Numerical study of Hythane in oxy-combustion in a burner with two separated jets

T. Mhadheb[a], M. A. Mergheni [a*],J. C. Sautetb[b], A. Mhimid[a]

(a) LESTE Ecole Nationale d'Ingénieurs de Monastir, 5019 Monastir, Tunisie
(b) *Normandie University, UNIROUEN, INSA Rouen, CNRS CORIA, 76000 Rouen, France*

* Corresponding author: Mohamed-ali.mergheni@coria.fr

Abstract:

The development of oxy-fuel burner with highly separated jets of fuel and oxidizer presents attractive perspectives because reactive separation generates a better thermal efficiency and a reduction of pollutant emissions by dilution effect. The aim of this work is to study the effects of the addition of hydrogen on the dynamic of the flame and the mixing between the jets.

The numerical simulation is carried out using Reynolds Average Navier-Stokes (RANS) technique using the turbulence model Realizable k-ε coupled to turbulent combustion EDM (Eddy disipation model). The numerical results show a good effect of hydrogen. In reacting case, statistical flow field quantities for velocity, mixture fraction and temperature are analyzed in details.

Keywords :
Oxy-flame, two Separated-jets, Hythane, Flame diffusion.

1. Introduction

The evolution of pollution standards associated to strict regulations which motivate the fall of fuel consumption, lead to optimize combustion plants performances. Large reductions of nitric oxide emissions have been successfully achieved in the past, by using either low NOx technologies of air burner or oxy-combustion systems. Numerous studies have particularly shown that the NOx output can be reduced remarkably by the use of oxygen instead of air

Methane is the major's component of the nature gas; it's a clean fuel to combust [1].

But there are two problems of using methane us fuel: the slow burning velocity and the low lean combustion capacity, consequently these decrease the engine power and increase the fuel consumption [2,3]. One of the power fuel methods to solve their problems is to blend or mix this gas with a fuel possessing a high burning velocity such us "hydrogen" [4] which is our study. Hydrogen is considered as a best gases candidate for methane due to its high reactivity, high diffusivity and high burning velocity [5] which is seven times higher than that of methane [6,7]. In addition, this source of fuel can be produced from fossil fuel and from a variety of feed stocks because hydrogen doesn't exist on earth as a gas, it must be separated from other elements, these include fossil resources as well as renewable energy such as biomass, water, power solar…[8,9]. However, it's seem to be limited due to some difficulties particularly on storage issues [10] on account of this low density (0.08 Kg/m3 at 300k and 1atm), wider range of flammability limits (from 4% to 75%) and very low ignition energy (0.02mj) [11].

The blending of methane and hydrogen would be the best substitution to overcome the local flame extinction and combustion instabilities [12] Consequently it's improves the combustion characteristics and reduce pollutant emissions [13,14]. OH et al [15] are experimentally investigated the effects of the hydrogen addition in diffusion oxy-methane flame. They observed that stability flame widened with an increase in the H_2 fraction. Long et al [16] are experimentally studied the effects of the adding of H_2 on the emissions and the heat transfer characteristics of oxygen-enriched laminar methane diffusion flame inside a furnace. They found that methane-hydrogen hybrid fuel combustion will be a benefit in helping the development of fundamental technologies with

answer to improve in furnaces and reduce pollutant emissions. S.Yon and Jean-charles Sautet [17] studied the effects hydrogen addition to the fuel jet on the velocity field in two separated jets in non-reacting flow. They show that the Hythane presents a perfect solution to ameliorate the mixing between the jets without changing the process geometry and with a low cost.

This paper investigates the effect of Hythane on turbulent oxy-combustion in a burner with two separated jets. The first jet supplies Hythane whereas the second one supplies pure oxygen. These tubes having a diameter of 6mm with a distance between them of the order 60 mm. The numerical simulation is carried out by using Fluent which solves the governing equations using the finite volume method. The Realizable-k-ε as a turbulent model. The turbulence-chemistry interactions scheme is modeled by the EDM.

