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Control of methane flame properties by hydrogen fuel addition: Application to power plant combustion chamber

Fethi Bouras [a] [b], Mohammed El Hadi Attia [b], Fouad Khaldi [a], Mohammed Si-Ameur [c]

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Abstract

This study presents a numerical investigation of the effects of mixing methane/hydrogen on turbulent combustion processes taking place in a burner similar to that integrated in gas turbine power plants. Thereby, in comparison to the reference case where the burner is fuelled by 100% of methane, the variations of the axial velocity field, temperature field and mass fraction of carbon monoxide field are examined for different percentages of hydrogen fuel injection. The computed results, obtained by using the software Fluent-CFD, are compared and validated against experimental reference data. Results show that the hydrogen addition to the methane has an impact on all physical and chemical parameters of the reactive system.

Introduction

The improvement of combustion processes performance in gas turbine power plants is based on the control of the injection and the composition of the fuel. For this raison, several studies are investigated in this way considering natural gas turbines as a source of power production. Whereas, the control of the flame behavior and the harmful emissions, CO and NO_x, are the main objective in the engine industry [1], [2]. The blending of hydrogen with hydrocarbon fuels may be improving the flame propagation speed enabling, thereby, a stable combustion at a lean mixture condition [3]. Recent researches in the area of combustion and burner design have been motivated by the desire to preserve a clean environment and reduce energy consumption. Experimentally, the effects on a spark ignition engine of hydrogen and methane mixtures have been considered. Effectively, these experiments showed the equivalence ratio at different percentage of mixtures of hydrogen and methane [4], [5]. The experimentations have well explained the injection sensitivity in which delay decreases with the increasing of temperature regardless of whether methane or hydrogen dominates [6], [7]. Therefore, the NO emissions increase, HC, CO and CO_2 emission values decrease and brake thermal efficiency values increase too following the hydrogen percentage addition [9], [8]. Moreover, the ignition behavior of the methane–hydrogen mixture, depending on pressure, resembles that of methane or hydrogen fraction is less than 40%, where the ignition delays down with the increasing pressure. For the hydrogen fraction equals to 60%, a negligible promoted effect of the pressure on the ignition of the methane–hydrogen mixture is exhibited [10], [11].

Many works studied the combustion characteristics of hydrogen-enriched methane flame at different swirl strengths. They investigated the role of swirl strength identification to the incoming mixture. Hereby, using the diagnostic that provides information on velocity, thermal field, and combustion generated OH, NO_x and CO species concentration in the flame; where the lean stability limit is extended by hydrogen addition [12], [13]. This stability limit can be reduced at higher swirl intensity to the fuel–air mixture operating at a lower adiabatic flame temperature. Also, the higher combustibility of hydrogen assists to promote a faster chemical reaction, raises temperature and reduces the recirculation flow in the reaction zone. The upstream of flame region is more dependent on the swirl strength than on the effect of hydrogen addition to the methane fuel. Furthermore, the addition of hydrogen increases the NO_x emission [14]. This, however, effect can be reduced by increasing either the excess air or the swirl intensity. For the fuel-lean case the NO_x emissions of the hydrogen-enriched methane premixed flame were found to be lower than the corresponding diffusion flame under same operating conditions. Furthermore, low swirl strength assists in reducing the cold flow recirculation into the reaction zone and helps in increasing the stability limit at a lower adiabatic temperature case too [15].

Recently, studies proved the advantage of modeling the turbulence/chemistry interaction for the fuel enrichment by H_2. The hydrogen addition shifts the reaction zone to upstream locations of the flame to cause an upgrade concentration of OH radicals. Consequently, the increase in the peak temperatures provokes the NO formation rate up in the reaction zone. However, this effect is diminished at a larger swirl strength to the flow [16]. The NO_x emission of hydrogen-enriched methane premixed flame is more dependent on the equivalence ratio compared to the diffusion flame, where the rapid cooling of the reaction zone happens. Also, an excess air entrainment from the surroundings is caused due to the unconfined case as compared to the diffusion flame case [3], [15]. Non-premixed turbulent combustion burning in a cylindrical combustor is a representative configuration of many academic and industry combustion systems. With the development of CFD tools and rapidly expanding computer capacity, turbulent models emerge as a tool for simulating 3D combustion that occurs in relatively complex systems [17], [18], [19]. Among studies interested in the interaction of turbulence/chemistry for the non-premixed combustion, we have cited Bouras et al. where focusing on a scalar dissipation rate fluctuations in non-premixed turbulent combustion using a stochastic approach [17], [18].

