Experimental and Numerical Analysis of Hydrogen Enriched Natural Gas Swirl Burner

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1. Introduction

The increasingly stringent ambient regulations pushed research efforts towards development of combustion devices (to be used for either energy production or propulsive systems) with reduced fuel consumption and low pollutant emissions. Unfortunately, the lean and ultra-lean combustion burners developed for this purpose suffer from the delicate issue related to flame stability. Local flame extinction is likely to occur as a consequence of lean combustion conditions associated with stretching and heat losses. This problem is further complicated when the combustion device has to operate with different fuel compositions [1]. The flame stability issue could be overcome by using fuel mixtures composed of a traditional hydrocarbon fuel and a small percentage of hydrogen. The higher flame speed and wider flammability limits of hydrogen as compared to traditional hydrocarbon fuels should sustain combustion under very lean conditions. Many attractive low or medium heating value fuel mixtures originated from biomass gasification or as crude oil refinery by-products contain some percentage of hydrogen [1]. Moreover hydrogen produced by steam or dry reforming will always contain some percentage of impurities such as CO or light hydrocarbons. In spite of the reasonably good knowledge and understanding of combustion behavior of “pure” fuels, the non-premixed combustion of fuel mixtures is still scarcely understood.

The aim of numerical analysis is to verify that we have the opportunity to simulate the flow, temperature and composition fields in the combustion chamber and the mutual interactions of these aspects.

1.1. Burner Geometry

The experimental apparatus is a laboratory-scale swirl burner (Fig. 1). The fuel is delivered by a central tube, while the swirling air flow is provided by a coaxial annulus. Details regarding the investigated burner typology are reported in [2]. Air swirl motion was imparted through an axial plus tangential air entry. The variation of the relative amounts of axial and tangential airflow controls the intensity of the swirl. Hydrogen and natural gas were mixed together about 300mm before the fuel nozzle exit. All tests were performed at ambient pressure and ambient temperature, with the flame confined by a cylindrical quartz chamber (192mm in diameter, 300mm in height). The burner is equipped with a radial injector that provides fuel admission transversal to the air stream and it is designated with eight circular holes. The radial injection creates a more stable flame in comparison to the axial injection used in previous investigations, and thus facilitates the use of a 2D-axial symmetric approach.

1.2. Mathematical modelling

The flow field in isothermal conditions and the flame were simulated with the Fluent 6.2 code using a 40,000 cells non-uniform unstructured computational grid in a steady 2D-axisymmetric approach. The grid was adapted to give high resolution in the flame region close to the inlets and save computational efforts elsewhere. Moreover, the 2D-grid sensitivity was tested using a 108,000 cells non-uniform unstructured computational grid.
In isothermal conditions the simulation obtained using a steady 2D-axialsymmetric grid was compared with that of a 3D grid. The geometry of the burner allows to use periodic boundary condition (angle 45°) and reduce the number of computational cells of the full grid (410000). For the spatial resolution the First-Order Upwind Scheme was adopted. The algorithms PRESTO! and SIMPLE [3] are respectively used for the pressure interpolation and for the coupling of pressure and velocity, as usually suggested for swirled flows [3]. The radiating heat transfer of the unconfined flames is calculated with the DO model [3]. The Standard k-ε model was used for the description of turbulent flow and different models for the turbulence-chemistry interactions.

2. Isothermal analysis

Figure 3 shows the comparison between numerical results and experimental measurements, referred, respectively, to mean axial and swirl velocity radial profiles at a distance from the efflux of h=2mm and h=24mm. In the isothermal analysis the fuel jet is replaced by an air stream. The oscillations that appear in the 3D results are simply a graphical effect due to the reinterpolation on the symmetry plane. The results show a general good agreement between the solutions obtained using 2D-axialsymmetric and 3D approach. This consideration allows to use the 2D-axialsymmetric approach for the reactive analysis and save computational costs. The model results well reproduce the experimental data obtained through LDV, although the axial velocity is slightly underpredicted.
3. Flame analysis

Flame analysis was carried out in the following conditions: 0%, 50% and 100% hydrogen content in the CH₄/H₂ fuel mixture. Adding hydrogen to natural gas at a fixed total volumetric flow rate reduces both the fuel mixture mass flow rate and the thermal power. Hydrogen improved and stabilized the combustion of natural gas near the burner head, increased flame temperature, as depicted in Fig. 4.

