed is a primordial parameter for the understanding of combustion processes. It can be used to model the burning rate of chemical species or the propagation speed of the flame surface for combustion simulations. It can also be used to predict length, thickness and stability behavior of a flame when designing combustion systems. The flame speed is known to depend not only on the thermo-physical properties of the ignitable mixture but also on hydrodynamic properties such as stretch caused by a strained, non-uniform flow [1,2]. These flow inhomogeneities modify the local balance of chemical reactions and transport processes (convection–diffusion) inside the flame. They occur e.g. in turbulent flames where the flames experience stretch whilst adapting to turbulent fluctuations. The concept of flame stretch is helpful to describe phenomena such as flame propagation, stabilization, extinction or modifications of internal flame structures. A theoretical review of the dynamics of stretched flames is given by Law [3].

Flame stretch is defined as the logarithmic Lagrangian time derivative of the area A of an element on the flame surface:

$$K \equiv \frac{1}{A}\frac{\mathrm{d}A}{\mathrm{d}t} \tag{1}$$

and the stretched laminar flame speed has been derived by means of a first order Taylor approximation for moderate stretch around

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* Corresponding author. Fax: +49 721 608 47770.
E-mail address: henning.bockhorn@kit.edu (H. Bockhorn).

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$S_L(K=0) = S_{L0}$ [4]:

$$S_L(K) \approx S_L(K=0) + \left.\frac{\partial S_L}{\partial K}\right|_{K=0} (K-0) \quad \text{or} \quad \frac{S_L(K)}{S_{L0}} = 1 - \frac{\mathcal{L}}{S_{L0}} K \quad (2)$$

with the flame stretch K, the Markstein Length $\mathcal{L} = -\partial S/\partial K$ and the unstretched laminar flame speed S_{L0}. Eq. (2) can be rewritten as

$$\frac{S_L(K)}{S_{L0}} = 1 - Ma\frac{\delta_{L0}}{S_{L0}}K = 1 - MaKa \quad (3)$$

to include the Markstein number Ma defined as the ratio of the Markstein length and the characteristic flame thickness δ_{L0}

$$Ma = \frac{\mathcal{L}}{\delta_{L0}} = -\frac{1}{\delta_{L0}}\frac{\partial S_L}{\partial K} \quad (4)$$

The Karlovitz number Ka appearing in Eq. (3) is proportional to stretch $Ka = K\delta_{L0}/S_{L0}$. The correlation in Eq. (3) is only valid for small and moderate values of stretch around zero due to the first order estimation from the Taylor series expansion. Although non-linear stretch expressions have been developed in the last years [5], most of them are adopted for the extrapolation of unstretched flame speed from spherically expanding flames. There, effects like heat loss or thermo-diffusive instability are not considered. Also, they are only valid for stretching due to curvature and for positive stretch values and contain the spherical flame radius as the only shape parameter. In the present study, the flame is stretched by both strain and curvature effects, covering the negative stretch range, too. As the aim of the work is to study the transient effect of stretch on flame propagation, a detailed analysis of the non-linear behavior in the range of large Ka is omitted.

By its definition, Ma measures the sensitivity of flame speed to stretch. In particular, Ma can be positive or negative depending on the ratio of thermal and mass diffusion, which is explained by thermal-diffusive instabilities or the effect of the Lewis number Le, respectively [2]. A vast variety of experimental and computational work has been conducted in the last decades regarding the effect of stretch on flame speed [6–13], which justified the asymptotic correlation given in Eq. (3). Most of the previous studies have been concerned with outwardly expanding spherical flames and counterflow flames. The spherical flame is, as mentioned above, only positively curved and the stretch can be evaluated only for a small range of radii of the spherical flame surface with limited data. Extrapolations are then performed to extract Ma and S_{L0}, which lead to additional error sources [5,14]. The opposed counterflow flame is not curved and only tangentially strained [2]. The influence of stretch due to curvature and strain may be investigated with these setups separately. For a realistic flame, however, flame propagation is determined by a combination of stretch caused by curvature and strain. The behavior of flame speed with respect to this overall stretch is not equal to the effect of solely strain or curvature [4]. Also, spherical and counterflow flames are only positively stretched and hence, influence of negative stretch is not considered. Therefore, further studies on the effect of flame stretch are necessary to extend the existing data and to gain a deeper understanding.

