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Hydrodynamic and chemical effects of hydrogen addition on soot evolution in turbulent nonpremixed bluff body ethylene flames

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Abstract

The evolution of soot in a turbulent nonpremixed bluff body ethylene/hydrogen (2:1 by volume) flame was investigated using a combination of experiments and Large Eddy Simulations and compared with a neat ethylene counterpart (Muelleret al., 2013). The maximum soot volume fraction in the recirculation zone and jet-like region of the ethylene/hydrogen case are significantly lower than that of the ethylene case. Flamelet calculations demonstrated that hydrogen addition suppressed soot formation due to the reduction of the C/H ratio, resulting in an estimated fourfold reduction in soot volume fraction due to chemical effects. Soot reduction in the downstream jet-like region of the flame is quantitatively consistent with this chemical effect. However, soot reduction in the recirculation zone is substantially larger than this analysis suggests, indicating an additional hydrodynamic effect. Large Eddy Simulation was used to further investigate soot evolution in the recirculation zone and to elucidate the role of hydrogen addition. For the same heat release rate and similar jet Reynolds number as the neat ethylene case, the addition of hydrogen requires a higher jet velocity, and this leads to a leaner recirculation zone that inhibits soot formation and promotes soot oxidation.

Keywords: Soot; Laser-induced incandescence; Large Eddy Simulation (LES); Bluff body flame; Turbulent nonpremixed flame

1. Introduction

Due to the importance of soot in practical transportation, propulsion, and power generation systems, soot formation, growth, and oxidation have

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been extensively studied. Most of these studies focus on laminar configurations since flow conditions are better controlled and characterized, which enables detailed analysis of soot evolution [1]. Nonetheless, most practical devices operate under turbulent conditions. The understanding of soot evolution in turbulent reacting flows and the small-scale interactions among soot, turbulence, and chemistry has been aided by Direct Numerical Simulation (DNS). In the past, these studies have been limited to two-dimensional configurations and/or empirical soot models to limit computational cost [2–5], but, recently, Attili et al. [6] performed the first three-dimensional DNS of turbulent nonpremixed jet flames employing a high-order statistical model of soot and a detailed chemical mechanism, which includes the soot precursor naphthalene, and investigated Damköhler number effects on soot formation and growth [7]. Nevertheless, similar to all combustion DNS studies, the Reynolds number was limited to 15,000.

To investigate jet flames at high Reynolds numbers, a combination of experiments [8–11] and Large Eddy Simulation (LES) [12–14] has been used. However, the jet flame configuration does not contain more complex fluid dynamics found in practical combustion systems such as recirculating flow. To bridge this gap, recent experiments and LES have been used to understand the role of recirculating flow on soot evolution in simple, canonical geometries. Mueller et al. [15] experimentally and computationally investigated a turbulent nonpremixed bluff body ethylene flame. Unlike jet flames, surface growth was found to dominate in the recirculation zone, highlighting the significance of hydrodynamics on soot evolution.

In the present work, an ethylene/hydrogen mixture sooting flame with the same bluff body configuration is investigated. During the thermal decomposition of hydrocarbon fuels, it has been shown that the addition of hydrogen slows down the formation of soot [16]. Extensive laminar studies have been conducted with simplified flow conditions to understand the overall suppression of soot formation in hydrogen added diffusion flames and have attributed such suppression to both dilution and chemistry effects, through the change of the flame temperature and the shift of the balance of the C_2H_2-addition reactions [17–21]. In addition to this chemical effect, to maintain the same heat release rate and similar Reynolds number as the ethylene bluff body flame [15], a faster central jet is needed, which will change the fuel to coflow air momentum flux ratio and affect the hydrodynamics.

The objective of this investigation is threefold: first, to understand the evolution of soot in the hydrogen added ethylene bluff body flame utilizing a combination of experiments and computations; second, to assess differences between hydrogen added and neat ethylene flames and further validate the LES model; and, third, to differentiate between the hydrodynamic and chemical effects of hydrogen addition.

2. Experimental methodology

The experimental setup used in the current study is similar to previous bluff body studies [22,23] and was kept the same as the previous ethylene case [15]. In brief, the outer diameter of the bluff body (D_B) is 50 mm, and the diameter (D_J) of the central fuel jet is 3.6 mm, from which an ethylene/hydrogen mixture (2:1 by volume) issued at 102.1 m/s. The heat release rate of the flame was kept the same at 42 kW to maintain similar thermal effects on the flow field. The central jet Reynolds number is 28,400, which is 8% smaller than that of the previous study with a Reynolds number of 30,900 and a jet velocity of 74.2 m/s [15]. The bluff body burner was mounted in a contraction with an exit cross section of 150 by 150 mm^2, from which air coflow issued at 23 m/s, which is the same as in the previous study.

The 1064 nm beam from an Nd:YAG laser was used for laser-induced incandescence (LII) excitation. The laser sheet had a height of 80 mm through the measurement volume and had a thickness of 0.3 mm. The operating LII fluence was kept at 0.9 J/cm^2 to ensure the independence of the signal to variations in the fluence caused by laser extinction [9,24]. In addition, data were only extracted from the laser-in side of the measurement to avoid nonlinear influences of beam steering [25]. A Gaussian distribution of the spatial fluence with a 8% standard deviation was achieved. All images presented in this work have been clipped at the edges where the laser sheet was found to exhibit low fluence.

The LII signal was filtered at 430 ± 10 nm and detected with an intensified CCD camera. A short gate width of 40 ns was used to reduce the size-dependent sensitivity of the signal [26]. The LII signal has been calibrated by laser extinction measurements as previously reported [15]. With this system, the in-plane resolution of the images is 0.26 mm/pixel in each direction, and the detection threshold is about 3 ppb.

The data presented in this work have been corrected for background interference and detector attenuation. According to the previous ethylene bluff body study, the estimated measurement uncertainty is about 25%.

3. Computational methodology

The modeling of soot-chemistry-turbulence interactions is aided by a statistical soot model, a modified Radiation Flamelet/Progress Variable (RFPV) combustion model for sooting flames, and a presumed subfilter PDF for closure. Complete details of the integrated LES model for sooting