2. Experimental system

The burner depicted in *Figure n °1* consists of two non-ventilated jets, separated by 60 mm with an inside diameter d= 6 mm [18]. One of the jet transports the fuel (Hythane) and the other the pure oxygen. The natural gas has used a density of 0.83 Kg m^{-3} and a net calorific value of 45 MJ/Kg. The oxygen is provided by Air liquid with a purity of 99.5% and a density 1.354 Kg m^{-3} (at 1atm and 15°C). The thermal power is fixed to 25 Kw.
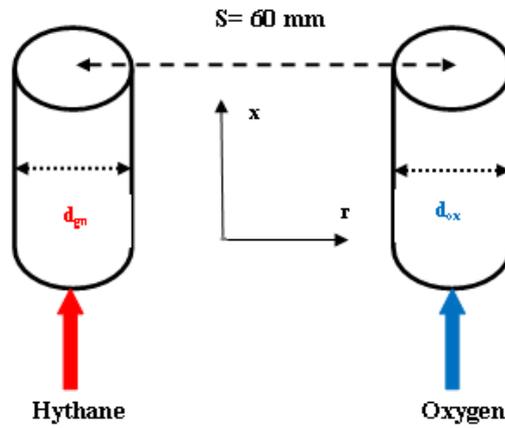

Fig1. Two-jet burner configuration.

Table 1 summarizes the mass flow rates and the velocity of the reactants as a function of the hydrogen enrichment at stoichiometry (φ=1).

φ	H$_2$ volume fraction (%)	$\dot{Q}_{CH_4}$ $\left[\frac{l}{s}\right]$	$\dot{Q}_{H_2}$ $\left[\frac{l}{s}\right]$	$\dot{Q}_{comb}^{total}$ $\left[\frac{l}{s}\right]$	$\dot{Q}_{O_2}$ $\left[\frac{l}{s}\right]$	U_{comb}^0 $\left[\frac{m}{s}\right]$	$U_{O_2}^0$ $\left[\frac{m}{s}\right]$
1	0	0.767	0	0.767	1.534	27.13	54.26
	10	0.739	0.082	0.822	1.521	29	53.76
	20	0.708	0.177	0.886	1.506	31.34	53.36

3. Computational and simulation method

3.1. Governing equations

This section describes the numerical model which solves the steady equations for conservation of mass, momentum, energy, and species for a separated jet burner. The turbulence is modulated by second order turbulent equations for turbulence kinetic energy κ and its rate of dissipation ε. The general form of the elliptic differential equations for an axisymetric flow is given by Eq. (1):

$$\frac{\partial}{\partial x}(\rho U\Phi) + \frac{1}{r}\frac{\partial}{\partial r}(r\rho V\Phi) = \frac{\partial}{\partial x}(\Gamma_\Phi \frac{\partial \Phi}{\partial x}) + \frac{1}{r}\frac{\partial}{\partial r}(r\Gamma_\Phi \frac{\partial \Phi}{\partial r}) + S_\Phi \qquad (1)$$

Where S_Φ the source terms and Γ_Φ the transport coefficient.

3.2. Turbulence modeling

The K-Epsilon model is considered one of the most widely used turbulence models as it provides robustness, economy and reasonable accuracy for a wide range of turbulent flows. It assumes that the turbulent regime is fully established throughout the field. In our study we chose the Realizable k-ε [19] to model hydrogen-methane/ oxygen diffusion flame. The term "achievable or realizable" means that the model satisfies certain mathematical constraints on Reynolds constraints, compatible with the physics of turbulent flows.

The k and ε in the realizable k–ε model are modeled with following transport equations:

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \tag{2}$$

$$\frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right] + \rho C_1 S\varepsilon - \rho C_2 \frac{\varepsilon^2}{k+\sqrt{v\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b + S_\varepsilon \tag{3}$$

3.3. Turbulence–chemistry interaction model (EDM)

Due to the complexity of turbulent flow and the chemical kinetics as well as the interaction between turbulence and the chemical reaction, it is impossible to perform a strict treatment. Consequently the Turbulence–chemistry must be modeled. In our study, the Eddy dissipation model "EDM" is considered to model turbulence-chemistry interactions. This was developed by "Magnussen and Hjertager" en 1976. It's based on the infinity fast chemistry assumption. The rate of the reaction depends only by the behavior of the turbulent flow and it's proportional to the dissipation rate of the turbulent vortices. However, the domain of validity is restricted to turbulent combustion which the number of Damkohler >1.

