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Conditional analysis of turbulent premixed and stratified flames on local equivalence ratio and progress of reaction

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ABSTRACT

Previous studies on the Cambridge/Sandia stratified burner have produced a comprehensive database of line Rayleigh/Raman/CO LIF measurements of scalars, as well as LDA and PIV measurements of velocity, for flames under non-uniform mixture fraction, under moderate turbulent conditions where the ratio of the turbulent velocity fluctuations to the laminar flame speed is of order 10. In prior work, we applied multiple conditioning methods to demonstrate how local stratification increases the levels of CO and H_2, relative to the corresponding turbulent premixed flame, and enhances surface density function (SDF) and scalar dissipation rate of progress of reaction (SDR), based on extent of temperature rise, at a particular location in the flame where the mixing layer and flame brush cross. In the present study, we examine the global features of selected flames at all locations, by obtaining probability density functions (PDFs) for species concentrations, SDRs, and SDFs, conditioned on local equivalence ratio and location in the flame brush throughout the domain.

We find that for most cases, species profiles as a function of temperature are well represented by laminar flame relationships at the local equivalence ratio, with some deviations attributable to either differential diffusion near the flame base and local stratification effects further downstream where the flame brush crosses the mixing layer. In particular, CO_2 is significantly affected by differential diffusion, and CO and H_2 by stratification. However, the stratification effects on the species are relatively minor when conditioned on local equivalence ratio, a simplifying result in the context of modeling.

Measurements of the gradient of progress of reaction and scalar dissipation rates, conditioned on local equivalence ratio, show that the thermal zone of the flame is thickened by turbulence: the mean SDF and SDR values are in general lower than those of unstrained laminar flames. The effect is greater under rich conditions, with conditional mean SDR decreasing to less than half of the corresponding laminar value. The extent of flame thickening is the same in the premixed as the stratified case, once the stratified measurements are conditioned on the same equivalence ratio.

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1. Introduction

In many practical devices, combustion takes place under turbulent stratified conditions, where fuel and oxidiser are not homogeneously mixed. Such a mixing strategy is often implemented intentionally, in order to extend the lean flammability limits and to achieve flame stability over a wider range of global stoichiometry. A consequence of the strategy is the presence of significant variations in reactant concentrations, which affects the rate of flame propagation and local pollutant formation.

Many experimental and numerical investigations have been undertaken to study turbulent flame propagation through spatially non-inhomogeneous mixture conditions in order to understand the effects of stratification on flame behavior [1–10,11–15]. The observed stratification effects depend strongly on the particular operating conditions (laminar or turbulent) and burner geometry (e.g. V-flame, bluff-body stabilized, piloted, combustion bomb). Under laminar and low turbulence conditions, heat and radicals from burnt richer regions feed the leaner regions, thus increasing the flame resistance to extinction, as demonstrated in laminar experiments and simulations [11,12,16]. A number of low Reynolds number DNS simulations have also demonstrated the effects of stratification on the global heat release rate. The sensitivity to stratification was found to depend on the extent of stratification, turbulence intensity and length scale [17–20]. In general, higher turbulence levels increase strain and lower the relative importance of the equivalence ratio gradients.

A number of test burners with controlled boundary conditions and practically relevant turbulence levels [1–5] have been tailored to study the effect of stratification on flammability limits [6], flame

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thickness [7–9], flame surface density and scalar dissipation rate [7,8], flame propagation speed [6,10], as well as its macro- and microstructure [21,22]. The studies have shown that stratification widens the lean flammability limits relatively to premixed cases [23], and that the mass fractions of CO and H_2 species can be affected [21,22]. Mean effects of stratification on flame surface density [7,8], curvature [8,24], and flame thickness [7–10], are relatively less pronounced. However, a few studies have identified a memory effect, and a corresponding increase in flame propagation rate relatively to premixed conditions [10–13,24].

Recent studies on the structure of stabilized stratified flames provide a suitable database for testing model assumptions. The Darmstadt group produced a turbulent stratified flame series with high levels of turbulence and stabilized by an inner stoichiometric pilot flame. These flames have been studied by Böhm et al. [3], Kuenne et al. [25], and Seffrin et al. [2] using Rayleigh and Raman scattering for scalars, and LDA measurements for velocity. Examining instantaneous temperature profiles and corresponding OH PLIF images, Böhm et al. [3] concluded that the effect of stratification on temperature profiles is secondary to that of the heat transport effect due to the three-dimensional flame geometry. A number of LES simulations continue to be used for comparison to the Darmstadt experimental database to understand the relative effects of stratification, turbulence, and heat transfer [26–28].

The Cambridge/Sandia stratified swirl burner was designed with two purposes in mind: (a) in complement to the Darmstadt burner, to produce a database of scalars and velocities for turbulent numerical model validation, now with a recirculation zone and (in some cases) swirl, and (b) to produce simultaneous scalar *gradient* information that can reveal the microstructure of scalars in premixed and stratified flames. The detailed database of scalars, velocity, and surface temperatures has been extensively discussed in a number of publications [21,22,29–34]. Regarding point (a), the database produced has been recently used for comparison with LES numerical simulations [35–38], providing insight into the potential successes and shortcomings of the various modeling approaches for premixed and stratified flames [39,40]. Mean and rms measurements are available in [41]. In particular, the detailed database led to the discovery that molecular transport has a strong effect on the transport of H_2O and CO_2 near the base of the flame, leading to an accumulation of the latter relatively to the former in recirculation zones [30], a phenomenon subsequently confirmed by simulations [42].

