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Effects of hydrogen addition on the structure and pollutant emissions of a turbulent unconfined swirling flame☆

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ABSTRACT

This article aims at investigating the effect of hydrogen addition on the temperature and pollutant emissions of turbulent unconfined swirling methane/air flame. A computational approach utilizing the steady laminar flamelet and the realizable k–ε combustion and turbulence models, respectively, has been used. The turbulence–combustion interaction has been modeled by a β-shaped presumed probability density function. The percentage of hydrogen in the fuel stream is modeled at a wide range from 0% to 50% of the fuel volume flow rate. Results show that with the increase of volumetric hydrogen percentage in the fuel stream the flame structure changes considerably. The size of maximum temperature region decreases significantly to a small region at flame tip and peak temperature rises which leads to increase in NO emission levels. The flame with 10% hydrogen is observed to be slightly of the general trend. This is deemed to be due to the change in flow field as a result of change in fuel density, while the amount of hydrogen is not effective enough to change the combustion characteristics of the flame.

1. Introduction

1.1. Background

The increasing regulations on pollution emissions are pushing the combustion research community to design cleaner and more efficient combustion systems. Meanwhile, hydrogen as a clean fuel with no CO, CO_2, SOx and UHC emissions, has a high potential for being used as a major fuel in future [1,2]. Unfortunately hydrogen is not freely found in nature and economical and eco-friendly methods of mass production are subject of further studies. In addition to that, when it comes to practice as a widely used fuel, hydrogen poses some disadvantages, mainly safety challenges in storage or transport as a result of high flammability and diffusivity which leads to high explosion risk [3,4].

The majority of research efforts focusing on hydrogen enriched combustion remained far from application since they were only considering the enrichment of liquid fuels. This remained evident until the use of Natural gas and other gaseous fuels embarked the power generation industry in the 1990s. The effect of hydrogen enrichment on liquid fuel is somehow limited since the combustion of such fuels depends primarily on the atomization and mixing process, which are controlled by mechanical methods. On the other hand, the effect of hydrogen addition on gaseous combustion is more radical since the combustion properties of such flames depend primarily on the fuel properties and initial conditions of the flame. For this reason, during the last decade, hydrogen enrichment of various gaseous fuels such as natural gas and propane has been identified as a very efficient method to ignite mixtures of such fuels below their lean flammability limits; which means a radical development in fuel saving technology. The physical essence behind such phenomenon is the elevated temperature resulting from the combustion of hydrogen as well as its superior reaction rate with oxygen. The elevated temperature boosts the Arrhenius reaction rate of the base fuel; while the high reaction rate of hydrogen consumes a portion of the oxygen in the lean mixture. Some of the most important relevant researches are discussed in the next section to articulate the significance of the present work.

1.2. Literature review

1.2.1. Modeling of turbulent hydrogen enriched combustion

For simulating the combustion in hydrogen-enriched gaseous flames, models which are based on fast chemistry assumption are the first to be considered due to their low computational cost. The conserved scalar model is one of such models which are based on the instantaneous relationship of the thermo-chemical properties of the flame as a function of the mixture fraction (conserved scalar). This model can be subcategorized with some other models including conserved scalar models with equilibrium chemistry, flame sheet, and laminar flamelet [5]. Ilbas et al. [6] used the latter model to simulate a turbulent CH_4/H_2 non-premixed jet flame. Mardani et al. [7] and Frassoldati et al. [8] used the Eddy dissipation concept to model similar flames. However their results show that

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Nomenclature

Latin letters

C_2	Constant value = 1.9
$C_{1\delta}$	Constant value = .44
C_μ	Constant value = 0.09
C_x	Constant value = 2
D	Mass diffusion coefficient
L_f	Flame length m
M_t	Turbulent match number
P	Probability Density Function
Re_s	Annular air Reynolds
Re_j	Fuel jet Reynolds
S_g	Swirl number
U, u	Velocity in axial direction $m.s^{-1}$
U_j	Fuel jet velocity $m.s^{-1}$
U_s	Axial velocity of annular air stream $m.s^{-1}$
W_s	Swirling velocity of annular air stream $m.s^{-1}$
W, w	Swirl velocity $m.s^{-1}$
X	Scalar dissipation
Y_i	Mass fraction of species^i
Z	Mixture fraction

Greek letters

ρ	Density $kg.m^{-3}$
k	Turbulent kinetic energy
μ	Dynamic viscosity $kg.m^{-1}.s^{-1}$
μt	Eddy viscosity $m^2.s^{-2}$
ε	Dissipation rate of turbulent kinetic energy $m2.s^{-3}$
σ_k	Turbulent Prantle number for k, = 1.0
σ_δ	Turbulent Prantle number for ε,=1.2
γ	Gas specific constant
ν	Kinematic viscosity C $m^2.s^{-1}$
$\varnothing$	Any thermo chemical property (i.e. temperature)

