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Numerical computations of premixed propane flame in a swirl-stabilized burner: Effects of hydrogen enrichment, swirl number and equivalence ratio on flame characteristics

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ABSTRACT

This paper investigates the effect of hydrogen addition and swirl intensity and equivalence ratio on characteristics of premixed C_3H_8–air flame, in a model burner. The numerical simulation is carried out using Reynolds Average Navier–Stokes (RANS) technique with Realizable k–ε as a turbulence closure model. The turbulence–chemistry interaction scheme is modeled using FR/EDM with three-step global reaction mechanism. The study is performed with two lean regimes of $\Phi = 0.3$ and 0.5 and four volumetric fractions of hydrogen $X_{H2} = 10\%$, 20%, 40% and 80% for two swirl numbers $S_n = 0.6$ and 1.05. First, validations of the computational models with the experimental data are performed, and a good agreement is found. Second, the effect of H_2 addition to extended lean flammability limits is addressed. Third, the differential diffusion effects on the accuracy of the predictions are studied and therefore should always be accounted for. Fourth, the effect of H_2 addition on the flow development and the flame characteristics is investigated. Results indicate that the H_2 addition affects strongly the flame structure. Two types of enriched flame are found, Balloon-type and M-type flames. The effects of H_2 addition on the reaction rates of C_3H_8 and H_2, the flow species and CO emissions are also analyzed.

Introduction

The environmental issues of electrical power generation and energy production play an important role in the economic development of modern power plants. In conventional power plants, the industrial gas turbines (GT) operate on hydrocarbons (i.e. natural gas) with lean premixed flames. The harmful combustion pollutants emitted from the conventional power plants force scientists to develop viable techniques to reduce it. Alternative energy such as blended hydrocarbon/hydrogen fuels have recently become important, particularly as an attractive solution to decline

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emission levels [1,2]. These blends have several advantages due to the beneficial hydrogen characteristics. Hydrogen has high specific energy on mass basis, it can be generated from various energy sources, it is renewable and it can be a very clean alternative to hydrocarbons, as there is no CO, CO_2, SO_x and UHC emissions from its combustion [3]. It is attractive to design premixed combustors which operate with hydrogen. But several technical problems remain which prevent its widespread adoption for power generation systems. The addition of small quantities of hydrogen to the reactants in premixed hydrocarbon combustors, can provide several beneficial changes in the burning velocity and temperature of a flame [4]; moreover, it could reduce the production of CO and NO_x [5]. Several studies have been conducted on the fundamental basis of hydrogen–hydrocarbon–air flames. It has been mentioned that the hydrogen addition to hydrocarbon–air flames can avoid the flame extinction and extended lean flammability limits [6,7]. There have been a number of studies focused on the stabilization and blowout limits of hydrogen enriched hydrocarbon–air flames [8,9]. It has been reported that the hydrogen enriched flames are less vulnerable to heat loss and strong strains, which improves its stability and also extends the flammability limit. There have been numerous studies of swirl-stabilized hydrogen enriched methane–air premixed flames [10–15]. It has been shown that the hydrogen addition resulted in a significant change in the swirling flame structure, indicated by a shorter and more robust appearing flame [11,13]. The hydrogen addition also reduces the size and shape of the recirculation bubble resulted from Vortex-Breakdown (VB) in swirl-stabilized premixed combustors [14].

