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

Analysis of turbulent flame propagation in equivalence ratio-stratified flow

Edward S. Richardson [a,*], Jacqueline H. Chen [b]

[a] *Faculty of Engineering and the Environment, University of Southampton, Room 5103, Building 13, Southampton SO17 1BJ, United Kingdom*
[b] *Combustion Research Facility, Sandia National Laboratories, Livermore, CA 94551-0969, USA*

Received 4 December 2015; accepted 20 June 2016
Available online xxx

Abstract

Equivalence ratio-stratified combustion is an important technology for achieving stable low-emission operation in internal combustion engines and gas turbines. This study examines how equivalence ratio stratification affects the physics of turbulent flame propagation using Direct Numerical Simulation. Three-dimensional simulations of a turbulent slot-Bunsen flame configuration are performed with accurate multi-step kinetic modelling for methane–air combustion. We compare one perfectly-premixed and three equivalence ratio-stratified cases with the mean equivalence ratio gradient aligned with, tangential to or opposed to the mean flame brush. The simulation results are analysed in terms of flame surface area and the burning intensity. The local effects of stratification are then investigated further by examining statistics of the displacement speed conditioned on the flame-normal equivalence ratio gradient. The local burning intensity is found to depend on the orientation of the stratification with respect to the flame front, so that burning intensity is enhanced when the flame speed in the products is faster than in the reactants. This effect of alignment between equivalence ratio gradients and flame fronts has been observed previously in laminar flames and it is found here that it also affects the global behaviour of turbulent flames. The flame surface area is also influenced by equivalence ratio stratification and this may be explained by differences in the surface-averaged consumption rate and differential propagation effects due to flame speed variations associated with equivalence ratio fluctuations.

Keywords: Stratified; Partially-premixed; Direct Numerical Simulation; Displacement speed; Flame surface density

1. Introduction

A wide range of practical combustion devices involve flame propagation in fuel–air mixtures which are not perfectly mixed. This study focuses on equivalence ratio-stratified combustion, in which a flame propagates through an inhomogeneous fuel–air mixture. Understanding and

* Corresponding author.
E-mail addresses: e.s.richardson@soton.ac.uk , e.s.richardson.99@gmail.com (E.S. Richardson).

http://dx.doi.org/10.1016/j.proci.2016.06.140
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predictive modelling for equivalence ratio-stratified combustion physics are important for the design of stratified-charge internal combustion engines as well as lean-burn gas turbine combustion systems.

Turbulent premixed combustion in the flamelet regime involves a propagating flame surface which is distorted by its interactions with the turbulent flow [1]. According to this description, the turbulent flame speed of a homogeneous mixture, S_T, will differ from the laminar flame speed S_L, according to,

$$\frac{S_T}{\langle S_L(\varphi)\rangle_s} = I_0 A' \tag{1}$$

where A' is the ratio of the turbulent flame area $A_{turb.}$ divided by the projected frontal area of the flame, A,

$$A' = \frac{A_{turb.}}{A}, \tag{2}$$

and the burning intensity I_0 is the ratio of the surface-averaged consumption speed to the surface-average of the laminar flame speed based on the local equivalence ratio, $\langle S_L(\varphi)_s\rangle$. The laminar flame speed is surface-averaged in this presentation because, in equivalence ratio-stratified flows, S_L varies depending on the local value of the equivalence ratio, $\varphi(\boldsymbol{x})$. Application of Eq. (1) to stratified combustion raises two distinct questions: first, how does stratification influence the flame surface area in a turbulent flame; and second, how does stratification influence the burning intensity? The objective of this study is to address both of these questions by examining DNS data for turbulent stratified combustion with realistic methane–air chemistry.

Previous theoretical and numerical studies suggest that fluctuations of the local flame speed due to equivalence-ratio stratification provide a mechanism for wrinkling the flame, described as a *differential propagation* [2]. Whether the differential propagation mechanism has a significant impact on the turbulent flame speed depends on the root mean square magnitude of the flame speed fluctuations $S_L{}'/\overline{S_L}$ [3] and the length scale of the equivalence ratio fluctuations [4,5,6]: it has been suggested that differential propagation can be significant if the magnitude of flame speed fluctuations is at least as large as the root mean square magnitude of turbulent velocity fluctuations, $S'_L \gtrsim u'$ [3], and if there is stratification at length scales between the integral scale and the scale where scalar dissipation timescale competes with the flame propagation timescale [7]. However flame surface density-based modelling approaches have been assessed in equivalence-ratio stratified flames and have achieved moderate success without considering effects of differential propagation [8,9]. Malkeson and Chakraborty examined turbulent DNS data for a range of equivalence ratio-stratified combustion conditions and noted that the propagation term accounting for differential propagation remains negligible for the conditions analysed [10].

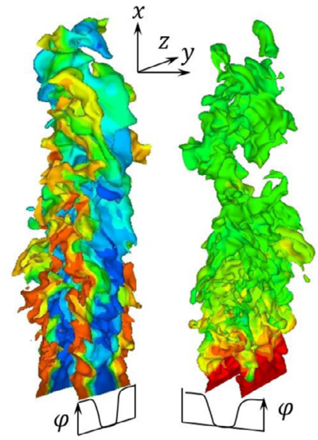

Fig. 1. Isosurfaces of progress variable equal to 0.65 coloured by mixture fraction (blue: $\varphi = 0.41$, red: $\varphi = 1.0$) for case C2 (left) and case C4 (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The effect of equivalence ratio variation on the local burning intensity has not been investigated in turbulent flame simulations with realistic chemistry. It has been found that flame-normal equivalence ratio gradients affect the propagation speed of laminar flames, due to the effect of equivalence ratio gradients on the molecular transport of radical species and hot products into the reaction zone [11]. It has been observed that *back-supported* flames yield higher propagation speed than flames in a homogeneous mixture, and that flames in a homogeneous mixture yield faster propagation speed than *front-supported* flames. The terms back-supported and front-supported describe flames in which the laminar flame speed on the product side of the flame is greater and less, respectively, than in the reactants. The present DNS study examines the impacts of differential propagation and front/back-support effects in turbulent flames simulated with realistic chemistry.

2. Equivalence ratio-stratified DNS

2.1. Simulation configuration

Effects of equivalence ratio stratification on turbulent combustion processes are investigated using Direct Numerical Simulation (DNS). The simulation configuration involves a slot-jet turbulent Bunsen flame that is periodic in the span-wise z-direction (the coordinate system is indicated in Fig. 1). Four cases (C1, C2, C4, C5) are considered that all have a mean equivalence ratio equal to 0.7,