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Lean or ultra-lean stretched planar methane/air flames

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Abstract

Lean premixed combustion has potential advantages of reducing pollutants and improving fuel economy. In some lean engine concepts, the fuel is directly injected into the combustion chamber resulting in a distribution of lean fuel/air mixtures. In this case, very lean mixtures can burn when supported by hot products from more strongly burning flames. This study examines the downstream interaction of opposed jets of a lean-limit CH_4/air mixture vs. a lean H_2/air flame. The CH_4 mixtures are near or below the lean flammability limit. The flame composition is measured by laser-induced Raman scattering and is compared to numerical simulations with detailed chemistry and molecular transport including the Soret effect. Several sub-limit lean CH_4/air flames supported by the products from the lean H_2/air flame are studied, and a small amount of CO_2 product (around 1% mole fraction) is formed in a "negative flame speed" flame where the weak CH_4/air mixture diffuses across the stagnation plane into the hot products from the H_2/air flame. Raman scattering measurements of temperature and species concentration are compared to detailed simulations using GRI-3.0, C_1, and C_2 chemical kinetic mechanisms, with good agreement obtained in the lean-limit or sub-limit flames. Stronger self-propagating CH_4/air mixtures result in a much higher concentration of product (around 6% CO_2 mole fraction), and the simulation results are sensitive to the specific chemical mechanism. These model-data comparisons for stronger CH_4/air flames improve when using either the C_2 or the Williams mechanisms.

Keywords: Hot products; Ultra-lean; Sub-limit; Counterflow flames; Raman scattering

1. Introduction

Lean combustion is currently under investigation due to its potential advantages in limiting thermal NO_x emissions and in reducing fuel consumption. It has been used in gas turbines and direct injection spark ignition (DISI) engines. But a critical problem is that lean combustion tends to produce unburned hydrocarbon pollutants. For example, in DISI engines, ultra-lean combustion is achieved by charge stratification. The fuel/air mixture is inhomogeneous, leading to the simultaneous formation of lean, rich, and stoichiometric regions. For the inhomogeneous reactants, Haworth et al. [1] simulated turbulent inhomogeneous combustion in DISI engines and found that hydrocarbon-rich fragments and oxidizer penetrate behind the primary heat-release zone to form a secondary reaction zone. Flames occurring in an inhomogeneously mixed fuel and air region are examples of partially premixed combustion. Some of this partially premixed mixture is so lean that it does not burn. But this ultra-lean mixture may still react if hot products interact with it. That is, under certain conditions, the lean

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mixture region can burn and thus reduce the potential pollutants. The interaction of lean mixture with hot products needed to maintain the lean region burning is the focus of this work.

Partially premixed flames have been studied widely. In particular, the downstream interaction between two premixed streams was investigated by Sohrab et al. [2]. Most practical flames are stretched. The stretch effect combined with other aspects such as the effect of Lewis number or curvature will modify flame structure significantly [3,4]. Considering the various conditions that exist simultaneously in inhomogeneous fuel/air reaction, a set of CH_4/air flames with a wide range of equivalence ratios and stretch rates impinging upon hot products are studied experimentally and numerically. The opposed jet burner generates counterflow flames that are widely used to study chemical kinetics and species transport under aerodynamic stretch. Using the opposed jet flames, partially premixed CH_4/air vs. air flame structures were investigated [5,6]. Lean partially premixed CH_4 and C_3H_8 flame structures vs. hot products have also been investigated [7,8]. In general, premixed flames [9,10] are much less sensitive to stretch than diffusion flames [11]. In the present work, stretch effects on the flame structure of the interaction between hot products and lean CH_4/air mixtures are studied with Raman scattering and detailed transport, complex chemistry numerical simulations.

2. Experimental system and flames examined

Measurement of major species and temperature are made along the centerline of an opposed jet burner using a non-intrusive Raman diagnostic system. The Raman system is the same as used previously and the details are given in [4,8]. Number density measurements of major species are directly related to their spontaneous Raman signal strengths, and since all major species are measured, the total number density of the local gas mixture is obtained and related to temperature via the ideal gas law (assuming pressure is 1 atm). For the present work, the opposed jet burner has been modified by inserting honeycomb metal "flow straighteners" into both nozzles. These inserts have 0.8 mm honeycomb cells that are 19 mm in length. The inserts provide a very uniform exit velocity profile for both the nozzles, as verified by hot wire anemometry traverses in non-reacting flow. In addition the new honeycomb metal inserts do not cause flame attachment of either H_2/air or hydrocarbon/air flames. The opposed jet burner was designed by Seshadri et al. [12] and has been used extensively for hydrogen- and hydrocarbon-fueled diffusion flames and for hydrocarbon-fueled premixed flames. With the honeycomb inserts, rather than wire screens, it can also be used for lean H_2/air premixed flames.

Eight flames, which are classified into three groups, are investigated by experiment and numerical simulation. All three groups have 300 K inlet conditions for both jets. Group A includes three flames of CH_4/air mixtures, all with an equivalence ratio 0.68, vs. lean H_2/air mixtures at stretch rates of 90, 140, and 210 s^{-1}. Group B includes three flames of CH_4/air mixtures, all with ϕ of 0.54, vs. lean H_2/air mixtures at stretch rates 90, 140, and 210 s^{-1}. Group C includes two ultra-lean sub-limit flames of CH_4/air mixtures ($\phi = 0.33$ or 0.43) vs. lean H_2/air mixtures at a stretch rate 140 s^{-1}. The maximum Reynolds number of jet flow is 1600 at a stretch rate 210 s^{-1}. All of the lean H_2/air mixtures have the same ϕ of 0.28 and the calculated OH, O, and H mole fractions for the H_2/air flames are of the order of 1×10^{-3}, 8×10^{-4}, and 5×10^{-4}, respectively. This equivalence ratio is chosen to cause the lean H_2/air flame to be detached from the exit of the burner but still be separated from the CH_4/air flame. CH_4 is a good alternate fuel because of its well-known chemical kinetics. Similar work has already been performed for planar C_3H_8/air flames vs. hot products, but problems were encountered with the opposed jet burner used at the time [7]. Because premixed H_2/air has a fast burning velocity and tends to attach to the mesh screen or sintered metal plate at the nozzle exit (used to provide a top hat velocity profile), the boundary conditions were not well established [7]. Here, a lean H_2/air flame with well-established boundary conditions is used to generate hot products so that only high temperature water vapor, O_2, and N_2 impinge upon the hydrocarbon flame. Thus, any CO_2 formed must come from the downstream interaction of the methane fuel and the hot products. The CO_2 is an indicator of the amount of CH_4 fuel that is burned.

3. Numerical simulations and mechanisms

Numerical flame simulation is performed with "OPPDIF" [13]. Detailed chemical kinetic mechanisms and transport data are used for numerical predictions. Four different chemical kinetic mechanisms are used for methane flames: one which models hydrocarbons with only one carbon atom (C_1) [14], one which models hydrocarbons containing up to two carbon atoms (C_2) [14], GRI-3.0 [15], and Williams et al. [16].

4. Results and discussion

Experimental results from the Raman scattering measurement are achieved based on relevant calibration curves obtained across a wide equiva-