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Transient response of a laminar premixed flame to a radially diverging/converging flow

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ABSTRACT

Laminar flamelets are often used to model premixed turbulent combustion. The libraries of rates of conversion from chemical to thermal enthalpies used for flamelets are typically based on counter-flow, stained laminar planar flames under steady conditions. The current research seeks further understanding of the effect of stretch on premixed flames by considering laminar flame dynamics in a cylindrically-symmetric outward radial flow geometry (i.e., inwardly propagating flame). This numerical model was designed to study the flame response when the flow and scalar fields align (i.e., no tangential strain on the flame) while the flame either expands (positive stretch) or contracts (negative stretch, which is a case that has been seldom explored) radially. The transient response of a laminar premixed flame has been investigated by applying a sinusoidal variation of mass flow rate at the inlet boundary with different frequencies to compare key characteristics of a steady unstretched flame to the dynamics of an unsteady stretched flame. An energy index (EI), which is the integration of the source term in the energy equation over all control volumes in the computational domain, was selected for the comparison. The transient response of laminar premixed flames, when subjected to positive and negative stretch, results in amplitude decrease and phase shift increase with increasing frequency. Other characteristics, such as the deviation of the EI at the mean mass flow rate between when the flame is expanding and contracting, are non-monotonic with frequency. Also, the response of fuel lean flames is more sensitive to the frequency of the periodic stretching compared to a stoichiometric flame. An analysis to seek universality of transient flame responses across lean methane–air flames of different equivalence ratios (i.e., 1.0–0.7) using Damköhler Numbers (i.e., the ratio of a flow to chemical time scales) had limited success.

1. Introduction

Numerical simulation of turbulent combustion has significance in practical devices, such as industrial furnaces, stationary gas turbines, aero-combustors or internal combustion engines. In particular, premixed turbulent combustion is a canonical case for the reactant state of some practical combustion systems, such as HCCI (Homogeneous Charge Compression Ignition) engines. The modeling of such systems is a challenging task due to the unsteady, multi-component and multidimensional nature, and the large range of length and time scales of these flows. These complexities have been discussed in the literature as part of the accurate determination of the rate of conversion of reactants to products, and the sensitivity of the turbulent flame speed to the geometry of the flame [1].

To decouple the small-scale chemistry from large-scale flow features, premixed turbulent flames have often been viewed as ensembles of premixed laminar stretched flames that are wrinkled and potentially torn by the turbulent flow field, in the so-called 'flamelet' approach [2]. The local burning characteristics have been calculated from strained laminar flames as a function of equivalence ratio, pressure, temperature, and strain rate [3], but without consideration of potential impacts of spatial gradients of these quantities over the flame surface or any temporal gradient. The effect of strain rate on the laminar premixed flame has been examined by many studies (e.g., [4]) and it has been shown how different phenomena can affect local burning rates when small sections of the turbulent flame experience a range of strain rates and curvatures locally [5].

Stretch rate (κ) as a mechanism to affect the rate of combustion was first introduced by Karlovitz et al. [6] as the Lagrangian time (t) derivative of an element of the flame surface area (A) as in Eq. (1).

$$\kappa = (1/A)(dA/dt) \quad (1)$$

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In that work, a planar combustion wave, exposed to a velocity gradient, was analyzed, while the impact of the motion of curved flame fronts normal to itself was first discussed by Markstein [7]. The combination of these two effects; namely, the underlying hydrodynamic strain and the flame surface curvature effects on an *interface* have been expressed as stretch rate [8, 9]. Matalon [8] introduced an expression (Eq. (2)) for calculating stretch rate of a flame in an arbitrary shape on the flame surface indicating by the function $F(X,t)=0$.

$$\kappa = \{v_f \nabla.\boldsymbol{n} - \boldsymbol{n}.\nabla \times (\boldsymbol{V} \times \boldsymbol{n})\}_{F=0} \tag{2}$$

where $\boldsymbol{V}$ is the fluid velocity, $\boldsymbol{n}$ is the local normal to the flame front and parallel to the gradient in the scalar field (local normal is considered positive when pointing from reactants to products), v_f is the speed of an identifiable flame surface feature and thus can be the local flame speed in laboratory coordinates. The first term on the right hand side of Eq. (2) represents the flame curvature effects and results from the divergent/convergent flow field and motion of the flame in that flow field. The second term illustrates the tangential strain rate and results from a non-uniform flow field across a scalar field of the flame. The summation of these two terms creates an equivalence between the strain and curvature effects, but that is strictly true only for an interface, while flames of a finite thickness and multiple scalar species add uncertainty to this equivalence and introduce some unique challenges regarding which interface to consider [10, 11].

