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The role of low temperature fuel chemistry on turbulent flame propagation

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ABSTRACT

A new high temperature, high Reynolds number, Reactor Assisted Turbulent Slot (RATS) burner has been developed to investigate turbulent flame regimes and burning rates for large hydrocarbon transportation fuels, which exhibit strong low temperature chemistry behavior. The turbulent flow characteristics are quantified using hot wire anemometry. The turbulent flame structures and burning velocities of n-heptane/air mixtures are measured by using planar laser induced fluorescence of OH and CH_2O with reactant temperatures spanning from 400 K to 700 K. It is found for the first time that for n-heptane/air mixtures there are four unique turbulent flame regimes, a conventional chemically-frozen-flow regime, a low-temperature-ignition regime, a transitional regime between the low- to high-temperature-ignition regimes, and a high-temperature-ignition regime, depending on the initial reactant temperature and heated flow residence time prior to the flame. The turbulent burning velocities have been measured for the first two regimes, chemically-frozen-flow and low-temperature-ignition regimes, in order to quantitatively address the role of low temperature ignition on the turbulent burning velocity. In the latter case, large amount of CH_2O formation has been observed in the pre-flame zone, signaling a significant change in the reactant composition and chemistry. At a given reactant temperature and turbulent intensity, the normalized turbulent burning velocities can be varied depending on the extent of low temperature fuel oxidation by varying the heated flow residence time and reactant temperature. The present results suggest that contrary to the previous studies, the turbulent flame regimes and burning velocities for fuels with low temperature chemistry may not be uniquely defined at elevated temperatures.

1. Introduction

Combustion in practical gas turbine engines, after-burners, and internal combustion engines are governed by turbulent premixed and partially premixed flames at elevated temperature and pressure at high Reynolds numbers [1,2]. Moreover, these engines utilize large hydrocarbon fuels such as gasoline, diesel, and jet fuels which have a strong low temperature chemistry behavior [3–7]. As such, not only the turbulence intensity but also the fuel chemistry and molecular transport will play an important role in affecting turbulent flame propagation and flame regimes.

Extensive experimental studies of turbulent premixed flames have been conducted in which the major focus has investigated the role of turbulent intensity on flame burning velocities and flame structures [8–11]. In addition, the effects of pressure [12,13], Lewis number [8,14,15], preferential diffusion [16], and turbulent flame geometry [17,18] have been examined. The measured turbulent burning velocity (S_T) normalized by the laminar flame speed (S_L) has been previously fit with a semi-implicit expression as a function of the turbulent intensity (u'), the Lewis number (Le), the turbulent integral length scale (l), and the laminar flame thickness (δ_f) [8–10,15] as shown below

$$\frac{S_T}{S_L} = 1 + CLe^{-1}\left(\frac{u'}{S_L}\frac{l}{\delta_f}\right)^n \tag{1}$$

where C represents a constant and n is an adjustable exponent. Various semi-implicit expressions of turbulent burning velocity have been proposed, however, questions still remain regarding their fidelity and accuracy [19].

A turbulent flame regime diagram called the Borghi diagram has been proposed in order to specify the flame response to turbulent intensity based on the turbulent time scale (l/u') and the flame time scale (δ_f/S_L) [10,20,21]. This diagram provides very insightful information for different flame regimes, defining the boundaries between wrinkled, corrugated, thin reaction zone, and distributed reaction zone flames. It has served as the base of turbulent experiments and modeling efforts using the flamelet concept [22,23]. Unfortunately, the above turbulent flame studies and the Borghi

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diagram have been either based on the assumption of a chemically frozen flow or flames of small hydrocarbons (e.g. H_2 and CH_4, excluding [19]) with only high temperature chemistry, and thus have not considered another important subject, the effect of low temperature fuel chemistry for transportation fuels at elevated temperature [3–7]. Consequently, only one chemical timescale, the flame burning time (δ_f/S_L) based on laminar flame structure has been included in previous studies.

In fact, almost all transportation fuels such as gasoline, diesel fuels, and aviation fuels exhibit prevalent low temperature chemistry behaviors that include low temperature ignition in the negative temperature coefficient (NTC) region and rapid fuel oxidation after the low temperature ignition [3–7]. Moreover, new combustion technologies, such as the twin annular premixing swirler (TAPS) burner [24], the trapped vortex turbine burner with extensive exhaust gas recirculation (EGR) [25], fuel reactivity controlled compression ignition (RCCI) engines [26], and flameless combustion devices [27], involve elevated temperatures and pressures which shorten the low temperature ignition delay time and render it comparable to the turbulent time scales. As a result, the expression for turbulent burning velocity (Eq. (1)) and the Borghi diagram may not apply due to the rapid change of species concentration and chemistry after the low temperature ignition. Recent direct numerical simulations (DNS) have revealed that the appearance of low temperature chemistry at elevated temperature can lead to many different combustion regimes ranging from low temperature ignition, low temperature flames, high temperature flames, and high temperature ignition [28–30]. A question naturally arises: How does the low temperature fuel chemistry at elevated temperature affect turbulent flame propagation and the Borghi diagram? Additionally, will the turbulent burning velocity still be a well-defined value when the low temperature reactivity alters the fuel composition and reactivity?

