Interaction of turbulent premixed flames with combustion products: Role of stoichiometry

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ARTICLE INFO

ABSTRACT

Stabilization methods of turbulent flames often involve mixing of reactants with hot products of combustion. The stabilizing effect of combustion product enthalpy has been long recognized, but the role played by the chemical composition of the product gases is typically overlooked. We employ a counterflow system to pinpoint the effects of the combustion product stoichiometry on the structure of turbulent premixed flames under conditions of both stable burning and local extinction. To that end, a turbulent jet of lean-to-rich, $CH_4/O_2/N_2$-premixed reactants at a turbulent Reynolds number of 1050 was opposed to a stream of hot products of combustion that were generated in a preburner. While the combustion product stream temperature was kept constant, its stoichiometry was varied independently from that of the reactant stream, leading to reactant-to-product stratification of relevance to practical combustion systems. The detailed structure of the turbulent flame front was analyzed in two series of experiments using laser-induced fluorescence (LIF): joint CH_2O LIF and OH LIF measurements and joint CO LIF and OH LIF measurements. Results revealed that a decrease in local CH_2O+OH and CO+OH reaction rates coincide with the depletion of OH radicals in the vicinity of the combustion product stream. These critical combustion reaction rates were more readily quenched in the presence of products of combustion from a stoichiometric flame, whereas they were favored by lean combustion products. As a result, stoichiometric combustion products contributed to a greater occurrence of local extinction. Furthermore, they limited the capacity of premixed reactants to ignite and of the turbulent premixed flames to stabilize. In contrast, lean and rich combustion products facilitated flame ignition and stability and reduced the rate of local extinction. The influence of the combustion product stream on the turbulent flame front was limited to a zone of approximately two millimeters from the gas mixing layer interface (GMLI) of the product stream. Flame fronts that were separated from the GMLI by larger distances were unaffected by the product stream stoichiometry.

1. Introduction

Lean premixed combustion is a straightforward strategy for reducing emissions and increasing efficiency but is difficult to implement in highly turbulent devices because of instabilities and the increased risk of blowoff [1]. Mixture stratification is an effective approach to improve overall-lean combustion stability where lean and weak flames are supported by regions of richer and more robust burning. In some systems, achieving homogeneous mixing is technically not possible and stratification, if not deliberate, is simply unavoidable. The practical relevance of stratified-premixed combustion has motivated an increasing body of work in fundamental combustion research [2]. Effects of mixture stratification are essentially twofold, depending on whether they are associated with either local or large-scale inhomogeneity of the reactant stoichiometry [3]. Studies of local reactant inhomogeneity in different laboratory configurations [4–12] have shown that stratification increases the turbulent flame speed as a result of larger turbulent flame density and curvature relative to the corresponding homogeneously premixed cases. Additionally, as flame fronts propagate across equivalence ratio gradients, front- and back-support can enhance the burning rates and extend the flammability limits [13–18]. These effects, however, seem to prevail at low turbulence intensities [19,20] and become dominated by turbulent transport as the turbulence intensity is increased [11,21,22] or by flame instabilities for certain types of fuels and mixtures [23].

For experiments at moderately turbulent conditions, Mastorakos [24] introduced a counterflow burner in which a stream of reactants was opposed to a second stream of combustion products diluted by air. In subsequent studies, we developed a new turbulence generation scheme [27] to increase the turbulent Reynolds

Nomenclature

c	progress variable
d_{nozzle}	nozzle separation distance
$f_i(T)$	LIF signal temperature dependence for species i (i.e., OH, CO, CH_2O)
k_{CH_2O+OH}	CH_2O+OH reaction rate
$k_{CH_2O+OH}^{LIF}$	product of CH_2O LIF and OH LIF signals
$k_{CH_2O+OH}^{max}$	peak CH_2O+OH reaction rate
k_{CO+OH}	$CO+OH$ reaction rate
k_{CO+OH}^{LIF}	product of CO LIF and OH LIF signals
k_{CO+OH}^{max}	peak $CO+OH$ reaction rate
l'	integral lengthscale
l_F	unstrained laminar flame thickness
v'	RMS axial velocity
x_n	flame-normal coordinate
z	axial burner coordinates
CH_2O_{max}	peak CH_2O LIF signal
CO_{max}	peak CO LIF signal
GMLI	gas mixing layer interface
GSP	gas stagnation plane
HR_{max}	peak heat release rate
Ka_t	turbulent Karlovitz number
K_{bulk}	bulk strain rate
K_{ext}	extinction strain rate
K_{ign}	ignition strain rate
OH_o	OH LIF signal for $x_n = 0$
OH_{max}	peak OH LIF signal
Re_t	turbulent Reynolds number
S_L	unstrained laminar flame speed
SR	strain rate for laminar flame calculation
T	temperature
T_{ad}	adiabatic flame temperature
T_b	product stream temperature
V_{bulk}	cold-inlet bulk velocity
X_i	mole fraction of species i (i.e., OH, CO, CH_2O)
$X_i{}^{max}$	peak mole fraction of species i (i.e., OH, CO, CH_2O)