3.4. Simulation details

The simulation is implemented by Fluent [20] version 6.3 using GAMBIT to design and to mesh the combustor. *Figure n °2* shows the physical domains of the combustor where the grid is very dense near the burner to obtain a more accurate prediction. The mesh is consisted of 42400 cells.

At the inlet, the methane is supposed to enter a pipe with a constant axial velocity profile (Table 1). At the axis of symmetry, $r = 0$, $V = 0$ and $\partial\Phi/\partial r = 0$ $(\Phi = U, \kappa, \varepsilon)$. At the outlet, the fully-developed condition of pipe flow is adopted, $\partial\Phi/\partial x = 0$ $(\Phi = U, V, \kappa, \varepsilon)$. At the wall, the velocities are assumed to be zero, and these no-slip boundary conditions are appropriate for the gas. These equations, called "wall functions", are introduced and used in finite difference calculations at near-wall points.
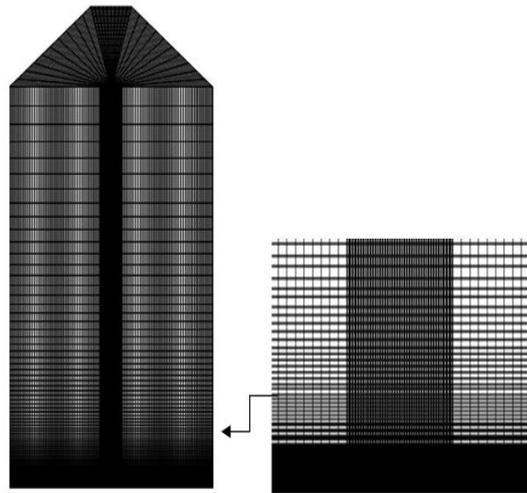

Fig 2. The staggered mesh used for numerical simulation.

4. Results and discussion

4.1. Experimental and numerical comparison

Before the effects of Hythane in oxy-flame, it's prior to validate the numerical model "Realisable k-ε" with the experimental data obtained by S.Yon and Jean-charles Sautet [17]. *Figure n°3* show comparisons

between our numerical and experimental results of radial velocity profiles at different locations in the combustion chamber. It shows two peaks. The first near the jet of Hythane (-33< y (mm) <-27) whereas the second in the oxygen jet (33< y (mm) <27).
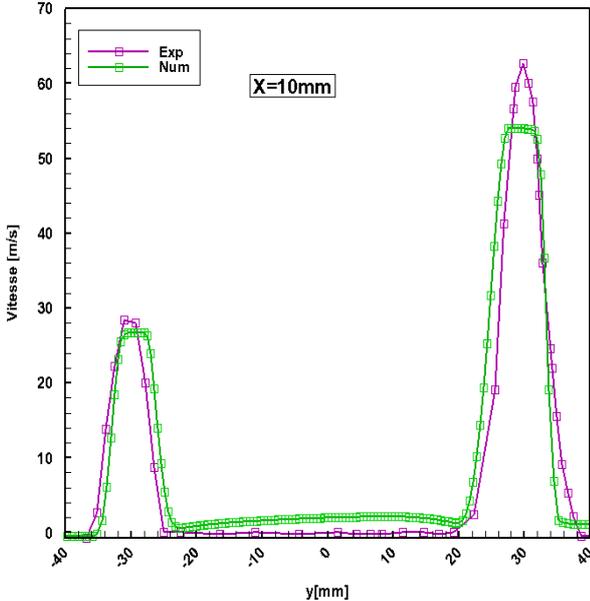

Fig 3. Validation of radial velocity profiles in x=10 mm.

As demonstrate in this figure, the maximum velocity values in the numerical simulation is of the order of 56 m/s while in experimental data, this maximum is legal to 64m/s. so of the velocity profiles, we observed a satisfactory agreement between the experimental and the numerical results.