In this numerical investigation, the turbulent combustion fueled by CH_4 and/or H_2 issuing into a hot and diluted co-flow air is considered to emulate the combustion in cylindrical burners. In general, the modeling is carried out using the LES model coupled with PDF approach to describe turbulence–chemistry interaction. In our contribution, we are interested in the effects of hydrogen enrichments methane fuel on some flame properties, i.e. velocity, temperature and carbon monoxide fraction. Results show that the hydrogen addition to methane leads to improve mixing and increase the turbulent kinetic energy decay along the flame axis.

Section snippets

Governing equations

The aerothermochemistry equations governing a gaseous combustion are summarized below for references [17], [18], [19], [20], [21], [22], [23]. Therefore, the filtered governing equations in LES for turbulent combustion can be written in Cartesian coordinates as: **Continuity:** $\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial}{\partial x_i}(\bar{\rho}\tilde{u}_i) = 0$

Momentum: $\frac{\partial \bar{\rho} \tilde{u}_i}{\partial t} + \frac{\partial}{\partial x_i} \left(\bar{\rho} \tilde{u}_i \tilde{u}_j \right) = -\frac{\partial}{\partial x_i} \left[\bar{\rho} \left(\overline{u_i u_j} - \tilde{u}_i \tilde{u}_j \right) \right] - \frac{\partial \bar{p}}{\partial x_j} + \frac{\partial \overline{\tau_{ij}}}{\partial x_i}$

Energy $\frac{\partial}{\partial t} \bar{\rho} \tilde{h} + \frac{\partial}{\partial x_i} \left(\bar{\rho} \tilde{u}_i \tilde{h} \right) = -\frac{\partial}{\partial x_i} \left[\bar{\rho} \left(\overline{u_i h} - \tilde{u}_i \tilde{h} \right) \right] + \frac{\partial \bar{p}}{\partial t} + \frac{\partial}{\partial x_i} \overline{u_j \tau_{ij}}$

Species $\frac{\partial}{\partial t} \bar{\rho} \widetilde{Y}_f + \frac{\partial}{\partial x_i} \left(\bar{\rho} u_i \widetilde{Y}_f \right) = -\frac{\partial}{\partial x_i} \left[\bar{\rho} \left(\overline{u_i Y_f} - \tilde{u}_i \widetilde{Y}_f \right) \right] + \bar{\dot{\omega}}_f$

Where: i=…

Large eddy simulation model

In this section, we deal with the tensor of the unsolved constraints τ_{ij} as the tensor velocity of deformation $\widetilde{S}_{ij}$ for subgrid models by the intermediary of a turbulent viscosity (ν_t), and a subgrid kinetic energy (k_{ll}). Therefore, we focus on the assumption of Boussinesq in which the small scales influence the large scales via the subgrid-scale stress [17], [18], [19], [20], [21], [22], [23]:$\tau_{ij} = 2\bar{\rho}\nu_t \widetilde{S}_{ij} - \frac{1}{3} k_{ll} \delta_{ij}$Where, the filtered strain rate tensor is defined by:$\widetilde{S}_{ij} = \frac{1}{2} \left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right) - \frac{1}{3} u$…

Experimental configuration and application domain

The configuration of the two coaxial jets that confine the combustor is given in Fig. 1. Where, it was the focus of numerous investigations because of its relatively simple geometry and its similarity to gas turbine burner [17], [18], [19]. Thereby, we investigated the numerical validation of the LES/PDF coupled models with the experimental data, to study the behavior of the non-premixed combustion fueled by mixture of CH_4 and/or H_2. Whereas, the study consists of three main parameters: axial…

Results and discussion

In this section, we begin with the validation of the coupled models described previously with the experimental data for the case supplied with only CH_4 [19]. After that, we introduce the effect of the hydrogen fuel injection with the methane. In addition, the same parameters used for the validation are used also to control the flame behavior supplied by the CH_4/H_2 mixture. Moreover, the presentation and comparison of results are based on normalizing length and velocity by using, respectively,…

Conclusion

The present work is a numerical analysis of the benefits of the enrichment of turbulent non-premixed methane flame by hydrogen injection. The FLUENT-CFD package was used to carry out the computations of combustion process in a cylindrical burner, by using the coupled models LES/PDF. The conclusions arising from this investigation are as follows:

- The computational results of the coupled dynamic model, LES, and scalar model, PDF, give a satisfactory agreement with the experiment data for the…

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