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Effects of strain rate, turbulence, reactant stoichiometry and heat losses on the interaction of turbulent premixed flames with stoichiometric counterflowing combustion products

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ABSTRACT

Intense strain, turbulence, heat transfer, and mixing with combustion products can affect premixed flames in practical combustion devices. These effects are systematically studied in turbulent premixed $CH_4/N_2/O_2$ flames using a reactant versus product counterflow system and independently varying bulk strain rate, turbulent Reynolds number, equivalence ratio of the reactant mixture, and temperature of the stoichiometric counterflowing combustion products. The flow field and the turbulent flames are investigated using particle image velocimetry (PIV) measurements and laser-induced fluorescence (LIF) imaging of OH. The OH-LIF images are used to identify the interface between the counterflowing streams, referred to here as the gas mixing layer interface (GMLI). The flame response for different flow conditions is compared in terms of the probability of localized extinction along the GMLI, the turbulent flame brush thickness, and flame position relative to the GMLI, by using an OH-LIF-based progress variable. The probability of localized extinction at the GMLI increases as the separation between the turbulent flame brush and the GMLI decreases. Flame fronts in the vicinity of the GMLI are more likely to extinguish as a result of heat losses, dilution of the reaction zone by the product stream, and large local strain rates. A higher probability of localized extinction at the GMLI is induced by either a larger bulk strain rate or a slower flame speed. As the turbulent Reynolds number increases, the corresponding increase in turbulent flame brush thickness enhances the interactions of the flame fronts with the GMLI. Heat losses are substantially less significant for cases in which the turbulent flame brush is sufficiently separated from the GMLI. For flames in close proximity to the GMLI, the effects of the product stream on the flame front differ for lean and rich reactant mixtures. These disparities are attributed in part to differences in the ignitibility of the reactant mixtures by the hot product stream.

1. Introduction

Turbulence levels, strain rate, and mixing with products of combustion affect the behavior of turbulent premixed flames in practical combustion systems. Large strain rates are typical of combustors with shear layers, flow impingement, or vortex breakdown. Mixing with hot combustion products is typically desired to stabilize premixed or stratified-premixed flames in intense turbulence at elevated Karlovitz numbers. Examples of flame stabilization techniques include intense swirl [1–3], pilot flames [4,5], and hot gas recirculation in the wake of a bluff body or a back-facing step [6–9]. On the one hand, flame stability is enhanced by the extra heat supplied by the combustion products [10–12]; on the other hand, dilution of the reaction zone [13] and heat loss, if the product stream temperature is below the adiabatic flame temperature [14], may lead to weakening of the flame.

We investigated the impact of these effects on turbulent premixed $CH_4/O_2/N_2$ flames in a counterflow burner with a turbulent stream of reactants opposed to a stream of hot combustion products in thermodynamic equilibrium. Turbulent counterflow flames provide a convenient benchmark for the study of phenomena relevant to practical combustion systems [15–24]. Advantages of the counterflow configuration include: the isolation of the flame from burner surfaces; flame compactness and short residence times; versatility of the experimental set-up, enabling the investigation of a broad range of conditions, including turbulence–flame interactions at turbulent Reynolds numbers of practical relevance.

The stabilizing effect of the enthalpy of the combustion products has been long recognized for laminar [10,25] and turbulent [17,18] premixed flames in the reactant versus hot-product

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counterflow configuration. For example, the burning rate of lean premixed flames is supported by heat gain from a stream of adiabatic combustion products of equivalence ratios closer to stoichiometric [12]. The significant effect of product stream stoichiometry on the mode of flame extinction was only recently demonstrated for laminar CH_4/air-premixed flames [13]. In particular, for a fixed product temperature above 1600 K, premixed flames extinguish more readily and abruptly by dilution of the reactive layer with stoichiometric counterflowing products than with lean products containing an excess of oxidizing species. In the present study, we investigate the effects of heat loss on turbulent premixed flames interacting with stoichiometric combustion products with different equilibrium temperatures.

Using laminar premixed flames for qualitative guidance, we recently examined [26] three lean-to-stoichiometric turbulent premixed counterflow flames at a turbulent Reynolds number of 1050 and a Karlovitz number of approximately 5, which is well below the threshold value of 100 that is typically assumed to be the boundary between flamelet and non-flamelet regimes [27,28]. We observed evidence of local extinction, and consequently of non-flamelet conditions, using simultaneous laser-induced fluorescence imaging measurements of CO and OH. Computational studies of *laminar* premixed flames with compositions identical to those of the turbulent flames provided insight into these non-flamelet conditions. In particular, they revealed that extinction occurred when the flames were very close to the gas stagnation plane and the oxidation layer extended beyond it, towards the product side [26]. The present study of turbulent premixed counterflow flames with localized extinction follows in the same vein, with the goal of furthering our understanding of the non-adiabatic interaction of turbulent flames and combustion products. We systematically investigate the influence of strain, turbulence level, and mixing with non-adiabatic combustion products on non-flamelet behavior.