Subscripts

i	In x direction
j	In Y direction

Superscript

$'$	Fluctuation
$''$	Variance
–	Favre average

such combustion model has shortcomings in prediction of minor species such as O and OH which consequently leads to error in NO predictions. The steady laminar flamelet model is known to perform better in terms of prediction of minor species. Several researchers [9–11] have used such model to simulate similar flames of CH_4/H_2. Yilmaz et al. [9] calculated the Probability Density Function (PDF) for temperature, mixture fraction and major and minor species mass fractions and compared the flamelet model with equilibrium model, showing that flamelet model yields better results within the reaction zone. Hossain et al. [10] compared Laminar flamelet model with equilibrium chemistry, constrained equilibrium chemistry and flame sheet model in a simulation of a non-premixed CH_4/H_2 bluff body flame. They showed that only major species are predicted with flame sheet model. It yielded good predictions for temperature and H_2O mass fraction but it over predicted CO_2 level. Temperature, H_2O and CO_2 were well predicted by constrained equilibrium model but it failed to accurately predict level of OH and CO. Similarly the equilibrium model, showed poor prediction of species mass fraction and temperature in general. They concluded that among studied models only laminar flamelet model predicted temperature and mass fraction of major and minor species with acceptable accuracy. A similar flame was modeled by Hossain and Malalasekera in [12,13] using flamelet model and by Hossain et al. [14] with a coupled radiation/flamelet combustion model, yielding reasonably good predictions at upstream locations.

1.2.2. Chemical reaction mechanisms in the laminar flamelet model

Chemical reaction mechanism with which the chemistry of the flame is simulated plays an important role in the laminar flamelet model performance. Ilbas et al. [6] used a reduced mechanism, including only seven species and Yilmaz et al. [9] used another reduced mechanism based on GRI mechanism [15] with 18 species. Frassoldati et al. [8] developed and implemented a new mechanism with 48 species and 600 reactions involved. Ravikanti et al. [11] used GRI2.11 and Mardani et al. [7] compared this mechanism with a reduced DRM-22 mechanism and found that the results yielded by the two mechanisms differ as slightly as 1%.

1.2.3. Turbulence modeling

Although the RSM is deemed to be capable of predicting flows with high strain rate and streamline curvature, its application in several studies yielded results that are controversial with respect to its theoretical basis. Meier et al. [16] used Reynolds Stress Model (RSM) to simulate a swirling flame and reported its failure in predicting the flow field. The use of RSM in modeling a swirling flow with a precessing vortex core (PVC) in a vortex separator has shown that the model is not capable of capturing the local velocity gradients, especially in the PVC region [17]. Besides, several convergence problems have been reported to exist for RSM simulations of vortex flows [18–20]. On the other hand several variants of the k–ε model have been used successfully to model swirling flows with recirculation zones and PVC in different combustion systems [21–31]. Jochmann et al. [32] compared the performance of the latter model with the RSM for predicting PVC in a gas turbine combustor and found the only slight differences exist between both models. Repp et al. [33] used the k–ε model and a second moment closure to simulate a similar flame and reported fairly acceptable results by both models. Frassoldati et al. [34] also used k–ε turbulence model to simulate a confined highly swirled flame and reported results that are in good agreement with measurements. Dally at al. [35] simulated a bluff body flame with similar fuel compositions with standard and modified k–ε and RSM models used with a flame sheet model and a beta probability density function. They reported that both RSM and standard k–ε failed to predict the flow field with sufficient accuracy. A fine-tuning of the k–ε model constant (Cε1 from 1.44 to 1.6) was proposed to improve the prediction of flow field. Same bluff body flame was simulated using a conditional moment closure combustion model by Kim and Huh [36]. They implemented the mentioned modification in k–ε model and reported overall good predictions of velocity and mixture fraction fields. However the local fluctuations of mixture fraction and velocity fields were not well predicted. Fine-tuning of the standard k–ε model constants can also be found in [6–8] in conjunction with EDC combustion model, where acceptable accuracy is reported. When used with laminar flamelet model, both the fine-tuned k–ε model and the RSM yielded acceptable results as reported in [10] and [11] respectively. Yilmaz et al. [9] compared the fine-tuned k–ε model with large eddy simulation (LES) with two subgrid models; the Smagorinsky-Lilly and RNG/k–ε models. Their results indicated that the modified k–ε model is capable of producing results that are in good agreement with measurements as well as with LES, which is significantly more expensive in terms of computational resources than any RANS model.

1.2.4. Objective and methodology

The objective of this research was mainly to investigate the effect of hydrogen addition on the swirling flame temperature, structure and pollutant emissions. In the present work a methane swirling flame (Sydney fame SM1) [37] is computationally investigated by the CFD