There have been only few studies dealing with the effect of different swirl intensities on hydrogen enriched hydrocarbon–air premixed flames. Syred et al. [16] carried out an experimental investigation to study and reduce the effect of flashback in a compact design generic swirl premixed burner. The authors investigated a range of different fuel blends for flashback and blow-off limits. These mixtures include methane, methane–hydrogen blends, pure hydrogen and coke oven gas. In addition, they studied three swirl numbers ($S = 1.47$, $S_{II} = 1.04$ and $S_{III} = 0.8$) by varying the number of inlets or the configuration of the inlets in the used compact burner. They reported for the higher swirl number $S = 1.47$, the central recirculation zone (CRZ) becomes enlarged and extends backwards over the fuel injector to the burner baseplate for all fuels, and causes flashback. For the lower swirl number ($S_{III} = 0.8$) it is shown the best flashback limits for methane based fuels with hydrogen content up to 30% and for hydrogen based fuels with hydrogen content $\geq$ 65% for equivalence ratio $\Phi \leq 0.65$. Kim et al. [17] performed an experimental study of the effect of hydrogen addition in CH_4–air premixed flames in a laboratory-scale swirl-stabilized combustor under unconfined conditions. They examined different swirlers (different swirl vane angles 30°, 45° and 60°) to investigate the effect of swirl intensity on enriching CH_4–air flame. The laboratory-scale premixed combustor operated at 5.81 kW. The authors reported that the flame area increases at upstream regions of the reaction zone due to the increased availability of ignition energy from the recirculation flow at increased swirl strengths to the flow. The flame area is also found to increase at the downstream locations from the burner exit by recirculation flow due to the higher centrifugal force with increased swirl intensity. They found also that for lower swirl intensity the NO concentration in the reaction zone reduces with increase in hydrogen content in the fuel mixture. For higher swirl intensity, the NO concentration increases with the increase of hydrogen content in the fuel mixture. Kim et al. [18] preformed another experimental study for the same swirl-stabilized premixed combustor by grading the same operating conditions and taking in account the confinement of the hydrogen enriched CH_4–air flame. They confirmed the previous findings of the past works about the extending of the lean stability limit by hydrogen addition. The authors reported also that, the stability limit is reduced at higher swirl intensity to the fuel–air mixture operating at lower adiabatic flame temperatures. They showed that the addition of hydrogen increases the NO_x emission; however, this effect can be reduced by increasing either the excess air or swirl intensity. They also compared emissions of NO_x and CO from the premixed flame with a diffusion flame type combustor. The authors found that the NO_x emissions of hydrogen-enriched methane premixed flame were lower than the corresponding diffusion flame under the same operating conditions for the fuel-lean case.

Because of the complex turbulent nature of reacting swirling flows, accurate numerical simulations of such flows require a carful choice of turbulence models. It is generally accepted that the Standard $k-\varepsilon$ model [19] can perform reasonably well for simulating simple turbulent flows. However, it appears inadequate for simulating reacting swirling flows. Sharif et al. [20] reported that the Standard $k-\varepsilon$ model shows overestimate the level of turbulent diffusion on a turbulent swirling flow in a cylindrical combustor. It is reported that the deficiency of the Standard $k-\varepsilon$ model is due to the use of isotropic eddy viscosity concept, which is not the case for most turbulent swirling flow structures that are anisotropic. In order to address the deficiency of the Standard $k-\varepsilon$ model, Shih et al. [21] purposed the Realizable $k-\varepsilon$ model by introducing a new eddy viscosity formula and a new dissipation rate equation. A numerical study using the Realizable $k-\varepsilon$ model is presented by AbdelGayed et al. [22] to simulate a premixed high swirl flow in a GT combustor. They found a quite good agreement between the calculated and measured axial and tangential velocities distribution over the whole combustor. They also well captured the IRZ. For combustion modeling of swirling flows, appropriate turbulence–chemistry interaction models are required to account for the chemistry of the flame and its interaction with the turbulent swirling flow in a detailed way. It is reported that the Eddy-Dissipation Concept model (EDC) [23] lead to good numerical predictions. Especially when its combined with detailed chemistry as found by De et al. [24]. They assessed the EDC in combination $k-\varepsilon$ turbulence models and chemical kinetic schemes for about 20 species, on the Delft jet in hot coflow. They mentioned that the Realizable $k-\varepsilon$ model exhibits better performance in the prediction of entrainment, compared by Standard $k-\varepsilon$ model. In addition, the EDC model correctly predicts the experimentally observed decreasing trend of lift-off height with jet Reynolds number. More simple and cost effective model, which take in to account the finite rate chemistry is the Finite-Rate/Eddy-Dissipation model (FR/EDM).

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