A schematic illustration of a premixed counterflow flame is shown in Fig. 1a. The turbulent flame stabilizes between a reactant mixture flowing from the top and a stream of hot combustion products flowing from the bottom. A virtual boundary, hereinafter referred to as the gas mixing layer interface (GMLI), separates the turbulent flame region on top from the stream of combustion products at the bottom. The GMLI indicates the contour of the turbulent mixing layer formed by the colliding streams of reactants and hot products. The locations of the flame front and the GMLI fluctuate in time, and the mean separation between them depends on the equivalence ratio of unburned reactants, φ_u, the turbulent Reynolds number, Re_t, and the bulk strain rate, K_{bulk}. The experiment enables us to vary these critical parameters systematically and independently from one another. In addition, we vary the degree of heat loss, or non-adiabaticity, by changing the product stream temperature, T_b. By studying the effects of each of these parameters, we elucidate the complex coupling between fluid dynamics, flame properties, and heat losses in turbulent premixed combustion. Based on the previous laminar flame studies [13], we expect that as a turbulent flame interacts with the stream of combustion products, the flame will be affected not only by large strain rates but also by heat losses and dilution of the reaction zone. We investigate the extent to which these effects are correlated with variations in the position of the turbulent flame brush with respect to the combustion product stream.

The article is organized as follows: after describing the experimental system and the laser diagnostics, we explain the methodology for analyzing data in the reference frame of the GMLI. We then present the flow field and strain rate pattern of a prototypical flame. Subsequently, we present the effects of the bulk strain rate and turbulent Reynolds number on the mean progress variable, conditioned on the distance from the GMLI. Finally, we examine the role of flame stoichiometry and heat losses on re-ignition following local extinction events.

2. Experimental methods

2.1. Turbulent counterflow burner design and experimental conditions

The counterflow burner consists of a highly turbulent jet of reactants at ambient temperature opposed to a stream of combustion products at elevated temperature with a turbulent flame

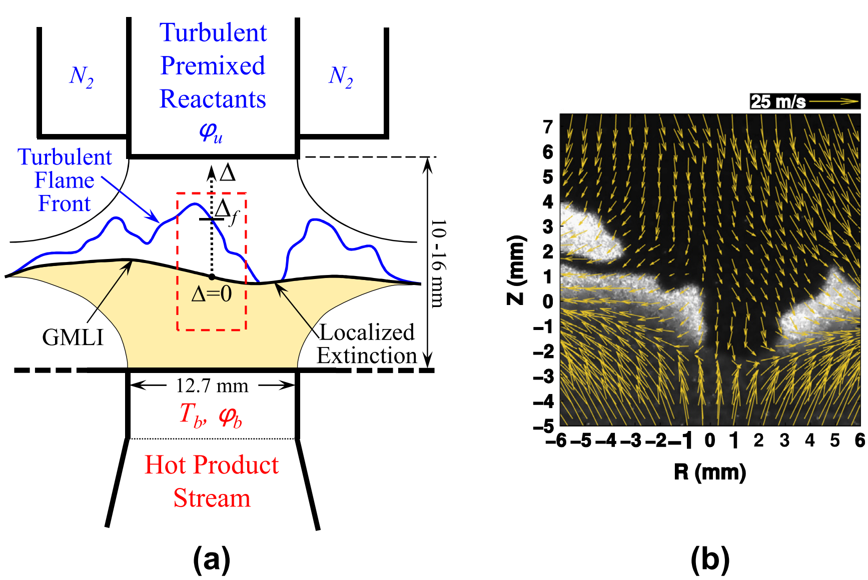

Fig. 1. (a) Schematic of a turbulent premixed flame of equivalence ratio φ_u with counterflowing products of combustion at temperature T_b and stoichiometry φ_b. The dashed red rectangle corresponds to the region of the OH-LIF measurements in Fig. 2. The axial coordinate in the reference frame of the gas mixing layer interface (GMLI) is denoted Δ, and the separation distance between the GMLI and the flame front is Δ_f. (b) Example of simultaneous single-shot PIV and OH-LIF measurements under the flow conditions of Table 3 and for φ_u = 0.85 (1 out of 9 velocity vectors displayed for clarity). The origin of (R,Z) cartesian coordinate system coincides with the centerline midpoint between the two nozzles.