The experimental studies also provided a rich database of the *probability distribution functions* (PDFs) of scalars and their gradients, which has not been sufficiently explored or compared to models, particularly after conditioning on the local equivalence ratio. In many modeling approaches for stratified flames, the two key variables involved are the progress of reaction,c (defined in more detailed further on, but here taken as linearly related to temperature) and the local mixture fraction. In particular, the mean gradient of the progress of reaction, ∇c, denoted by the surface density function (SDF), and the corresponding scalar dissipation rate (SDR), $\chi_c = D\nabla c \cdot \nabla c$, are directly related to the mixing rate and thus to the reaction rate. Sweeney et al. [21,22,29] demonstrated how local stratification affects the SDF and SDR at a particular location in the flame, where the mixing layer and flame brush cross [29]. That study showed that for the same local equivalence ratio, an increase in the local gradient of mixture fraction leads to increased scalar dissipation.

In the present study, rather than considering the very narrow question of the effect of the local gradient of mixture fraction, as was done in [29], we examine the global features of the stratified flame, by analyzing the statistics of species mass fractions, SDR, and SDF, conditioned on local equivalence ratio and location in the flame brush throughout the flame, using the same original dataset. The present paper therefore has the following objectives: (a) to compare the PDFs of state space of the scalars (species and temperature) to that of unstrained laminar flames, conditioned on the local equivalence ratio; (b) similarly, to compare the PDFs of gradients of progress of reaction and scalar dissipation values, conditioned on equivalence ratio, and (c) to compare the resulting PDFs of equivalence ratio and progress of reaction with numerical simulations of Proch and Kempf [37].

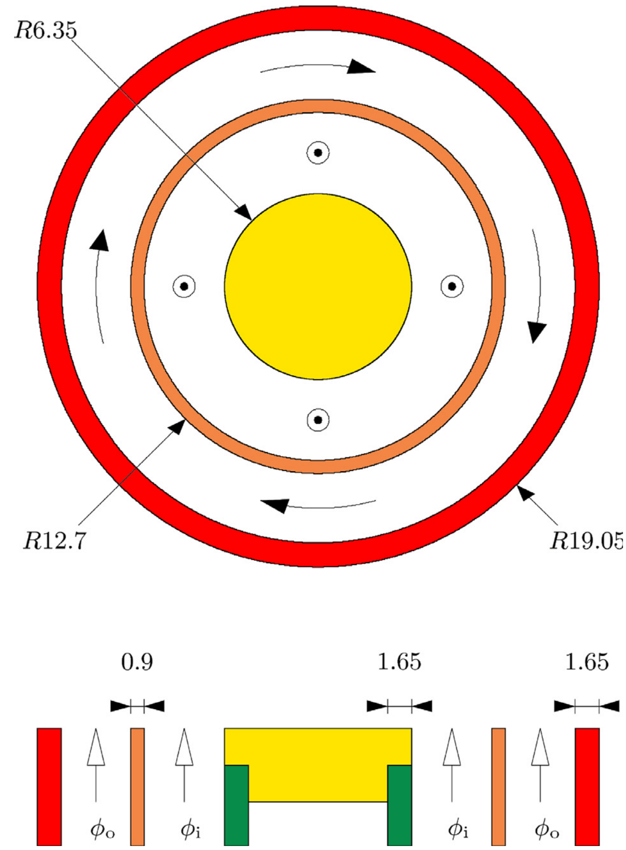

Figure 1. Top and side view of the burner geometry exit. The arrows indicate the direction of flow and swirl [21].

2. Experimental details

2.1. Cambridge/Sandia stratified swirl burner

The burner has been described in previous publications, but the outlet geometry is reproduced in Fig. 1, from [21]. The burner was designed to generate reacting flow conditions representative of turbulent flows in practical systems, including sufficiently high turbulence levels, swirl, and operation under premixed and stratified conditions. The inlets consisted of co-annular tubes with a development length exceeding 25 hydraulic diameters to ensure well-developed turbulent flow. A ceramic central bluff body was used to stabilize the flame with minimal heat loss – measured surface temperatures are available in [34]. Mass flow controllers were used to control the equivalence ratio of the inner annulus (ϕ_i) and the outer annulus (ϕ_o) independently, allowing the stratification ratio ($SR = \phi_i/\phi_o$) to be varied for a fixed global equivalence ratio (ϕ_g).

2.2. Operating conditions

The operating conditions analyzed in the present study are shown in Table 1, spanning premixed and stratified cases without swirl. The fixed bulk velocities were chosen to maximize the Reynolds numbers in the flows given the physical constraints imposed by the mass flow controllers available and the maximum throughput of the laboratory air supply. The bulk velocity in the outer annulus, $U_o = 18.7$ m/s, was

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