4.2. Velocity field

Figure n°4 shows the contour and profile of radial velocity field at stoichiometry of 0% and 20% hydrogen fuel composition. It could be observed from this picture that a recirculation zones are created between two nozzles. Recirculation zone due to the difference between the velocity values of the Hythane and the oxygen jets which led to the rigorous backward pressure gradient and subsequently it favors the mixing and accelerates the fusion of jet allowing the flame stabilization.
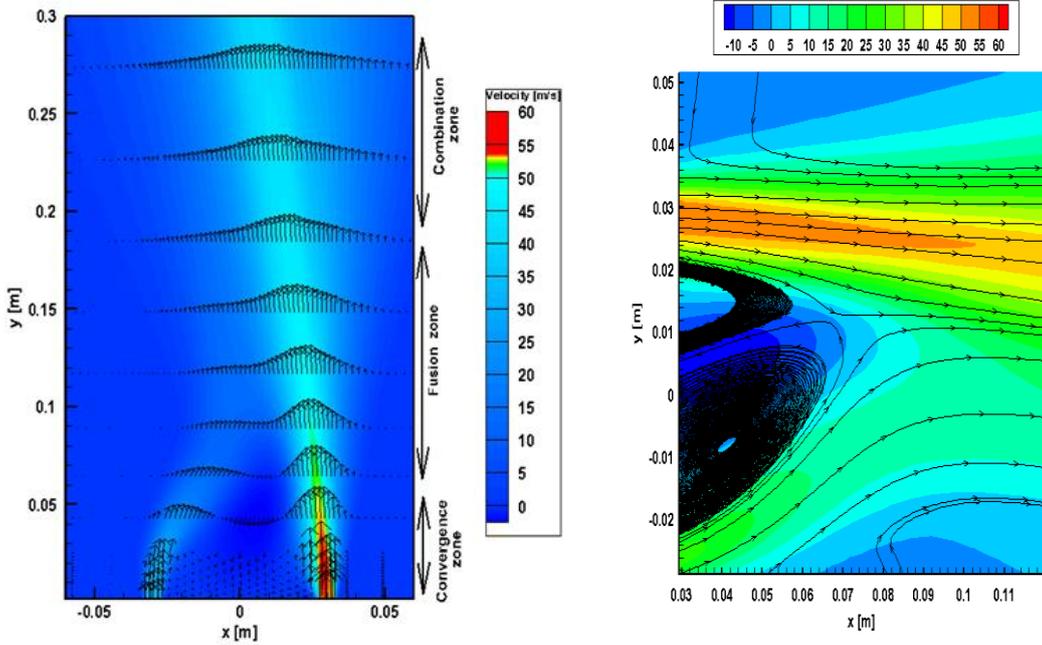

Fig 4. Velocity field of Hythane

4.3. Effect of adding hydrogen to the flame velocity

The burning velocity is a useful parameter to investigate the jet flame structure; it provides a good understanding for the fluid dynamics in the reaction. The *figures '5a' and '5b'* shows values of burning velocities plotted at three percentages of hydrogen (0%,10%,20%) at stoichiometry. It indicates in closer to nozzle (x=10mm) as the values of hydrogen fraction increase the values of burning velocities are generally increased. However, in x=100mm; the hydrogen effects decreases indicating that the hydrogen enrichment accelerate the mixing more downstream dues to high molecular diffusivity and higher flammability of Hythane.
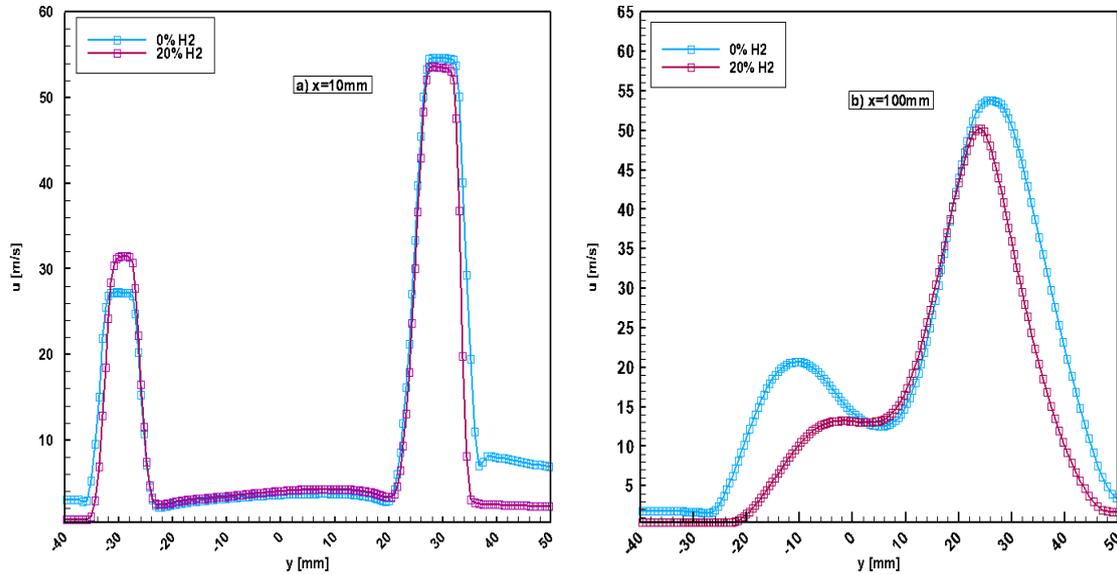

