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Turbulent transport in premixed flames approaching extinction

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Abstract

The turbulent transport in premixed flames approaching extinction has been characterised in terms of statistical properties using an opposed jet burner featuring fractal grid generated turbulence. The burner was used in a symmetric twin flame configuration featuring pre-vaporised cyclopentane and JP-10 (exo-tetrahydrodicyclopentadiene) at equivalence ratios of 0.75 and 0.85. The choice of fuels follows from the practical importance of JP-10 as an aviation fuel with cyclic C_5 compounds appearing as breakdown products. The bulk velocity was set to 3.0 m/s resulting in a turbulent Reynolds number of 120. The obtained data includes conditional velocity statistics, flame curvature information and scalar fluxes. The conversion between conventionally and Favre averaged statistics follows the Bray–Moss–Libby theory and the assumption that finite reaction interface thickness effects can be neglected. The impact of deviations from the latter on statistics is explored and results suggest that the effect is modest for interface thicknesses less than 20% of the turbulent flame brush. The experimental data obtained is sufficient to enable terms up to and including triple correlations to be evaluated in closed form. The work also clearly illustrates the rapid transition from non-gradient to gradient turbulent transport as the extinction limit is approached.

Keywords: Fractal grids; Premixed; BML; Opposed jets; Liquid fuels

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1. Introduction

Bilger et al. [1] observe that turbulent premixed combustion is commonly agreed to be inherently complex with increasingly wide application in internal combustion engines, modern gas turbines for power generation and jet engine afterburners [2]. The increased use stems from a desire to reduce emissions while obtaining higher efficiencies. Bray et al. [3] derived the arguably most successful framework (BML) for analysing turbulent premixed combustion on the basis of a statistical description and Bray [4] presented a recent review of the approach. The current contribution considers statistically stationary flames in the context of this framework through experimental measurements using a twin flame opposed jet geometry featuring fractal grid generated turbulence. The

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density segregation technique derived by Goh et al. [5] is used to detect flame iso-contours and to obtain conditional statistics. Opposed jet flames have been used extensively in the past (e.g. [6–10]) and recent contributions include those of Geipel et al. [11], Goh et al. [12,13] and Coriton et al. [14].

The use of fractal grids to generate multiscale turbulence was proposed by Vassilicos and Hunt [15] and subsequently investigated by Hurst and Vassilicos [16] and Stresing et al. [17]. Fractal grids have shown significant promise in generating elevated levels of turbulence while maintaining flows free of bulk instabilities. The ideal grid for the opposed jet configuration was identified by Geipel et al. [11] and found to produce a 100% increase in Reynolds stresses compared to traditional grids with 4 mm holes as used previously by Böhm et al. [18]. Comprehensive statistical information for twin methane and propane flames has also been obtained by Goh et al. [13] using synchronised velocity and scalar statistics to provide conditional dissipation and flow field structure information via conditional Proper Orthogonal Decomposition (CPOD). A revised configuration was used by Goh et al. [12] to study the transition from conventional premixed turbulent JP-10 flames to a Homogeneous Charge Diffusion Ignition (HCDI) [19] related flameless oxidation mode using single JP-10 flames. It was observed that conventional flames ceased to exist after transition to flameless oxidation, with reaction interfaces residing on the instantaneous stagnation plane, similar to flames close to extinction as observed by Kostiuk et al. [6]. Furthermore, a shift from non-gradient to gradient turbulent transport was observed for flames beyond the normal extinction point [12] as the combustion mode shifted to flameless oxidation. Under such conditions, reactant conversion must be supported by hot combustion products emerging from one of the nozzles.

By contrast, the current study considers turbulent transport in flames approaching extinction in a conventional back-to-back twin flame configuration that can more readily be related to conventional premixed turbulent flame theories (e.g. BML). Density segregation methods e.g. [5,12,20], used in the current work, result in flame isocontours one pixel in width. For flames with a broader reaction interface, the probability of detecting a burning mixture may become significant. The effect has been assessed experimentally through comparisons with OH-PLIF [12,21] and the current work provides a further theoretical analysis of the impact on statistics. The approach is based on a stochastic analysis of the impact of the ratio of the flame thickness (δ_f) or, more generally, the instantaneous interface thickness (δ_I) to the turbulent reaction zone (flame brush) thickness (δ_t). The analysis supports the conclusion [12] that the impact on reaction progress variable (c) statistics is negligible under the current experimental conditions. The finding allows direct comparisons of experimental results with theoretical investigations of premixed turbulent flames stabilised in evolving multiscale turbulence. Finally, a set of equations [22] that enable the closed form conversion between conventionally and Favre averaged terms, up to and including triple correlations, on the basis of presented experimental data are reported.

2. Experimental techniques

The turbulent opposed jet configuration corresponds to that of Goh et al. [12] with the exception that the optimal fractal grids identified by Geipel et al. [11] were used in both nozzles in order to produce a twin flame configuration. Impact plates were placed upstream of the fractal grids in order to isolate upstream conditions from grid generated turbulence [23] and hence to simplify the boundary conditions leading to a reduced size of the physical domain required for computational studies. The nozzle exits were one nozzle diameter D (= 30 mm) apart. Twin premixed flames of cyclopentane and JP-10 were investigated using equivalence ratios (ϕ) of 0.75 and 0.85. Flow rates were such that mixtures from each nozzle had a bulk velocity (U_b) of 3.0 m/s (at 298 K). Cyclopentane and JP-10 were heated to 353 K and 473 K, respectively, with nozzle exit temperatures of 333 K and 408 K maintained in order to prevent fuel recondensation.

The flow control system was the same as used by Goh et al. [12] with uncertainties in flow rates $\leqslant$0.8% for each fluid. Flow rates of cyclopentane and JP-10 were metered and vapourised using Bronkhorst CoriFlow M53 and CEM W-303A units with the vapourised fuel stream mixed with air and split equally using two needle valves. Measurements performed using GCMS on the reactant stream using an Agilent 7890A series GC with a 5975C inert MSD/DS Turbo EI Bundle equipped with 60 m DB-1 column have confirmed that no cracking of the fuel takes place. Coflow velocities were set to 0.3 m/s to remove any large scale bulk motion. The reactant streams were mixed further with seeded air within heated hoses, temperature controlled with an accuracy of ±1 K, for about 3 m before being introduced into the nozzles. A digital camera was used to capture the CH chemiluminescence from both flames and measurements performed only when CH intensities were equal.

Particle Image Velocity (PIV) measurements were conducted in 2D using a 120 mJ Solo-New Wave Nd:YAG laser. Both the upper and lower streams were seeded with aluminium oxide particles of about 3 μm diameter with correlation between Mie scattered images calculated using

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