Investigation of Swirl Stabilized CH$_4$ Air Flame with Varied Hydrogen Content by using Computational Fluid Dynamics (CFD) to Study the Temperature Field and Flame Shape

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Abstract-In the current paper, numerical simulations of the combustion of turbulent CH$_4$-H$_2$ are presented employing the standard k-epsilon and the RNG k-epsilon for turbulence closure. The Fr-ED concept is carried out to account for chemistry/turbulence interaction. The hydrogen content is varied in the fuel stream from 0% to 100%. The numerical solutions are validated by comparison with corresponding experimental data from the Combustion Laboratory of the University of Milan. The flow is directed radially outward. This method of fuel injection has been already been explored experimentally. The results show that the structure of the flame is described reasonably and both standard k-ε and RNG k- ε models can predict the flame shape. The general aspect of the temperature profiles is well predicted. The temperature profiles are indicating a different trend between CH$_4$ and CH$_4$/H$_2$ fuel mixtures.

Keywords-RNG k-epsilon; swirl; hydrogen; CFD; CH$_4$

I. INTRODUCTION

Lean combustion emerges as a potential and an advantageous concept to attain efficiently the combustion process and control NO$_x$ emissions in power-generation gas turbines [1–3]. The best approach to obtain a stable lean flame is to add a highly reactive fuel to a traditional hydrocarbon fuel. Due to its high chemical reactivity, hydrogen could be used as a useful fuel addition to enhance the combustion of natural gas. The use of hydrogen in blended fuel can be a good option regarding combustion characteristics, such as extending the lean flammability limits [4, 5] and the environmental advantages by decreasing the emissions [6]. The research on the combustion of NG–H$_2$ fuel mixtures is open and growing. Studies [5, 7-9] on NG–H$_2$ hybrid flame stability behavior are at the center of attention. Authors in [10-11] conducted an experimental investigation on laminar LPG-H$_2$ jet diffusion flame and NG-H$_2$ turbulent flame respectively and affirmed that a very small fluctuation in the visible flame length, in up to 20% of hydrogen addition, enhances the flame length when higher hydrogen concentrations are injected. In the other hand, different investigations [5, 7, 8, 12, 13] were undertaken on the height of the blue cone and pointed out the influence of hydrogen injection in the increment of the combustion rate, the reduction of CO, CO$_2$ and HC emissions, and the extension of the stable lean limit of natural gas burner [1, 9-12, 14-16]. Authors in [17] developed an experimental investigation in optically accessible propane/ hydrogen burner and found that

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the flame pattern of the hydrogen is of a weak turbulent flame [18]. A significant reduction in both CO emissions and soot concentration with hydrogen addition was reported in [4, 11, 12] when turbulent jet diffusion flame was characterized. Authors in [19-21] report an increase in flame adiabatic temperature and a reduction in flame thickness. Authors in [15] investigated the counterflow of NG/H_2–air partially premixed flame numerically and experimentally. They stated that the influence of prompt NO_x was important in the total NO_x formation. One of the purposes of this paper is to support certain theories and assumptions drawn from experiments in swirl flames. The goal was to obtain qualitatively correct predictions. This work focuses on the numerical simulation of turbulent flames utilizing well known turbulence and combustion models [22, 23].

Leaner flames due to the hydrogen addition with different various hydrogen-hydrocarbon mixtures lead to thermo-diffusive instabilities which have an impact on flame propagation and stability [24, 25]. More details are needed about the interaction of these types of flames with turbulence in practical devices (swirl-stabilized burner). A better understanding of the fuel improvement on the fundamental flame properties is critical to the development of combustion systems and the role of hydrogen on these systems appears to be an important parameter. The goal of the current study is the investigation of flame behavior by the use of numerical simulations with the RANS model to treat turbulence coupling (the standard /RNG k-epsilon) and the Fr-ED model to represent the turbulence/chemistry interactions. For this purpose, the effect of hydrogen addition in methane flames has been examined by modeling a swirl-stabilized combustor in radial injection. The aim is to give more information on the influence of hydrogen enrichment on the CH_4 flame properties and a comparison is presented between the experimental results and the numerical solutions by considering a flame shape, temperature field, and velocity vectors.

