Study of Propane/Air Burning Velocities with Mixture Preheating and N_2 Dilution

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Abstract

Laminar flame speeds of propane/air mixtures were determined experimentally over an extensive range of equivalence ratios at room temperature, 500 K and 650 K and atmospheric pressure. The N_2 dilution effects on the laminar flame speed were also studied at these conditions for selected equivalence ratios. The experiments employed the stagnation jet-wall flame configuration in which the flow velocity was obtained by using Particle Image Velocimetry (PIV). The laminar flame speed was obtained using linear extrapolation to zero stretch rate. The measured flame speeds were compared with literature data and numerical predictions using a published detailed kinetic model [1]. The predictions agree generally well with the experimental data.

Keywords: flame, combustion, diluent, mixture preheating, and laminar flame speed, burning velocity

Introduction

Laminar flame speed data, as well as flame libraries that can be constructed from kinetic models validated with flame speed data, are critical input parameters for performing advanced numerical simulations, particularly for gasoline direct injection (GDI) engines. The measurement of laminar flame speed has received considerable attention in the published literature for various fuels burning in air at room temperature and pressure (e.g.[2]). However, the extrapolation of these data to initial temperatures, pressures, equivalence ratios, and dilution (EGR) levels important to engine combustion and to fuels utilized in engines is not simple. The specific objectives of the present work were to experimentally determine laminar flame speeds of propane/air mixtures over a range of equivalence ratio and N_2 dilution, for room temperature, 500K and 650K, with particular interest near lean flammability and sooting limit conditions. The effect of N_2 dilution on the laminar flame speed have also been studied for selected equivalence ratios and initial reaction temperatures (0.8 and 1.1 at 300 K, 1.1 at 500 K and 650 K) with dilution volume percentages up to 40.

Experimental Methodology

The experimental configuration used, a single jet-wall stagnation flame, was introduced some time ago by Egolfopoulos et al. [3], and is discussed in more detail elsewhere [4,5]. When the strain rate is low, the flame front is far away from the non-adiabatic stagnation plate; therefore, the upstream heat loss has minimal effect on the flame propagation. The experimental setup includes a stagnation plate under which a premixed flame burner is located. The premixed reactant flow is preheated upstream by using inline heaters. The temperature of the air/gas inline heaters is automatically controlled. Several 1.6 mm exposed-junction fast-response thermocouples are used to measure the temperatures. The final temperature of the mixture, which is measured 3.8 cm away from the nozzle exit and under the screen of the nozzle, is used as the final control temperature. The flow is seeded with 0.3-0.7 micron Boron Nitride particles, and the velocity of the entire flow field can be obtained using PIV. A Continuum® Minilite PIV Nd:Yag laser is used as the PIV light source and the light beam is shaped into a thin light sheet using cylindrical and spherical lenses. The images at two different times are recorded by double exposure using a Kodak DCS 460 digital camera with resolution of 3060x2036 pixels. The recorded images, in appropriate digital form, are subsequently analyzed using an in-house auto-correlation code. The PIV code utilizes self-optimizing FFT algorithms, variable interrogation window size, and sub-pixel peak detection techniques. In addition, customized filtering algorithms implemented in the code facilitate auto-detection of flow centerline and the flame edge, thus allow the processing of large data sets (reducing statistical experimental errors) with minimal user interaction. Additional features include algorithms for automatic interrogation peak selection/rejection as well as stretch rate/ reference flame speed determination. The use of this software package eliminates the human bias in determining the stretch rate manually, which is commonly used in the literature of PIV related flame speed study.

Results and Discussion

Figure 1 shows the measured propane/air mixture flame speeds for different equivalence ratios at room temperature with comparison of literature data [6-9]. The overall agreement among different data sets is generally very good, and the present data agree within 4% with the most recent measurements of Ref. [6,7]. Figure 1 also shows the predicted results using the kinetic mechanism of Qin et al. [1]. Laminar flame speed was computed with the Sandia PREMIX [10] code. The reaction mechanism used here [1] has been optimized against ignition delay and room temperature flame speed data for a number of C_1-C_3 hydrocarbon fuels. As can be seen, the model of Qin et al. [1] agrees very well with the entire body of experimental data, which is not surprising since it was optimized to reproduce the data of Vagelopoulos et al. [6,7].

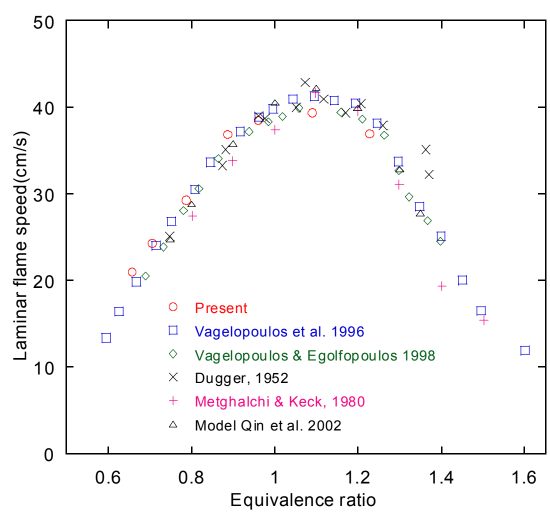

Figure 1: Atmospheric pressure room temperature laminar flame speeds for propane/air mixture.

