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Characterization of extinction/reignition events in turbulent premixed counterflow flames using strain-rate analysis

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Abstract

We investigate extinction/reignition events in two contrasting turbulent premixed flames of the Yale turbulent counterflow flame (TCF) burner, that are both qualitatively and quantitatively different. One of the two chosen flames is a high-burning (HB) flame with a low probability of local extinction while the other flame is a low-burning (LB) flame with a high probability of local extinction. In recent work, we successfully studied the turbulent premixed flames of the Yale TCF burner using the large-eddy simulation/probability density function (LES/PDF) methods. In this present study, the main motivation is to investigate how the compositional structure of the two turbulent flames are related to that of laminar flames. To this end, steady, one-dimensional, strained, opposed-jet laminar flame calculations are performed to investigate the effect of strain rates K on the laminar counterparts of HB and LB, and to evaluate the extinction strain rates S_{ext} for the two flames. Subsequently, a normalized distance Z is defined in terms of the mixture fraction ξ, which is calculated based on the mass fraction of N_2. The scatter plots from the particle data of (a) CH_2O mass fraction $Y^*_{CH_2O}$ *vs.* progress variable p^* and (b) temperature T^* *vs.* the normalized distance Z^* are quite different for the two flames with more samples close to the extinguished laminar profile for the LB flame than for the HB flame. The cell-mean profiles of T *vs.* Z resemble the laminar profiles at different strain rates even though the LES/PDF are non-trivially 3D and unsteady. These cell-mean profiles are used to evaluate the instantaneous equivalent steady strain rate (ESSR) S for the two flames. The cumulative distribution function (CDF) of S, conditional on $S < S_{ext}$ (i.e., burning samples), is somewhat similar, with the distributions being broad without a peak close to the bulk strain rate. However, comparatively, more samples of the LB flame have the ESSR values above the extinction strain rate, i.e., $S > S_{ext}$. The scatter plots of the ESSR S *vs.* the fresh product layer thickness Δ_f quantify the thinning of the product layer as the strain rate S increases.

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The scatter for the HB flame follow the corresponding laminar profile quite closely, whereas, the thicknesses observed for the LB flame are higher compared to its laminar prediction.

Keywords: Large-eddy simulation; Probability density function methods; Turbulent premixed counterflow flames; Extinction/reignition; Strain rate

1. Introduction

Turbulent counterflow flames (TCFs) have garnered significant attention in recent years in the combustion community studying turbulence-chemistry interactions due to their many advantages, including, the achievement of high Reynolds numbers, the realization of a range of combustion regimes from stable to local extinction/reignition, and the fact that they are more compact than jet flames [1–3]. The main motivation of computational studies on TCFs has been to test the underlying models for their validity and accuracy across a broad range of flame con ditions [4–7].

Recently, we successfully applied the large-eddy simulation/probability density function (LES/PDF) methodology [8–10] to study turbulent premixed flames of the Yale TCF burner under various conditions that were previously studied experimentally [11,12]. The turbulence-chemistry interactions of the turbulent premixed flame with the counterflowing hot stoichiometric combustion products were investigated by comparing revealing conditional statistics from the simulations to those from the experiments. We found excellent agreement between the LES/PDF simulations and experiments for different flame conditions ranging from fully burning to nearly extinguished [12]. Furthermore, we investigated the LES/PDF equations in the direct numerical simulation (DNS) limit [13] by considering two laminar premixed flames. It is shown in [12] that when the conclusions of this DNS limit study are applied to the 3D LES/PDF simulations of the turbulent premixed counterflow flames, the calculated flame speed is close to the corresponding laminar flame speed for the observed mixing rate. This observation likely explains the success of the models.

In this present work, we consider two contrasting turbulent premixed flames from this LES/PDF computational study that are very different, qualitatively and quantitatively, to investigate the extinction/reignition events in more detail. The first flame is a high-burning (HB) flame with a low probability of extinction whereas the second one is a low-burning (LB) flame with a high probability of extinction. The main aim of the present work is to investigate the extent to which the compositional structure of the turbulent flames is related to that of strained laminar flames. This is achieved by examining the particle data on the centerline from the unsteady, 3D LES/PDF simulations and comparing the cell-mean profiles of temperature T to the corresponding profiles from steady, 1D, strained, opposed-jet laminar flame calculations.

Previous laminar flame calculations in the opposed-jet configuration have been performed [2,4,14,15] to shed light on the behavior of their turbulent counterparts. A similar approach to that employed in the current work was employed in the previous works [2,4], wherein the scatter plots of species and temperature from the experiments of turbulent partially premixed methane/air flame are compared to laminar flame profiles at different strain rates. The conditional mean of the experimental data from the scatter plots of species and temperature is well represented by a strained laminar flamelet. It is also observed that close to extinction, the measured scatter is closer to the laminar flamelet with the extinction strain rate.

The remainder of the paper is organized as follows. In Section 2, a brief description of the experimental study of the Yale TCF burner is provided, followed by a brief description of our previous LES/PDF computational study. We then draw attention to the two turbulent premixed flames studied in the present work. In Section 3, the focus is on differentiating the two turbulent premixed flames by analyzing the particle data from the LES/PDF simulations. The conclusions from the study are drawn in Section 4.

2. Yale turbulent counterflow flame (TCF) burner in the premixed mode

2.1. Yale/Sandia experimental study

The experimental configuration [11] consists of two coaxial opposed nozzles placed at a distance d apart. The top stream is a fresh, cold reactants stream of homogenous premixed $CH_4/O_2/N_2$ mixture with equivalence ratio ϕ_u at turbulent Reynolds number Re_t and unburnt temperature $T_u = 294$ K. The bottom stream consists of hot stoichiometric combustion products with measured temperature T_b, which is below the adiabatic flame temperature. The turbulent reactants stream then interacts with the counterflowing hot stoichiometric product stream to form a turbulent premixed