The generalized finite rate approach, that is based on the resolution of the transport equations for the species involved in the calculation and accounts for the effect of finite rate chemistry was used to take into account the turbulence/chemistry interactions. In particular, two different turbulent combustion models were used in conjunction to an appropriate kinetic scheme. The Finite Rate-Eddy-Dissipation Model (FR-ED) [4] was used with simple global kinetic mechanisms, while the EDC model [5] by Magnussen allowed to use detailed kinetic mechanisms. The kinetic model used in the EDC model simulations comes from Kee [6] for methane and hydrogen combustion.

### 3.1. 100% methane feeding

The first flame that was analyzed describes the combustion of pure methane. The FR-ED model was used with the two-steps kinetic scheme (methane-air-2step) of the Fluent database [3], while the EDC model with the detailed kinetic mechanism of Kee [6]. The comparison between experimental results and numerical ones is shown in Fig. 5. The solution obtained using the simplified kinetic model differs significantly from that obtained using the detailed mechanism. In particular, the EDC model produces a flame which is detached from the burner head and with a different morphology. The structure is less open and the temperature peak is less intense than the experimental data. The solution obtained using the simpler model generally shows a higher flame temperature. The velocity profiles were measured through PIV. Unfortunately this technique didn’t allow to measure the velocity correctly near the burner head (h=3mm). Generally the CFD simulations overpredict the velocity.

Figure 3. Comparison between experimental measurements (symbols) and model predictions of axial (U) and tangential (W) velocity profiles, using 2D and 3D computational grids.
3.2. Mixture feeding

The combustion of a H₂/CH₄ mixture was studied using the same models applied to the combustion of pure methane but adding a single step global H₂ oxidation reaction to the 2steps methane scheme. Therefore, the FR-ED model was coupled with the sum of the kinetic schemes methane-air-2step and hydrogen-air [3].

In this case of the fuel mixture the FR-ED model didn’t allow to simulate the flame which extinguished. This result confirms that this model cannot correctly be coupled with a multistep kinetic scheme. The EDC with Kee’s scheme, on the contrary, allowed to simulate the flame without extinguishment. It produces a flame similar to that obtained from the FR-ED model with pure methane feeding, obviously with a higher flame temperature and combustion intensity. The CFD modeling slightly underpredicts the velocity profiles and the flame in comparison to the measurements (fig. 6).

Figure 4. Temperature maps [K] at 0% (up), 50%(centre), 100% (down) of H₂ in the fuel.

Figure 5. Temperature and axial velocity profile in the methane alone flame.
3.3. 100% hydrogen feeding

The last flame that was analyzed refers to the combustion of pure hydrogen. The FR-ED model was simply coupled with the 1step hydrogen oxidation [3], while the EDC model with the kinetic scheme of hydrogen combustion described in [7].

For this case the experimental data are not available. From the modeling activity it is possible to observe that the maximum temperature near the burner head is higher using the EDC model than using FR-ED (fig. 7). This is an unexpected result and is different form the results obtained for the pure methane flame. This fact could be partially explained as an effect of the kinetic mechanism and also observing the tangential velocity profile at coordinated h=3mm (fig. 8). The EDC combustion model produces a different motion field respect of FR-ED model and therefore a different flame structure.

4. Conclusions

The aim of numerical analysis is partially achieved. The first result is that it was verified the possibility to use a 2D axial symmetric grid instead of a full 3D simulation for this particular
burner. A good agreement between experimental data and model results was obtained in isothermal conditions. Flame conditions require a proper model to describe the interactions between chemistry and turbulence. The EDC model by Magnussen, coupled with a detailed kinetic mechanism, succeeded in simulating the major characteristics of the flame generated burning a mixture of H₂ and CH₄.

Figure 8. Axial velocity profiles in the pure hydrogen flame.

The next activity will involve the use of a more appropriate kinetic scheme, for the use of EDC model with the pure methane feeding, and the evaluation of pollutants emissions using a kinetic PostProcessor as described elsewhere [8]. Moreover, a LES simulation of this burner will be useful to evaluate the effect of the turbulent structures on the flame.

5. References