Fig 5. The burning velocity of different percentage of hydrogen fraction in tow locations x=10mm and 100mm at stoichiometry ('a' and 'b')

4.4. Effect of the addition of hydrogen to the turbulence

The effects of fuel composition (H_2- enrichment) on turbulent kinetics (TKE) and turbulent intensity (I) is presented in *figure n°6*. Three fuel compositions were considered pure methane (0%H_2-100%CH_4), (10%H_2-90%CH_4) and (20%H_2-80%CH_4). According to these results, it has been observed in x=10mm, two other peaks which have not appeared in the curve of the velocity, one next to the nozzle of oxygen and the second on the left of the Hythane. These areas are known by the external recirculation zone but between the nozzles remains stable. This evolutions corresponding to the convergence zone where the jets are not yet in contact. In addition, by analogy of turbulent velocity profile, TKE show a rise with 20% of hydrogen favoring the combination of two jets. While in the far field, whether for TKE or I, we note an increase between the jets and this means that the vortexes devoleppes favoring a better mixing between the fuel and the ambient air.
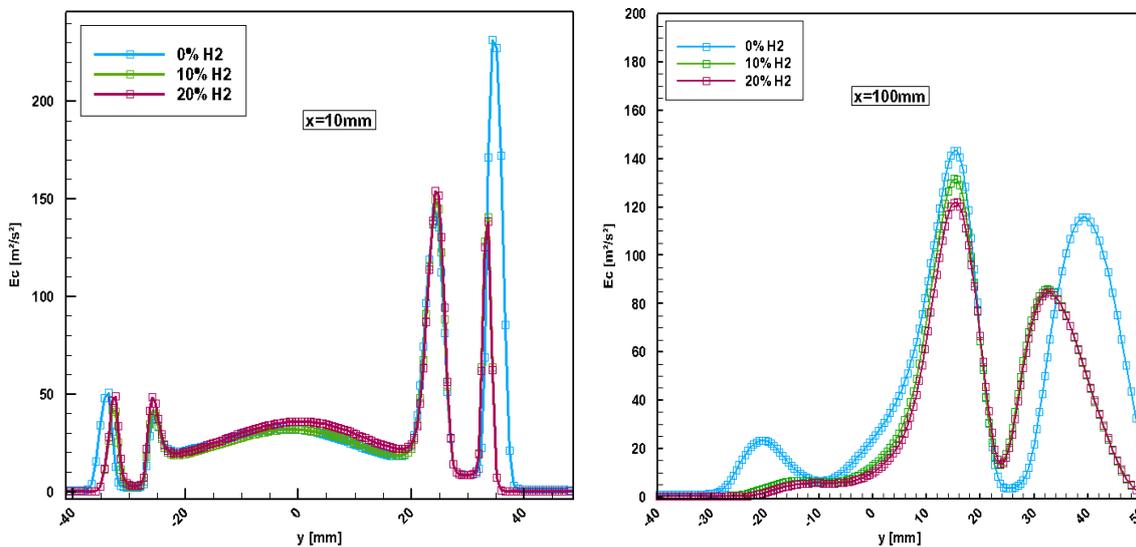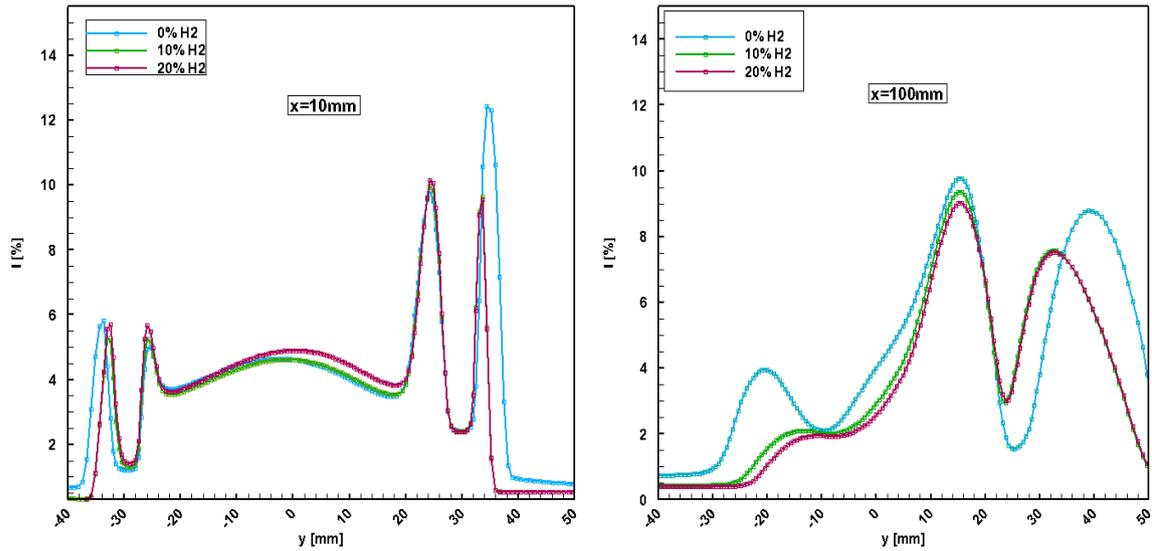
Fig 6. The turbulent kinetic energy Ec and to the turbulent intensity I of different hydrogen fraction.

