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Proceedings of the Combustion Institute 000 (2016) 1–8
Proceedings of the Combustion Institute
www.elsevier.com/locate/proci

Effects of equivalence ratio variations on turbulent flame speed in lean methane/air mixtures under lean-burn natural gas engine operating conditions

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Received 3 December 2015; accepted 5 September 2016
Available online xxx

Abstract

Direct numerical simulations (DNS) of turbulent premixed methane/air flames are carried out to investigate the effects of equivalence ratio on the turbulent flame speed in lean mixtures. Turbulent flames are simulated as statistically stationary following a Lagrangian framework using an inflow–outflow configuration. The inflow velocity is dynamically adjusted at run-time to stabilize the flame brush location within the computational domain. Linear forcing is applied inside the unburned mixtures to maintain the turbulent intensities at desired levels. For the same turbulence properties, several equivalence ratios near the lean limit are selected and it is shown that the normalized turbulent flame speed is a function of the equivalence ratio. Velocity and length scales of the imposed turbulence are then selected in such a way that the Karlovitz and Damköhler numbers remain constant for flames of different equivalence ratios. Simulations are run for more than 80 eddy turnover times and the turbulent flame speed is derived by averaging the inflow velocity. The results show that equivalence ratio does not have an explicit effect on the normalized turbulent flame speed above the lean limit. Analysis of flame surface area shows that surface wrinkling generated by eddies of different scales is not affected by variation in equivalence ratios when the Karlovitz and Damköhler numbers are fixed. Furthermore, flame surface generated by large-scale eddies is independent of the Karlovitz and Damköhler numbers. Examining the flame surface statistics, it is shown that the flame surface normal is preferentially parallel to the most compressive strain rate direction for all equivalence ratios.

Keywords: DNS of turbulent premixed flames; Premixed flame speed; Lean-burn; Natural gas engines

1. Introduction

In recent years, natural gas has received increased attention as an alternative fuel source for internal combustion engines employed in transportation and power generation applications. It is

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http://dx.doi.org/10.1016/j.proci.2016.09.011
1540-7489 © 2016 by The Combustion Institute. Published by Elsevier Inc.

known that natural gas produces 25–30% less carbon emissions per unit energy than conventional fuels [1,2]. Lean-burn natural gas engines are particularly attractive because of their potential of lower NO_x emissions and enhanced thermal efficiency compared to engines operating under stoichiometric conditions. However, due to the presence of equivalence ratio variations inside the engine chamber, misfire can occur especially under lean-burn conditions. It is therefore important to understand how flame propagation is dependent on equivalence ratio near the lean limit.

Flamelet-based models are one of the most widely used models in modeling premixed turbulent combustion. For example, the G-equation model is based on the premise that the premixed turbulent flame could be represented by the isosurface of a scalar field G [3,4]. The instantaneous flame front, assumed to be infinitely thin, is represented by an isosurface of the scalar quantity G at $G \equiv 0$. In the transport equation for G, turbulent flame speed S_T is used to model the global effects of turbulence on enhancing chemical reaction rates through flame surface augmentation and enhanced transport. The use of a single variable S_T greatly simplifies the modeling by eliminating the stiff chemistry source terms. Indeed, by assuming *á priori* closure for the turbulent flame speed, multidimensional simulations have been carried out in rather complex geometries such as bombs [5], SI engines [6,7] and industrial burners [8,9]. It is important to note that several definitions of turbulent flame speeds exist. To avoid ambiguity, in this paper we will define turbulent flame speed as the velocity at which the unburned mixture enters the flame zone in the direction normal to the mean flame front. Numerous correlations for S_T have been proposed in the past and a majority of the existing correlations involves the ratio of turbulence intensity to laminar flame speed ($u_{\rm rms}/S_L$) [8, 10–12]. Dependencies of S_T on the ratio of the length scales (L_o/δ_L), or alternatively the Damköhler number (Da) have also been reported [8,12]. Here, S_L and δ_L denote the flame speed and flame thickness of an unstrained laminar flame, respectively, while $u_{\rm rms}$ and L_o represents the root-mean-square of turbulent velocity fluctuations and the integral length scale, respectively.

The effects of equivalence ratio (ϕ) on S_T normalized by the laminar flame speed S_L are still not well understood. This understanding is of importance in lean-burn engines where fluctuations in equivalence ratios can be consequential on engine performance and where efficiency and emissions considerations require operation as close to the lean limit as possible. Specifically, it is not known whether the equivalence ratio effect is exerted only through its effect on the laminar flame speed S_L and flame thickness δ_L. Limited work has been carried out to characterize the equivalence ratio effects. Bell et al. performed "2D" DNS of premixed methane flames at equivalence ratios $\phi = 0.55$ and 1.00 [13]. They found a change in the Markstein number as ϕ is varied which, in turn, modified the turbulent flame speed. Fru et al. carried out DNS of premixed methane-air flame kernels subjected to various turbulence intensities at five equivalence ratios [14]. They observed that for a fixed value of $u_{\rm rms}/S_L$, S_T/S_L varies with equivalence ratios. However, neither of the two works has taken into account the effects of length scales, i.e., L_o/δ_L. In addition, the studied flames are subjected to decaying turbulence which introduces ambiguity into the definition of $u_{\rm rms}/S_L$.

In this work, we set out to investigate the influence of equivalence ratio on the turbulent flame speed using DNS. By forcing the turbulence inside the fresh mixtures, we ensure that the premixed flame is interacting with non-decaying turbulence such that velocity and length scale ratios between the flow field and flame are clearly defined and held invariant. The rest of the paper is organized in the following manner. Section 2 discusses the numerical methods, chemistry mechanism and the simulation setup. Section 3 presents the results of turbulent flame speed at various equivalence ratios. The explicit influence of ϕ on S_T is examined. Characterization of flame surface generated by turbulent eddies of various scales is also performed. The effects of flow strain rates with respect to the flamelet are discussed. The paper then closes with summary and conclusions in Section 4.

2. Computational setup

2.1. The numerical model

The results presented in this work are obtained using the in-house low-Mach code HOLOMAC (High-Order LOw-MAch number Combustion) [15]. It solves the 3D conservation equations for multi-component mixtures with CHEMKIN interface for computing the chemical source terms. Spatial discretization is performed using a 6th-order implicit compact scheme [16]. The convection terms are advanced in time using a 2nd-order Adams–Bashforth (AB2) scheme while the diffusion terms are advanced using an explicit 4-step Runge–Kutta–Chebyshev (RKC) method. The divergence condition is enforced using a projection–correction method, i.e., at each time step, the hydrodynamic pressure is solved from a variable-coefficient Poisson equation using Fast Fourier Transform (FFT) and is used to correct the provisory velocity.

It is well known that DNS with multi-step chemistry is computationally intensive. In this work, a 13-species reduced mechanism developed by Sankaran et al. (2007) [17] is employed. In addition, the following global chemical mechanism that is able to predict the laminar flame speed is

Please cite this article as: Zhiyan. Wang et al., Effects of equivalence ratio variations on turbulent flame speed in lean methane/air mixtures under lean-burn natural gas engine operating conditions, Proceedings of the Combustion Institute (2016), http://dx.doi.org/10.1016/j.proci.2016.09.011