II. NUMERICAL METHODOLOGY

The conservation equations governing reactive flows solved by code FLUENT [26] are mass, momentum, species, and energy using several models described with finite volume methods [27]. The schematic of the partially premixed swirl-stabilized burner configuration can be seen in [5]. The grid is shown in Figure 1. The geometry is open to atmospheric pressure and the meshing of all computational domain examined in this work was set up with GAMBIT [24]. The meshing is non-uniform, with a fine meshing in zones of great interest. The numerical simulations carried out in this study were generated using a segregated, implicit solver. The coupled equations were solved with second-order accuracy in time and momentum, continuity, and turbulence parameters. The algorithms PRESTO and SIMPLE were respectively used for the pressure interpolation and for the coupling of pressure and velocity. A uniform velocity profile was assumed for the inlet conditions, and the inlet turbulence intensity was set to 11%. At the inlet, the boundary conditions were validated by the experiments. Theoretically, zero gradient condition is taken at the outlet boundary. These boundary conditions can be listed as follows: inlet, outlet, and wall boundary conditions. The DO

model was used to calculate the radiating heat transfer of the unconfined flames [28]. The experimental apparatus is a laboratory scale swirl burner [5]. It consists of two concentric pipes with the annulus (outer radius, R_b = 18mm) supplying the central pipe (r_{int} = 7.5mm) injecting the fuel mixtures (swirled air). The fuel mixture is radially injected into the swirled air stream through 8 circular holes. The holes are distributed on the circumferential section located 3mm upstream from the exit of the burner.
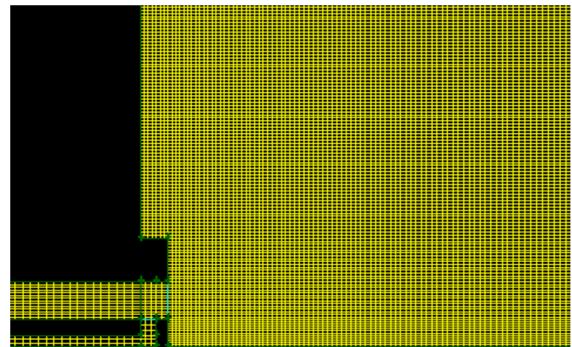

Fig. 1.   Numerical grid of the burner/furnace system.

III. TURBULENCE MODEL

To solve the turbulence problem, the two equation-based RANS standard k-ε turbulence model was used [29]. It is a semi-empirical turbulence model based on isotropic eddy-viscosity hypotheses. The RNG k-ε model is considered as a new version of the k-ε family of turbulence models. It is derived by a statistical technique called renormalization group method [30].