4.5. The effects of hydrogen enrichment on the temperature distribution

Figure n°7 presents a comparison of the temperature between the pure methane (100% CH_4) and Hythane (20% H_2). It shows that the temperature is promoted as hydrogen is added. In addition, we observed that the temperature remains raising even exhaust gases, this is mainly related to the oxygen concentration.
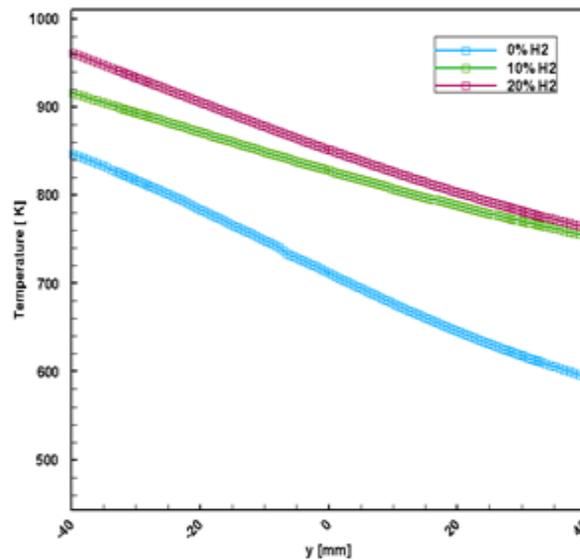

