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Response of flame thickness and propagation speed under intense turbulence in spatially developing lean premixed methane–air jet flames ☆

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ABSTRACT

Direct numerical simulations of three-dimensional spatially-developing turbulent Bunsen flames were performed at three different turbulence intensities. The simulations were performed using a reduced methane–air chemical mechanism which was specifically tailored for the lean premixed conditions simulated here. A planar-jet turbulent Bunsen flame configuration was used in which turbulent preheated methane–air mixture at 0.7 equivalence ratio issued through a central jet and was surrounded by a hot laminar coflow of burned products. The turbulence characteristics at the jet inflow were selected such that combustion occured in the thin reaction zones (TRZ) regime. At the lowest turbulence intensity, the conditions fall on the boundary between the TRZ regime and the corrugated flamelet regime, and progressively moved further into the TRZ regime by increasing the turbulent intensity. The data from the three simulations was analyzed to understand the effect of turbulent stirring on the flame structure and thickness. Statistical analysis of the data showed that the thermal preheat layer of the flame was thickened due to the action of turbulence, but the reaction zone was not significantly affected. A global and local analysis of the burning velocity of the flame was performed to compare the different flames. Detailed statistical averages of the flame speed were also obtained to study the spatial dependence of displacement speed and its correlation to strain rate and curvature.

1. Introduction

In many practical applications for power generation, such as stationary gas turbines, there has been a strong interest in achieving lean premixed combustion. The advantages of operating at lean mixture conditions are high thermal efficiency and low emissions of NOx due to lower flame temperatures. Lean premixed combustion tends to be different from combustion at stoichiometric conditions in certain key aspects. For example, lean flames tend to be thicker and propagate more slowly due to the lower flame temperature. A thicker flame is more susceptible to disruption and stirring by the small scale eddies of turbulence. Similarly, the turbulent velocity fluctuations can have a higher impact due to the lower flame speed. For these reasons, the influence of turbulence on premixed flame propagation is expected to be different at lean conditions compared to stoichiometric conditions.

Traditionally, the phenomenal description and modeling of turbulent premixed flames has been based on the ratio of the turbulence scales to the characteristic flame scales. In the regime where the flame time scale is shorter than the entire range of turbulence time scales, the chemistry and turbulence do not interact and hence can be decoupled. Such a flame can be represented by a locally thin and one-dimensional flamelet. However, when the flame is thicker and the relative turbulence intensity higher, as could be expected in lean premixed combustion for the reasons mentioned above, the small eddies of turbulence can enter the

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flame structure. Peters [1] has provided a model for flame propagation in the regime where the turbulence scales are capable of penetrating and influencing the preheat zone, but are incapable of penetrating the reaction zones. This regime is called the thin reaction zones (TRZ) regime.

Premixed flame structure consists of a broader preheat layer upstream of a narrower reaction layer. Usual modeling approaches for the TRZ regime assume that the turbulent eddies can enter and influence the preheat layer and that the reaction zone, being an order of magnitude thinner than the preheat layer, is not penetrated. The assumption of an order of magnitude disparity in the thickness of the preheat layer versus the reaction layer is based on theoretical analysis of the flame structure using activation energy asymptotics. It is customary to define the preheat layer thickness based on the maximum thermal gradient and the reaction layer thickness based on the full width at half maximum of heat release rate. In practical fuels such as methane–air, especially at lean and preheated conditions, the preheat layer is only around two to three times wider than the reaction layer. It needs to be determined if the reaction layer indeed stays intact in the entire TRZ regime despite the fact that it is not as thin as commonly assumed.

There are several outstanding questions on the response of flames in the TRZ regime that remain to be answered definitively. First, it is not clear whether the flame dynamics in this regime are dominated by the entrainment of small eddies into the flame structure or the large scale flow straining which does not alter the flame structure. The penetration of the local flame structure by small eddies is expected to cause thickened flames in the TRZ regime [1,2]. However the competitive effect of the large scale structure is expected to thin the flame. Thus, it unclear whether flames are thicker or thinner in the TRZ regime. Several experimental studies in this regime have reported [3,4] thicker flames, while others have reported thinner flames [5,6].