IV. RESULTS AND DISCUSSION

A. Flame Shape

The consequence of hydrogen addition is studied using CFD and compared against measurement data [31, 32]. Streamlines were obtained by two-dimensional (2-D) PIV measurements, in a region located immediately downstream of the exit throat of the burner. Flame imaging of the spontaneous flame emission is used to gain a general understanding (see Figure 2(a)). We can see the simulation plot from the right side. Although these diagnostics provide a somewhat different view of the flame, they provide complementary information. In general, the simulated image of the investigated flame (100% CH_4) shows a very similar shape compared to the experimental ones, typical of high swirl processes in transverse injection. The comparison shows that standard k-ε is slightly over-predicted at most locations whereas the RNG k-ε model results are quite good [33]. Figure 2(a) shows the sudden expansion nozzle at the lower part of the combustion chamber and two locations of high product formation rates are located: one is on centerline in an upside-down V-shape, which can also be clearly seen in the photo of the flame in the experiment and the second in red color indicates a high product formation rate, which means an area with high chemical reaction production rates. The use of finite-rate-Eddy dissipation model generates a reaction at the mixing zone.
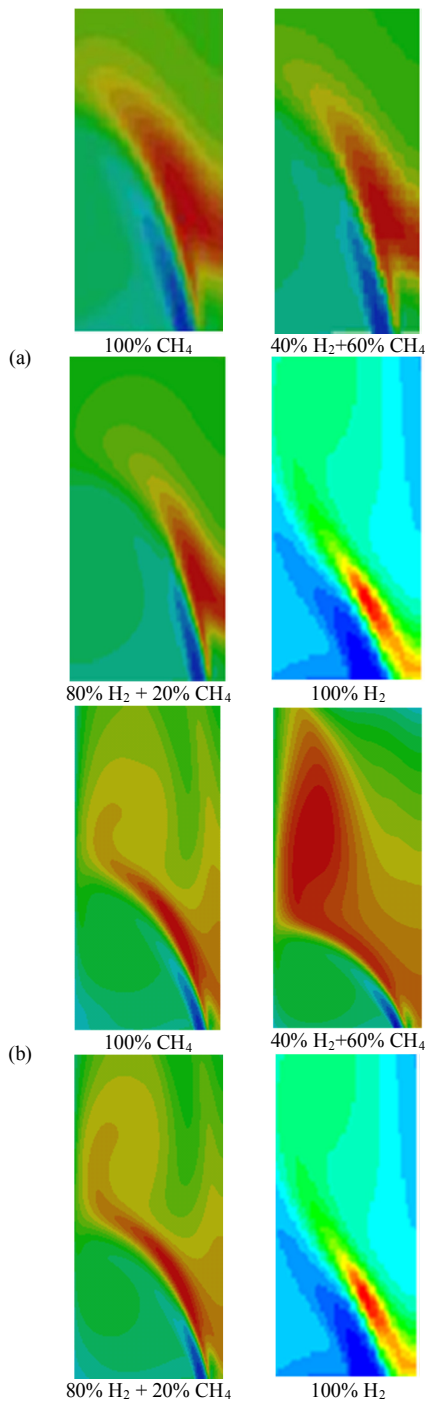
Fig. 2.   Flame shape and position comparison of the simulation (right) and the flame photo from the experiment (left): (a) standard k-ε model, (b) RNG k-ε model.

The experimental reaction takes place at the center of the zone where a strong inner recirculation zone appears, whereas reaction occurs with a certain delay, when simulation is considered. The impact of the different percentage of H_2 blending to the CH_4–air flame on the global flame characteristics is shown in Figure 2 (different flame shapes and positions).
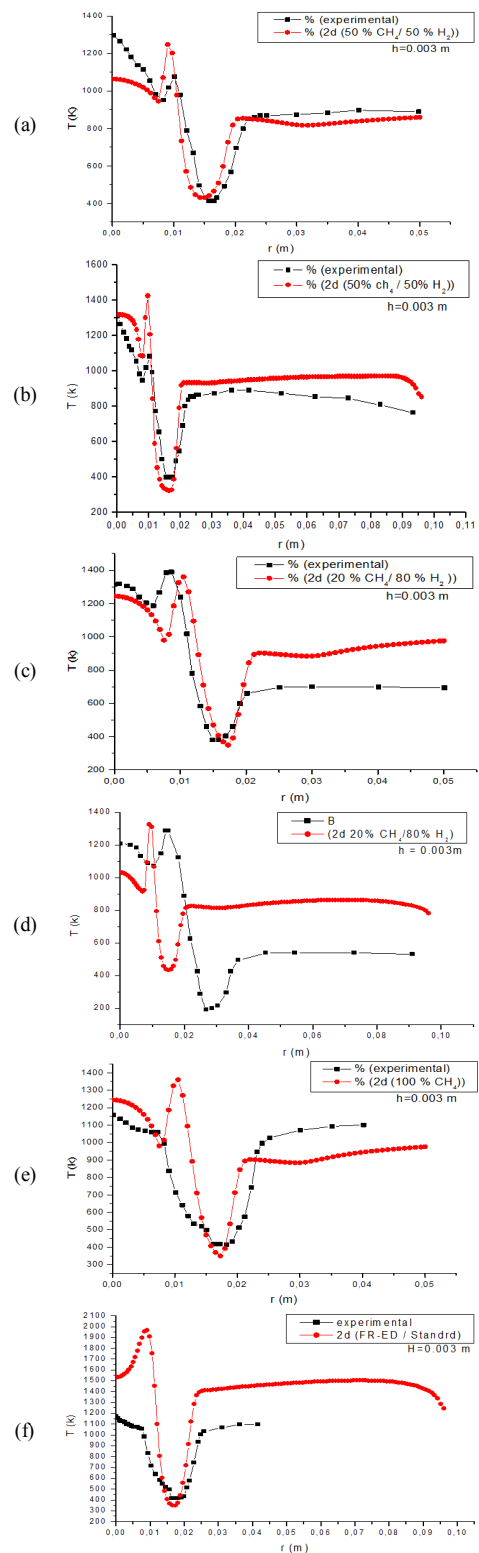