Fig 7. The temperature profiles of different hydrogen fraction

4.6. Main Species

The incomplete combustion of fuel is the mainly source of CO, CO_2 generation. The mass fractions of CH_4, CO_2 and CO for 0% and 20% hydrogen at stoichiometry are plotted in *figure n°8*. For all species, it exist a difference between the mixture of pure methane and the methane- hydrogen blend. In fact, the mass fraction of the three species are decreased when the methane is substituted by the molecule of carbon is decreased. For example, the rate of reduction of the maximum of CO up to 15% with the 20% hydrogen enrichment.
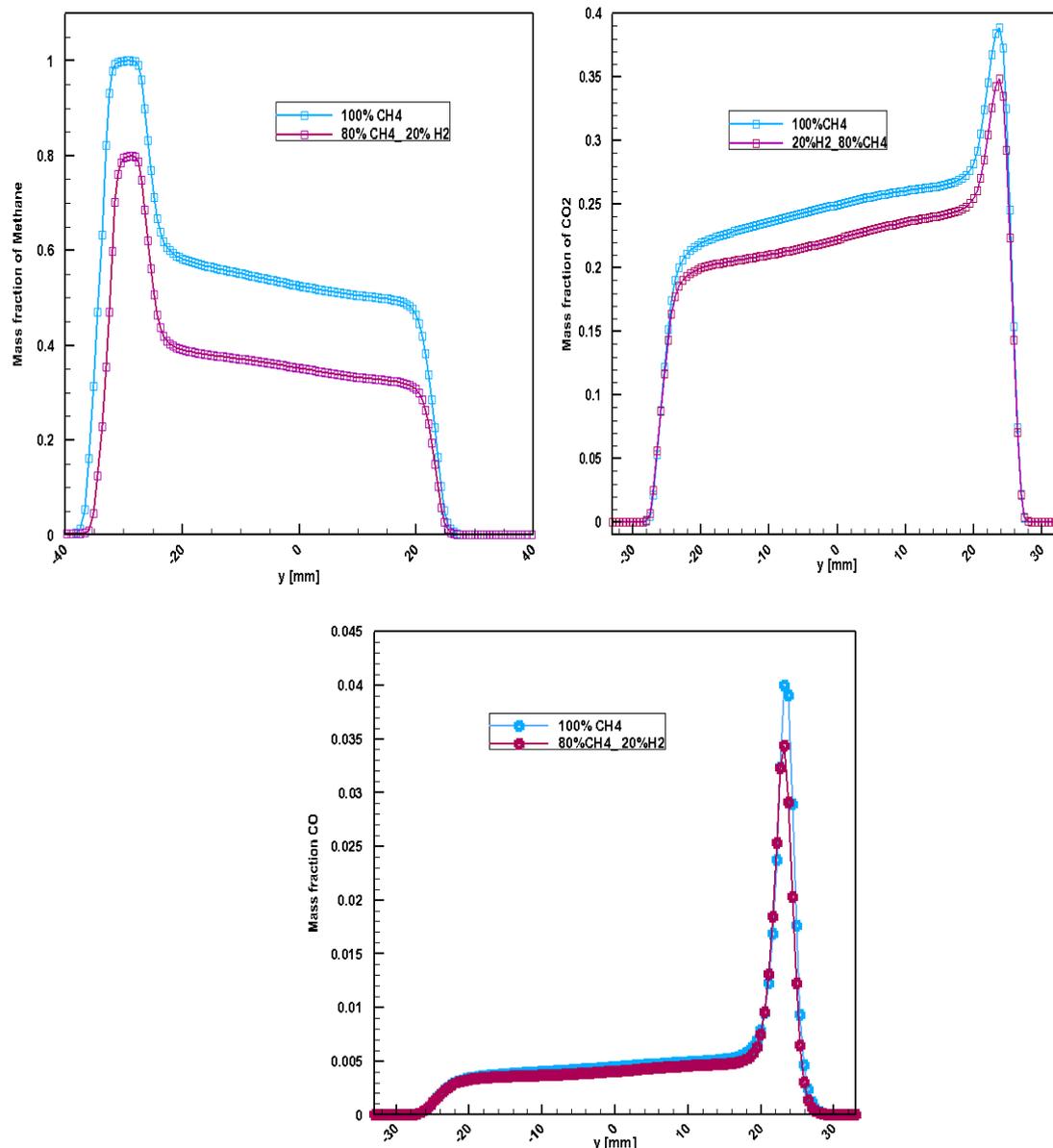
Fig 8. The mass fraction of CH_4, CO_2 and CO for 0% and 20% hydrogen at stoichiometry.

Conclusion

This work reports the results of numerical investigation of (methane-hydrogen) /oxygen from burner with two highly separated jets. The numerical results are in good agreement with the experimental data. It found that addition of hydrogen has a good influence in the diffusion oxy-flame. The main results are summarized as follows:

-   A rise of the turbulent velocity up to 18.7%
-   An average increase of the turbulent Kinetic energy and intensity.
-   The mass fraction of CO and CO_2 is decreased with increase of hydrogen enrichment load to reduce the harmful products of methane combustion.