The goal of this paper is to address the question regarding the role of low temperature fuel chemistry on turbulent combustion. We have developed a new experimental platform capable of controlling the fuel reactivity at elevated temperature and the onset of the low temperature ignition regime of large hydrocarbon fuels, enabling the study of low temperature fuel chemistry on the turbulent flame propagation and turbulent flame regimes. The new, reactor-assisted turbulent slot (RATS) burner provides an experimental foundation to investigate turbulent/chemistry interactions in both the thin flame reaction regime and the low temperature ignition regime by measuring, quantitatively, turbulent burning velocities and flame structures of premixed turbulent flames. Turbulent flow fields have been characterized by use of hot wire anemometry, and turbulent burning velocities and flame structures of lean n-heptane/air mixtures at elevated temperatures spanning 400–700 K have been measured using OH and CH_2O planar laser-induced fluorescence (PLIF) imaging techniques. Changes of flame structure and turbulent burning velocity with the increase of fuel reactivity are reported here for the first time. The fundamental mechanism of the drastic change of flame structure due to low temperature fuel reactivity and its implication to turbulent flame regimes and modeling are discussed.

2. Experiment

2.1. Development of reactor-assisted turbulent slot (RATS) burner

A new RATS burner has been developed with the experimental capability of generating large turbulent Reynolds numbers and providing the capability to control fuel reactivity through careful reactant mixing and heating. The cross-sectional schematic of the RATS burner is shown in Fig. 1. The nozzle exit has a 10 mm × 100 mm rectangular cross-section with a 2 mm nozzle exit wall thickness, resulting in hydraulic diameter (D_H) of 18.19 mm. The stainless steel burner is 55 cm tall with diverging (bottom) and converging (near the nozzle exit) sections and an internal heated volume of ~650 cm^3. This provides sufficient residence time (20–140 ms, depending on desired Reynolds number, Re_D) in the heated flow reactor section to control the pre-flame low temperature chemical reactions. The fuel is pre-vaporized and rapidly mixed with a preheated hot air stream at the bottom of the reactor. The reactor heating system consists of a 61 cm long heavy duty in-line heater (HottWatt HA2-24) to heat the bulk air flow to the desired temperature (up to 700 K). In order to maintain a constant temperature of the premixed fuel/air stream in the flow reactor, two radiation panel heaters are used to heat the outer sidewalls of the entire burner. The reactor temperatures are measured at varying points along the length of the burner to ensure temperature uniformity within 10 K from the desired set point. To sustain a flame at large Reynolds numbers, a pilot flame consisting of stoichiometric methane/air is applied. The pilot flame is generated by flowing the methane/air mixture through a 1 mm wide × 100 mm long channel which runs parallel and adjacent to each side of the main reactant flow channel as shown in Fig. 1.

To control the turbulent intensity, the burner provides two locations for the installation of turbulent generator plates. Schematics of two turbulent generator plates are shown in Fig. 2. The first turbulent generator is located before the final convergence of the flow channel, 130 mm upstream from the nozzle exit, and consists of a 2 mm thick plate with four equally spaced crosses machined into it, resulting in a 78% blockage ratio. The other turbulent generator is located just before the exit of the nozzle, 30 mm upstream from the nozzle tip, and consists of a 100 mm × 10 mm plate with twenty-five 2 mm × 10 mm slots evenly distributed along the length of the plate, providing a 50% blockage ratio.

2.2. Characterization of turbulent flow field with hot-wire anemometry

The turbulent flow field has been quantified by use of hot-wire anemometry. The hot-wire probes used are 2.5 μm in diameter (d_w) (90% Pt 10% Rh) single-wire, normal probes manufactured by etching Wollaston wire to produce a sensing length of ~2 mm (l_w), resulting in an $l_w/d_w \sim 800$. The probes are operated by Dantec Streamline constant temperature anemometry (CTA) system in 1:1 bridge mode, with a sampling frequency (f_s) of 80 kHz. The raw data is low pass filtered at $f_a = f_s/2 = 40$ kHz to prevent aliasing. All measurements reported in this study have been taken 3 mm above the burner exit along the centerline. Hot-wire measurements have been performed at multiple locations along the length of the burner and at different heights, indicating uniform velocity profiles and isotropic turbulence. Calibration of the hot-wire is performed by measuring a calibrated volumetric flow rate of air through the open burner (i.e. without turbulent generators). Measurements and velocities of the open burner have been verified with measurements from a pitot probe calibrated wind tunnel, revealing very close agreement between the two calibration techniques. In summary, the two plate turbulent generation scheme provides uniformly distributed turbulence, resulting in normalized turbulent intensities (u'/U) spanning from 12% to 15% over the range of Re investigated (2000–40,000) as shown in Fig. 3.

The hot-wire data is further processed to provide a measurement of the integral (l) and Taylor (λ) turbulent length scales. The turbulent length scales are determined similar to an approach demonstrated by Coppola and Gomez [31] in which the turbulent power density spectra as a function of both the frequency and wave number are modeled using correlative expressions. Typical power density spectra along with the correlative fits can be seen