In counter-flow configurations, due to the planar flame shape, the divergence of the scalar field ($\nabla.\boldsymbol{n}=0$) becomes zero and subsequently the first term in Eq. (2) is eliminated; however, misalignment of flow and scalar fields (($\boldsymbol{V} \times \boldsymbol{n}) \neq 0$) results in a non-zero value for the second term. Therefore, the laminar premixed flame in this geometry is strained. A time-dependent investigation in this geometry was performed by Saitoh and Otsuka [12] for both premixed and diffusion flames numerically and experimentally. They varied the velocity normal to the stagnation plane sinusoidally around its mean. They concluded that the positional amplitude of temperature and concentration fluctuations decreased with increasing oscillation frequency. In a similar work, Stahl and Warnatz [3] carried out a numerical investigation on the transient response of strained flamelets. They studied the influence of time-dependent sinusoidal change of strain rate on the flame front behavior. The dependence of flame oscillation amplitude and phase shift with frequency of the strain rate was analyzed and it was concluded that the amplitude of flame position oscillation decreases and the phase shift increases with an increase in frequency.

These studies showed that in a counter-flow configuration, the response of a strained flame to a periodic change in flow velocity and strain rate is not instantaneous, implying limitations in validity of the quasi-steady laminar flamelet assumption in premixed turbulent modeling. As part of this endeavour, Petrov and Ghoniem [13] revisited the validity of this assumption by analyzing the transient response of premixed methane–air laminar flames to both stepwise and periodic changes in strain rate over a range of Lewis numbers and flame temperatures. They concluded in a flamelet model, the response of laminar premixed flames can be considered instantaneous for two conditions. First, over the entire range of Lewis number only for high flame temperatures, and second, intermediate flame temperature when Lewis number equals unity. Thus, for low and intermediate flame temperatures and non-unity Lewis numbers, the model could be modified to reflect the lag between flow and flame.

The above investigations were concerned with transient response of strained flames, while fewer studies have been concerned with the effects of curvature. Giannakopoulos et al. [14] numerically studied the effect of flame curvature by using spherically outwardly propagating flames. This geometry has also been used extensively to study the influence of flow rate on stabilized [15] and flame–stretch interactions in premixed flames (e.g. [16]). In this geometry, due to the alignment of flow and scalar fields, the tangential strain rate (the second term in Eq. (2)) is null, but the flame is stretched because of the motion of the curved flame. In this condition, flame stretch varies with time as the flame propagates outward and has a positive value at all times.

In premixed turbulent combustion, the local flame experiences both positive and negative stretch. Kostiuk and Bray [5] studied the distribution of stretch rates on the flamelet surface, it has been shown that in an outwardly propagating spherical flame, 30–50% of the flame is under compression (i.e., negative stretch rates) at any time. Therefore, modeling the region of negative stretch rates in terms of consumption velocity and analyzing the mean effects of stretch rate on conversion from reactants to products is of importance. However, as mentioned previously, the geometry considered in the literature to analyze the flamelets, namely, counter-flow flame configurations, only involves positive stretch.

In this paper, through the consideration of an inwardly-propagating premixed cylindrical flame that is forced to radially expand and contract, a numerical investigation has been made to revisit the quasi-steady assumptions for laminar flamelet models when the flame is subjected to both positive and negative stretch. Furthermore, since the flame stretch in this work is due to the motion of a curved flame, the second term in Eq. (2) is zero and the effects of tangential strain are eliminated. Finally, in order to study the effect of equivalence ratio on transient response of a laminar flame to a periodic flow, two fuel lean flames are compared with the stoichiometric condition.

In premixed turbulent combustion, the time-varying vortices stretch the flamelets and cause small curvature on flame fronts; therefore, generating libraries to describe the flamelets based on steady laminar stagnation point flames (planar strained flames) has been challenged in some ways [17]. One of these challenges is related to the instantaneous structure of a turbulent flame where the flame front includes positive stretch and negative stretch at certain locations. The planar strained flames, which are only positively stretched, are not capable of describing the concave curved flame fronts towards the fresh gases. As it has been mentioned earlier, most premixed turbulent flames involve negative stretch and highly curved flame fronts, therefore, to generate a more rigorous flamelets library to model a premixed turbulent flame, in addition to a counter-flow configuration, one needs to include the time-dependent motion of a curved flame. The model that has been proposed and developed in this paper enables us to study this aspect of flamelets and include the negative stretch in the computations of a laminar premixed flame.

2. Model description

It was desired to create one-dimensional radially (cylindrical) outward flow of a pre-mixture of CH_4 and air (O_2 and N_2) of specifiable composition and temperature, as depicted in Fig. 1. The mass flow rate of reactants ($\dot{m}$) was imagined to occur along the axial coordinate (Fig. 1-a) and then be distributed radially outward through a porous cylinder with characteristics to create a uniform diverging flow. It is at the exit plane of the porous cylinder that the computational domain begins. The computational domain ends at the inflow surface of a larger concentric porous cylinder where the identical mass flow is extracted. The system is assumed to be of sufficient axial length and neglecting of gravity that flow that is one-dimension in the radial direction is obtained, and independent of the axial or azimuthal coordinates.

When the computational domain (grey area in Fig. 1-b) is filled with the gas mixture, it is ignited and a cylindrical flame (red dotted lines in Fig. 1-b) forms between the inlet and outlet