Figure 2 compares the present data for the different unburned gas temperatures, 500 K and 650 K, with predictions using the same model. As can be seen, the model again shows a good overall agreement with the data; however, deviations

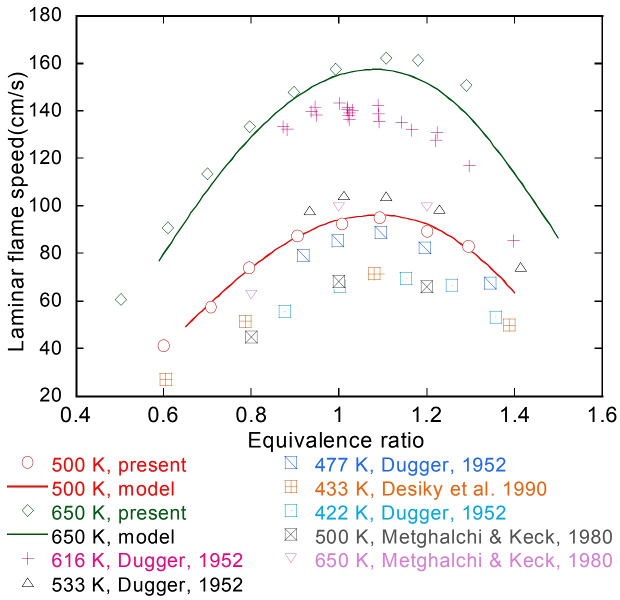

Figure 2: Comparison of atmospheric pressure laminar flame speeds for propane/air mixture at preheat temperatures.

become significant at the lean limits and on the rich side for the 650 K case. Figure 2 also displays the present data in comparison with the limited data available in the literature. Our results appear to be consistent with the extensive data set of Dugger [8] taken at 7 different unburned gas temperatures (from 200 to 616 K) using the Bunsen burner apparatus, and the data of Desoky et al. [11] at 433 K obtained with the spherical bomb method. The data extracted from the temperature-dependent spherical bomb measurements of Metghalchi and Keck [9] at 500 and 650 K are considerably lower than those from the present study, with differences up to 38 %.

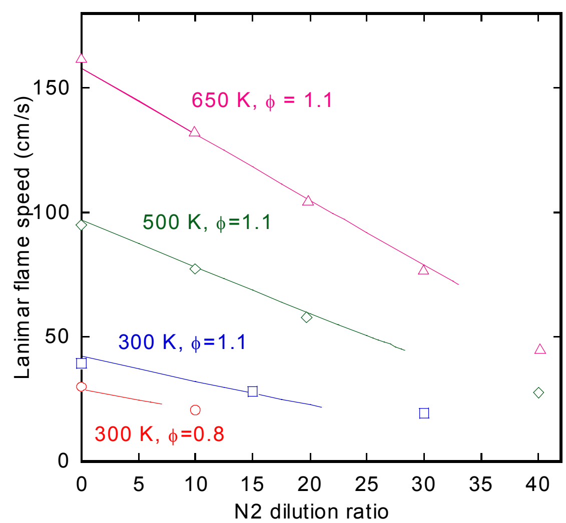

Figure 3: Atmospheric pressure laminar flame speed with N_2 dilution for equivalence ratio 0.8 at 300K, and 1.1 at 300, 500, and 650K (symbols represent the present experimental data, lines the model prediction of Qin et al. 2000).

Figure 3 shows the experimental results for propane/air mixture with N_2 dilution. The dilution ratio is defined here as volume percentage of diluent over the total volume (diluent + air + fuel). As can be seen, for the cases considered in the present study, i.e., three different unburnt gas temperatures (300, 500, and 650 K) and the dilution levels from 0 to up to 40 %, the measured laminar flame speeds exhibit nearly linear dependencies on the dilution ratio. Moreover, the theoretical results obtained using the same reaction mechanism again agree very well with the experiments and confirm the same linear trend. This result clearly contradicts the commonly accepted belief of non-linear nature of the correlation between the laminar flame speed and the dilution ratio, even at relatively low levels of dilution [12-15].

Conclusions

Laminar flame speeds for propane/air mixtures at atmospheric pressure with mixture initial temperature of 300 K, 500 K and 650 K were determined on a stagnation flame using PIV. The measured values agree well with the modeling results based on the recent detailed reaction mechanism of propane oxidation [1], with a significant difference on the rich side of

650 K. Both the data and model predictions have revealed a linear relationship between the laminar flame speeds with the dilution ratio contrary to the commonly suggested nonlinear correlations.

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