Fig. 3.   Radial distribution of mean temperature: (a) RNG k-ε 50% CH_4 - 50% H_2, (b) standard k-ε 50% CH_4 - 50% H_2, (c) RNG k-ε 20% CH_4 - 80% H_2, (d) standard k-ε 20% CH_4 - 80% H_2, (e) RNG k-ε 100% CH_4, and (f) standard k-ε 100% CH_4.

It can be observed both from the experiments and the numerical simulation that the structure of the flame, i.e. central recirculation zone shape, changes with H_2 addition. Enhances in H_2 concentration in the mixture increase the axial velocity and decreases the size and strength of the recirculation region. Similar behavior was reported in [34].

B. Temperature Field

To provide more information in this section, the computational solutions were compared with the measurements. To examine the role of turbulence closure models, the same configuration was modeled using the standard k-ε and RNG k-ε turbulence models. The mean temperature profiles are shown in Figure 3, reporting a different trend between NG and H_2/NG fuel mixtures.
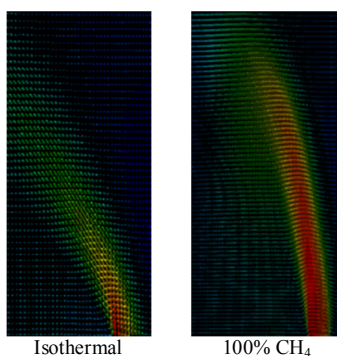

Isothermal   100% CH₄

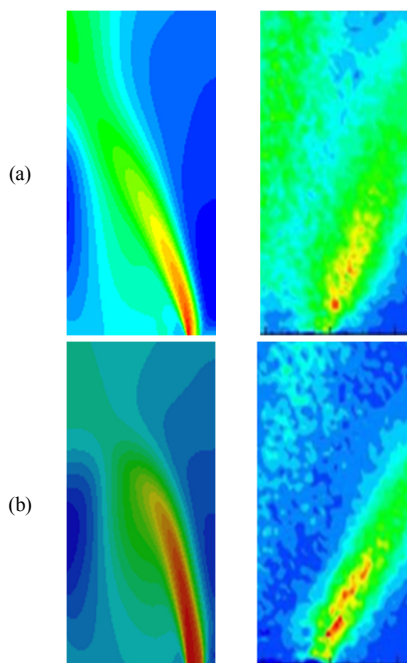Fig. 4.   Experiment (left) and simulation (right) velocity vectors.

Fig. 5.   Velocity fluctuations. Comparison of the experimental data and simulation results: (a)100 % CH_4, (b) 20% CH_4 + 80% H_2 flame.

The calculated temperature profiles are in agreement with the experimental results. When moving on radial direction, the numerical simulation agrees well with the trend of the experimental data. The calculated temperature indicating the existence of the hot area of the flame and then finally to the limit which assigns to the recirculation zone. The temperature profiles can be split in into three separate areas as reported in Figures 5 and 6.