A more important quantity of interest is the burning velocity of turbulent premixed flames, both from fundamental understanding and modeling perspectives. One important question [7] encountered in premixed combustion is, “how fast can we burn?”. In an attempt to quantify and model the influence of turbulence on premixed combustion, a premixed flame is treated as a surface separating the fresh reactants and burnt products. This allows the influence of turbulence on combustion to be distinguished into two important phenomena – (i) an increase in the flame surface area within the same volume through wrinkling and aerodynamic straining of the flame and (ii) a change in the burning rate of the flame per unit surface area with respect to a laminar flame. Based on this concept, a model for the turbulent burning velocity has been suggested by Bray [8], Candel and Poinsot [9]. In this model, the mean turbulent burning velocity can be written as,

$$S_{\mathrm{T}} = S_{\mathrm{L}} \cdot I_0 \cdot A', \tag{1}$$

where S_{L} is the laminar burning velocity, I_0 is the efficiency factor to account for change in burning velocity per unit area and A' accounts for the increase in surface area. Formulating turbulent burning velocity in this manner allows models to be derived for the two contributing factors, I_0 and A'. For example, one can model the change in burning velocity per unit area of the flame, I_0, based on a laminar strained flame and then account for the increase in flame surface area through a flame surface density model [10]. An improved understanding of the relative contribution of I_0 and A' on the burning velocity in the TRZ regime is required. Also, the physical mechanisms and relative contributions of flame surface area generation and flame surface burning efficiency needs to be understood for improving premixed combustion models in the TRZ regime. This is made possible through the ability to perform high fidelity direct numerical simulations (DNS) of turbulent premixed flames in statistically stationary configurations that allows quantitative and converged statistics of the relevant quantities to be extracted.

Here, 3D fully-resolved DNS of turbulent premixed combustion are performed in a spatially-developing slot-burner Bunsen flame configuration with a detailed methane–air chemical mechanism. The first simulation from this study was published in Ref. [11] along with a study of the flame structure and thickness. This study was later expanded to a series of three simulations in the TRZ regime at successively higher turbulence intensities as part of a parametric study. In this paper, we publish those three simulations along with data analysis. The slot jet flame configuration chosen is one of the many configurations that can be used to simulate a stationary premixed flame. Dunstan et al. [12] have compared the influence of the configuration geometry on flame speed statistics using three canonical configurations, namely freely propagating planar flames, stagnation flow planar flames and rod-stabilized V-flames. Their results show that the burning velocity will have a strong dependence on the flame geometry, which itself would depend on the orientation of the shear and flow divergence with respect to the flame surface. The data presented in this paper using a slot jet configuration provides statistics in the presence of strong mean shear that is aligned in roughly the same direction as the mean flame brush. There is also a strong spatial dependence of the flame characteristics due to the downstream development of the jet. Due to these characteristics, the jet configuration chosen in this DNS study and also by Bell et al. [13] are the closest to laboratory premixed jet flames.

The paper is organized as follows. Sections 2 and 3 presents the problem configuration and numerical method used in the study. This is followed by results and discussions in Section 4 where the data is analyzed to obtain statistical measures of the influence of turbulence on flame structure. In particular the effect of turbulent strain on preheat layer thickness and the integrity of the reaction layers are studied. Also statistical measures of the influence of turbulence on the burning velocity of the flame are presented. The contribution to the burning rate due to wrinkling of the flame (A') and the enhancement of burning rate per unit surface area (I_0) are determined. Then, the response of the flame surface displacement speed to strain rate and curvature are studied.

2. Problem configuration

The simulation was performed in a slot-burner Bunsen flame configuration. The slot-burner Bunsen configuration is especially interesting due to the presence of mean shear in the flow and is similar in configuration to the burner used in experimental studies, for example by Filatyev et al. [14] and numerical simulated using DNS by Bell et al. [13]. Aside from the similarity in configuration, the parameter space explored in this work is quite different since that flame is within the flamelet regime while the present work is in the TRZ regime. This configuration consists of a central reactant jet through which premixed reactants are supplied. The central jet is surrounded on either side by a heated coflow, whose composition and temperature are those of the complete combustion products of the reactant jet. This arrangement is similar to the pilot flame surrounding slot burners commonly used in experiments [14]. The reactant jet was chosen to be a premixed methane–air jet at 800 K and $\phi = 0.7$. The unstrained laminar flame properties at these conditions computed using PREMIX [15] are as follows:

1. Flame speed, $S_{\mathrm{L}} = 1.8$ m/s.
2. Thermal thickness based on maximum temperature gradient, $\delta_{\mathrm{L}} = 0.3$ mm.