Combustion and Flame 196 (2018) 237–248

Contents lists available at ScienceDirect

Combustion and Flame

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

Predicting the consumption speed of a premixed flame subjected to unsteady stretch rates

Meysam Sahafzadeh[a], Seth B. Dworkin[a,*], Larry W. Kostiuk[b]

[a] Department of Mechanical and Industrial Engineering, Ryerson University, 350 Victoria St., Toronto, Ontario M5B 2K3, Canada
[b] Department of Mechanical Engineering, University of Alberta, 116St. and 85 Ave., Edmonton, AB T6G 2R3k, Canada

ARTICLE INFO

Article history:
Received 7 April 2018
Revised 16 June 2018
Accepted 18 June 2018

Keywords:
Laminar premixed flames
Transient response
Stretch rate
Consumption speed
Burning rate
Frequency response analysis

ABSTRACT

The stretched laminar flame model provides a convenient approach to embed realistic chemical kinetics when simulating turbulent premixed flames. When positive-only periodic strain rates are applied to a laminar flame there is a notable phase lag and diminished amplitude in heat release rate. Similar results have being observed with respect to the other component of stretch rate, namely the unsteady motion of a curved flame when the stretch rates are periodic about zero. Both cases showed that the heat release rate or consumption speed of these laminar-premixed flames vary significantly from the quasi-steady flamelet model. Deviation from quasi-steady behavior increases as the unsteady flow time scale approaches the chemical time scale that is set by the stoichiometry. A challenge remains in how to use such results predictively for local and instantaneous consumption speed for small segments of turbulent flames where their unsteady stretch history is not periodic.

This paper uses a frequency response analysis as a characterization tool to simplify the complex nonlinear behavior of premixed methane air flames for equivalence ratios from 1.0 down to 0.7, and frequencies from quasi-steady up to 2000 Hz using flame transfer functions. Various linear and nonlinear models were used to identify appropriate flame transfer functions for low and higher frequency regimes, as well as extend the predictive capabilities of these models. Linear models were only able to accurately predict the flame behavior below a threshold of when the fluid and chemistry time scales are the same order of magnitude. Other proposed transfer functions were tested against arbitrary multi-frequency stretch inputs and were shown to be effective over the full range of frequencies.

1. Introduction

Understanding turbulent combustion is important due to its common occurrence in industrial applications such as internal combustion engines and furnaces. The challenges related to predicting turbulent combustion behavior have been discussed extensively in terms of their time-dependent and multidimensional nature, as well as having a large range of hydrodynamic time and length scales interacting with these scales of the chemistry [1]. That said, the formulation of these problems is well-posed by a system of partial differential equations and algebraic constraints that represent the conservation of mass and energy, as well as considerations of momentum and individual species while being subjected to convection, diffusion, and chemical reaction. All these phenomena are captured in direct numerical simulations with appropriate boundary conditions, but their solutions, due to these equations being highly nonlinear and strongly coupled, come at a significant computational cost [2], and thereby create the need for model-level understanding.

The focus of this paper is on premixed combustion in the Damköhler and Karlovitz regimes where reaction occurs in identifiable flame structures that are locally subjected to unsteadiness in the flow. The objective of this paper is to further develop a model of a flame for the practical purpose of capturing the impact of unsteadiness on the rates of conversion from reactants to products. To be explicit, no consideration is given here to spatial variations of composition or temperature along a flame, which can be another important characteristic of turbulent flames that are not perfectly mixed.

Important insights into the relevance of this problem can be gleaned from considering simpler non-turbulent situations of prescribed unsteady or periodic hydrodynamics to interact with a flame. Aldredge [3,4] considered a flow field under the condition of weak flame stretch to analyze the dependency of turbulent premixed burning velocity on the intensity of flow velocity fluctuations. It was concluded that at least part of the "bending effect,"

* Corresponding author.
E-mail address: seth.dworkin@ryerson.ca (S.B. Dworkin).

https://doi.org/10.1016/j.combustflame.2018.06.021
0010-2180/

which is normally seen in premixed combustion occurring in high-intensity turbulence [5], results from local flame stretch modifying the local consumption speed. For a better understanding of the relationship between flame surface advection and the intensity of flow excitation, Aldredge [6] studied the advection of a flame front in a transient periodic flow (spatially and temporally) where different levels of turbulent intensity of flow perturbations were considered analytically and numerically. In recent research, Aldredge [7], has studied the flame surface and burning rate increase due to wrinkling by analyzing the effect of multiscale periodic transient flow on isothermal-flame propagation. It was concluded that flames behave differently in low, intermediate and high intensities. In Aldredge's work, due to the restriction of transient flame surface growth, the local normal propagation speed was kept constant and equal to the adiabatic planar flame (laminar flame speed). These results were consistent with those obtained in earlier investigations, but also showed that flames behave differently in low, moderate, and high velocity fluctuations. It was also confirmed that the unsteady stretch rate effects and transient response of laminar flames should be considered in non-DNS turbulent modeling of flames.