The same results were obtained in [35]. The highest temperature shows that the flame takes place in the inner recirculation zone. When burning 100% NG, the peak temperature of the flame is quite close to 1150K, while its experimental value is estimated as 1250K. The peak temperature of the 80% H_2 flame increases to about 1800K, as we seen in the experiment [31, 32]. An unexpected temperature value is determined by the CFD when the k-e model is considered. At the periphery, a region characterized by quite uniform temperature values is established. This is related with the formation of a corner recirculating flow induced by the radial expansion of the air stream and by the wall confinement. This model succeeds to predict the hot zone of the flame while over predict the calculated temperature. When $r = 0.05$m, the model agrees with the experimental results. On the other hand, a good agreement is obtained when the RNG k- ε model is used. The RNG k-ε model results are in good accordance with the experimental measurements, and are comparable to the results obtained with the k-ε model, despite the lack of accounting for non-isotropic turbulent shear stresses expected in the swirling flow. It can be observed that the predicted radial profiles of temperature of the two models are reasonable at most of the axial locations.

C. Mean Flow Fields

To provide more information on the nature of the flow, we focus our solutions on the behavior of this type of flame by showing the existence of the Central Recirculation Zone (CRZ). The numerical solution shows an open swirl flow core. The Figure points out a more closed form with a small but strong recirculation region. The reaction zone estimated by simulation is not located on the axis as indicated by the measurements. The dynamic flow field is affected greatly by the combustion that redefines a velocity distribution. This discrepancy is mainly the result of shortcoming of the turbulence model which might overestimate the decay of turbulence intensity for these swirling flames. Under-combustion regime (Figure 4), in a region located immediately in the exit of the burner clearly indicates the existence of a CRZ. The width of the CRZ is smaller than under when burning 100% NG. Similar behavior was reported in [29]. As the H_2 percentage increases, the above regions reduce in size and move closer to the reactant outlet. When burning 100% NG, the axial flow fields by introducing velocity vectors obtained by the simulation are more large than the 80% H_2 flame.

Another important parameter describing the flow field, is the velocity fluctuations (Figure 5). Both results show an increase of the intensity a few mm downstream of the respective flame zone. A CRZ can be found, where the axial velocity is smaller than zero. This recirculation increases the flow divergence in the combustion chamber. In general, the numerical solutions agree well with the experimental results

(100% methane flame), but we failed to predict the inner recirculation zone with precision.

V. CONCLUSION

Numerical simulations of a turbulent $(CH_4\text{-}H_2)$/air flame were conducted in this study. The H_2 percentage varied in the mixture from 0% to 100%. The numerical investigation involved simulations employing the standard k-ε and the RNG k-ε for turbulence closure. The Fr-ED model is used to represent the turbulence/chemistry interactions. Numerical solutions were compared to experimental measurements which were used for model validation. The results show that the structure of the flame is described reasonably in both standard k-ε and RNG k-ε models which can predict satisfactorily the flame shape with the RNG k-ε model providing better performance than the k-e model. From the flame simulations, the hydrogen addition alters considerably the global flame characteristics by different flame shapes and flame positions. It can be observed from the experiments and the simulations that the structure of the flame varies with hydrogen blending.

In general, the temperature data were well represented. The RNG k-ε model consistently demonstrated superiority over the standard k-ε turbulence model. The dynamic flow field is affected greatly by the combustion. A region located immediately downstream of the exit throat of the burner clearly indicates the existence of a CRZ. Under combustion conditions the width of the CRZ is smaller than under when burning 100% NG. It was concluded that the use of a 2D axial symmetric grid is a promising toolbox for modeling turbulent combustion and can be used for predicting the operating conditions of complex industrial furnaces.

NOMENCLATURE

Y_R	Mass fraction of a particular reactant R
$v'_{i,r}$	Stoichiometric coefficient for reactant i in reaction r
$v''_{i,r}$	Stoichiometric coefficient for product i in reaction r
N	Number of chemical species in the system
$M_{w,i}$	Molecular weight of species i
$M_{w,j}$	Molecular weight of species j
$M_{w,R}$	Molecular weight of a particular reactant R
k/ε	Large-eddy mixing time scale
A	Empirical constant equal to 4.0
B	Empirical constant equal to 0.5.
α	Thermal diffusivity [$m^2 . s^{-1}$]
β	Thermal expansion coefficient [K^{-1}]
ϕ	Solid volume fraction
Θ	Dimensionless temperature
μ	Dynamic viscosity [$kg. m^{-1}.s^{-1}$]

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