Greek letters

φ_b	product stream equivalence ratio
φ_u	fresh reactant equivalence ratio
Δ	axial distance from GMLI
Δ_f	flame-front axial coordinate with respect to GMLI
$\|\nabla OH\|_{max}$	OH LIF signal maximum gradient

Fig. 1. Principle of a flame back-supported by combustion products.

equivalence ratios of the reactant and product streams were varied independently. Regime diagrams of turbulent premixed combustion [36] provide a conceptual framework to systematize the turbulence-flame interactions but rely on oversimplified assumptions and neglect the effects of mixture stratification.

The role of product stoichiometry is often overlooked relative to the product temperature even in laminar flame studies. The enhancing effect of heat fluxes on heat release and extinction limits has been long recognized [37] and validated [17,38–40]. In an adiabatic system, stoichiometric combustion products are expected to provide stronger support than either lean or rich flames at lower temperature. With a new focus on the effects of product stoichiometry, the quasi-steady extinction of strained laminar CH_4/air-premixed flames was investigated numerically using detailed chemistry and transport mechanisms in Ref. [41]. For product temperatures exceeding 1600 K, two modes of extinction occurred depending on the product stoichiometry: abrupt extinction, when the products were nearly stoichiometric and smooth extinction when the products came from a lean flame. The presence of oxygen in lean counterflowing combustion products at a mole fraction as low as 10^{-2} prevented abrupt extinction. The present study investigates these scenarios under broader conditions, including a rich product stoichiometry and turbulent flow.

Laser diagnostics were employed for simultaneous laser-induced fluorescence (LIF) imaging of either CH_2O and OH or CO and OH. For appropriate choices of the LIF excitation and detection schemes, the product of the LIF images yields in the first case a quantity proportional to the forward reaction rate of $CH_2O+OH \rightarrow HCO+H_2O$, and in the second case a quantity proportional to the forward reaction rate of $CO+OH \rightarrow CO_2+H$. The peak reaction rate of the former reaction is correlated with the primary peak of heat release for lean-to-stoichiometric CH_4/air premixed flames [42–44]. The latter reaction is a critical step for the conversion of CO to CO_2 that accounts for a third of the heat release as the dominant contribution in the oxidation layer of premixed flames.

The following sections begin with an introduction of the flow conditions, burner and experimental methodologies. The results are divided into three sections. After discussing the global stability and ignition limits of the flames, we examine the flame structure, address the influence of the combustion products and the nature of the flame front topology for different product stoichiometries.

2. Experimental methods

2.1. Turbulent counterflow burner and experimental conditions

The counterflow configuration (Fig. 2a) consisted of a turbulent stream of premixed reactants issuing from the upper nozzle and

number to values on the order of one thousand and examined the interaction of turbulent premixed flames with hot combustion products in the same counterflow configuration [25,26]. The equivalence ratio of the flame generating the stream of products was maintained at unity while parameters controlling the fluid dynamics, such as the bulk strain rate and the turbulent Reynolds number, and the chemistry, such as the reactant equivalence ratios and the temperature of the product stream, were varied independently.

The present study focuses on large-scale stratification effects pertaining to the interaction of premixed flames with hot combustion products that originate from a flame of different stoichiometry. Figure 1 illustrates such a situation relevant to systems involving large recirculation zones such as swirl-stabilized combustors, stratified-premixed gas turbines [28–31] and trapped vortex combustors [32–35]. Combustion products from flame fronts of local equivalence ratio φ_b may be advected towards and interact with flame fronts of a different equivalence ratio, φ_u. In this study, except for some global ignition experiments, the temperature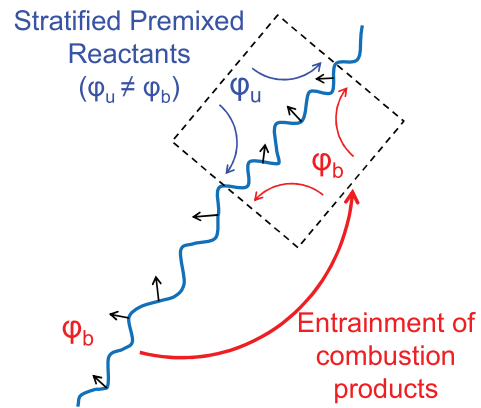 of the products was kept constant while the