It has been suggested that the transient response of stretched flames in turbulent combustion could be captured through an overall Markstein number, modified with the frequency and flame transit time [8]. This approach only seeks to estimate the overall turbulent flame speed while foregoing any information of the local and inhomogeneous rates of heat release, and it is unclear if it can address the challenges of operating across the spectrum of frequencies previously observed.

A conceptual modeling approached that allows for estimation of local burning rates with pre-calculated complex chemistry is based on flamelets, which when summed together collectively represents a turbulent flame. In their classical premixed form, flamelets provide a local consumption speed of the flame (referenced to their reactant state), which are generally assumed to be local planar structures subjected to a specified steady strain rate and of fixed reactant composition. (This consumption speed, S_L, is the rate mass is converted from reactants to equilibrium products per unit area of flame, and divided by the density of the reactants, and can readily be converted to the local heat release rate per unit flame area knowing the enthalpy of reaction.) The validity of these assumptions has been challenged in terms of the response of laminar flames to changing positive strain rates [9], or mixture composition fluctuations [10]. Key observations for these planar flames included that the flame responded in a quasi-steady manner at low frequencies, but at high frequencies the burning rate response became significantly attenuated, as well as having a phase lag. Clavin and Joulin showed that in high frequency, the flame behavior is universal (regardless of Lewis number) [11]. Sahafzadeh et al. [12] showed the same results occur when flame stretch was created through the motion of a curved flame where both positive and negative transient stretch rates were applied. As a result, within an unsteady flow, classical flamelet models would predict the wrong magnitude of local burning, and any expected maxima or minima events would occur at the wrong time. Lastly, an alternate approach to reduce the computational load of complex chemistry is to use reduced chemistry and simple transport properties. It has been found that the transient response of a stretched flame is not necessarily captured accurately due to the change in the internal flame structure [13].

In the current work, the approach is to model the full chemistry and then estimate the instantaneous local consumption speed by a frequency response analysis in the form of a flame transfer function using the local stretch history as the input. The broader concept using a transfer function in combustion has been used to study flame instabilities [14]. Linear [15] and non-linear [16] frequency response analyses of laminar [17] and turbulent [18] premixed flames have been considered. The motivation of the aforementioned works were to describe the flame response to flow velocity perturbations as a flame transfer function in order to study and model flame instabilities due to acoustic waves. In [19], the transfer function is defined by the ratio of the normalized flame area to velocity fluctuations. In theoretical studies, such as [20], a *G*-equation was used to characterize the flame front by its mean and perturbation components. Then solving by Laplace transforms the frequency response was obtained.

Thermo-acoustic instabilities have been studied using a nonlinear describing function (instead of a linear flame transfer function), which was determined experimentally [16]. The flame response was estimated as a function of frequency and amplitude of perturbation acting on the combustion region. It was concluded that nonlinear mechanisms dominate the dynamics of real systems and gave a better representation of the flame dynamics. Therefore, linear and nonlinear flame transfer functions or flame describing functions have been widely used to study the flame instability in turbulent combustion. In these functions, the input was considered to be velocity fluctuations and output was usually heat release.

Although the mathematical approach is similar to that of instability analysis, in this study the frequency response analysis was obtained based on detailed numerical simulations of laminar premixed flames in order to connect stretch rate to local consumption speed in unsteady situations. Frequency response analysis provides simple closed mathematical relations that can replace large portions of the system of partial differential equations used in direct numerical simulations. Transfer functions are also independent of the form of the input excitations; therefore, the system response can be developed on one set of inputs (*e.g.*, sinusoidal) and then used for any arbitrary inputs such as step functions, ramp functions, or the unsteadiness of turbulence.

2. Frequency response analysis

To create a useful transfer function from a frequency response analysis, consideration needs to be given to the input and output of the transfer function. Within the context of premixed turbulent flame modeling in the flamelet regime, the goal is often to represent the flame as an interface with burning rates that vary over the surface depending on local conditions. For example, basic flamelet libraries are used to assign a consumption speed to an element of the flame depending on its equivalence ratio and stretch rate. Since one of the goals of the current work is to better account for the unsteadiness in turbulent flames, which includes unsteadiness in stretch rate, the input to the transfer function was chosen to be the varying stretch rate and the output is the varying local consumption speed. By choosing stretch rate, the transfer function is expected to be independent of the geometry that creates it, and therefore applicable to flamelets of a turbulent flame.

The numerically modeled flame used to produce the results for this frequency response analysis has been previously reported in the combustion literature [12], and is therefore only briefly described here. Figure 1 shows the one-dimensional laminar premixed flame that was simulated in a cylindrically symmetric geometry. Reactants of methane and air of a specifiable equivalence ratio flow radially outward from the inlet boundary ($r = 5$ cm) and through the outlet boundary ($r = 11$ cm). The mean and fluctuating components of the inlet mass flow rate were specified so that all the chemical reactions occur within the domain and are well removed from the boundaries. The model is based on a finite volume approach for solving the discretized equations for mass, momentum, energy, and species. The thermodynamic and transport properties come from CHEMKIN, and the reaction mechanism is based on GRI 3.0 involving 36 species and 219 reactions.