Moreover, there is obviously an influence of time history on the flame and its propagation if the flow is unsteady because the flame adjusts itself transiently to the unsteadily stretched flow within a certain relaxation time. This relaxation time depends on the time scale of unsteady fluctuations of the flow and varies at different locations of the flame surface, because the intrinsic structures of the flame are altered locally. In turbulent flows, the effect of specific, isolated time scales of fluctuations on the flame's dynamics cannot be studied, as turbulent eddies fluctuate with a broad-band frequency spectrum and are coherent to each other. The influence of unsteady flow on flame propagation was investigated for one-dimensional, counter-flowing, premixed methane/air and hydrogen/air flames with harmonically excited flow conditions [15–17] and for turbulent methane/air flames from direct numerical simulation (DNS) [18,19]. In all these cases, it was found that the displacement of the flame surface is attenuated at frequencies above the inverse of the flame transit time $\tau_{L0} = \delta_{L0}/S_{L0}$, which corresponds to the time required to cross the flame. Similar computational results have been obtained for one-dimensional and two-dimensional premixed flames placed in a spatially periodic flow in [20], where the average flame propagation speed increases with increasing fluctuation amplitude and wavelength of the imposed flow. In [21], unsteady effects of stretch have been studied for premixed hydrogen/air flames by using two-dimensional DNS, where different levels of turbulence intensity were prescribed to interfere with the flame. The correlation of flame speed—expressed as the consumption speed of fuel—with stretch at moderate turbulence intensities obtained from DNS is shown in Fig. 1 taken from [21] for different equivalence ratios. A large scattering of the flame speed with stretch is discernible so that the asymptotic theory from Eq. (3) seems to be only qualitatively applicable to turbulent conditions. It was further shown for different equivalence ratios that the Markstein numbers descrease as the ratio of turbulent time scale to the flame transit time decreases. The effect of global stretch on the turbulent flame speed is studied in [22] based on measurements of expanding flames in a fan-stirred bomb vessel. A turbulent Markstein number was introduced via the linear analogy for the laminar case, which was shown to be only applicable for weakly curved flames. Otherwise, a non-linear expression should be used to describe the experimental data. In all of the referenced work, a distinct influence of unsteady stretching on the

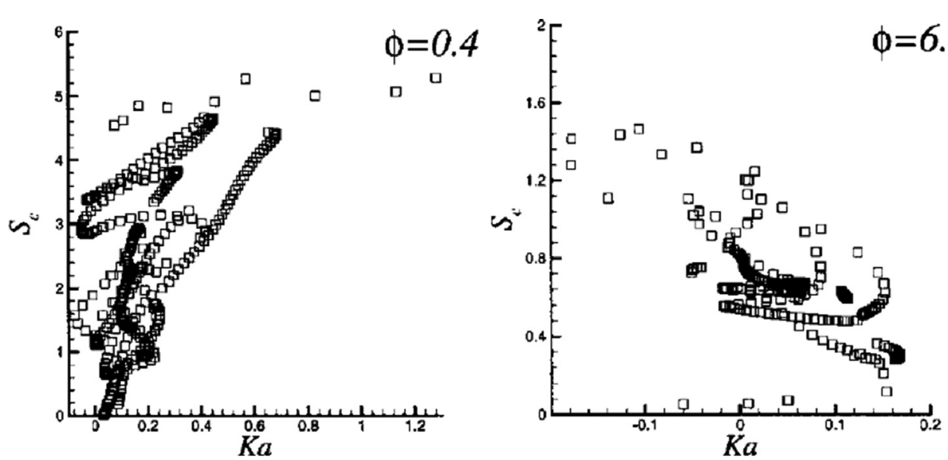

Fig. 1. Correlation of normalized consumption speed with normalized stretch Ka obtained from DNS of turbulent premixed hydrogen–air flames (taken from [21]).

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