References

[1] J. Wang, Z. Huang, C. Tang, H. Miao, Numerical study of the effect of hydrogen addition on methane–air mixtures combustion, International Journal of Hydrogen Energy, Volume 34, p.1084–1096, 2009.
[2] S. Rousseau, B. Lemoult, M. Tazerout, Combustion characteristics of natural gas in a lean burn spark-ignition engine, Journal of Automobile Engineering, Volume 213, p.213-48, 1999.
[3] S. Shrestha, G. Karim, Hydrogen as an additive to methane for spark ignition engine applications.
International Journal of Hydrogen Energy, Volume 24, p.577–586, 1999.

[4] H. Erjiang, H. Zuohua, H. Jiajia, Experimental and numerical study on laminar burning characteristics of premixed methane–hydrogen–air flames, International Journal of Hydrogen Energy , Volume 34, p.4876–4888, 2009.

[5] M. Zhang, J. Wang, Y. Xie, W. Jin, Z. Wei, Flame front structure and burning velocity of turbulent premixed CH4/H2/air flames, International Journal of Hydrogen Energy, Volume 38, p.11421–11428, 2013.

[6] G. Karim, Hydrogen as a spark ignition engine fuel. International Journal of Hydrogen Energy, Volume 28, 569–577, 2003.

[7] S. Bell, M. Gupta, Extension of the lean operating limit for natural gas fueling of a spark ignited engine using hydrogen blending. Comb Sci. and Techn., 123, (1997), p.23-48.

[8] X. Zhang, H. Yamaguchi, Y. Cao, Hydrogen production from solar energy powered supercritical cycle using carbon dioxide. International Journal of Hydrogen Energy, Volume 35, p.4925–4932, 2010.

[9] J. Nowotny, C. Sorrell, L. Sheppard, Solar-hydrogen: environmentally safe fuel for the future, International Journal of Hydrogen Energy, Volume 30, p.521–544, 2005.

[10] S. Frolov, Self-ignition of hydrocarbon–hydrogen–air mixtures, International Journal of Hydrogen Energy, Volume 38, p.4177–4184, 2013.

[11] S. D Emami, Md. Kasmani, M. D. Hamid, Kinetic and dynamic analysis of hydrogen-enrichment mixtures in combustor systems, Renewable and Sustainable Energy Reviews, Volume 62, 1072–1082, 2016.

[12] A.M. Briones, S.K. Aggarwal, Effects of H2 enrichment on the propagation characteristics of CH4–air triple flames, Combustion and Flame, Volume 153, p.367–383, 2008.

[13] K.T. Aung, M. Hassan, G.M. Faeth, Flame stretch interactions of laminar premixed hydrogen/air flames at normal temperature and pressure, Combustion and Flame, Volume 109, 1–24, 1997.

[14] Z.H. Huang, B. Liu, J.J. Zheng, X.L. Gu, B. Huang, Experimental investigation on performance and emissions of a spark-ignition engine fuelled with natural gas–hydrogen blends combined with EGR, International Journal of Hydrogen Energy, Volume 34, p.528–539, 2009.

[15] J. Oh, D. Noh, The effect of hydrogen addition on the flame behavior of a non-premixed oxy-methane jet in a labscale furnace, International Journal of Hydrogen Energy, Volume 62, p. 362–369, 2013.

[16] W. Long, N. Kobayashi, L. Zhanyong, H. Huang, Experimental study on the effects of hydrogen addition on the emission and heat transfer characteristics of laminar methane diffusion flames with oxygen-enriched air . International Journal of Hydrogen Energy, Volume 41, 2023–2036,2010.

[17] S. Yon, J-C. Sautet, Effects of hydrogen addition to the fuel jet on the velocity field in a two separated jets configuration in non-reacting flow, 16th Int Symp on Applications of Laser Techniques to Fluid Mechanics Lisbon, Portugal, p.09-12 , 2012.

[18] S. Yon, Oxy-combustion de l'Hythane dans des brûleurs à jets fortement séparés, Université de Rouen, 2013.

[19] T.H. Shih, W.W. Liou, A. Shabbir, Z. Yang, et J. Zhu, A New eddy-viscosity model for high reynolds number turbulent flows : model development and validation, Computers Fluids, Volume 24(3), p. 227–238, 1995.

[20] VVAA. Fluent 6.3 user's guide; 2006.