Effect of Low Co-flow Air Velocity on Hydrogen-air Non-premixed Turbulent Flame Model

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Abstract

The aim of this paper is to provide information concerning the effect of low co-flow velocity on the turbulent diffusion flame for a simple type of combustor, a numerical simulated cases of turbulent diffusion hydrogen-air flame are performed. The combustion model used in this investigation is based on chemical equilibrium and kinetics to simplify the complexity of the chemical mechanism. Effects of increased co-flowing air velocity on temperature, velocity components (axial and radial), and reactants have been investigated numerically and examined. Numerical results for temperature are compared with the experimental data. The comparison offers a good agreement. All numerical simulations have been performed using the Computational Fluid Dynamics (CFD) commercial code FLUENT. A comparison among the various co-flow air velocities, and their effects on flame behavior and temperature fields are presented.

Keywords: CFD, Turbulent flame, low co-flow velocity, Jet diffusion flame, FLUENT.

الخلاصة

الهدف من هذا البحث هو لتوفير المعلومات المتعلقة بسرعة الهواء الجانبية وتاثيرها على اللهب المضطرب الغير مختلط داخل محرق بسيط، حيث تم تنفيذ محاكاة عددية لاحتراق لهب مضطرب وغيرمختلط الى الهيدروجين–الهواء. أن نموذج الاحتراق المستخدم لغرض التحقيق يقوم على اساس الجمع بين التوازن الكيمائي والحركي لتبسيط الصعوبة في ميكانيكية التفاعل الكيميائي. تأثير زيادة سرعة الهواء الجانبية على درجة الحرارة وسرعة اللهب المحورية والدائرية وعلى المتفاعلات تمت دراستها بشكل عددي ومبين. النتائج العددية المستحصلة من البرنامج قورنت مع النتائج العملية لغرض اثبات الحل وصحته والنتائج تشير الى تطابق جيد. كل الحالات المنفذة في هذا البحث تمت باستخدام برنامج فلونتFLUENT . ألمقارنة المستخدمة لبيان تاثير سرعة الهواء الجانبية على تصرف اللهب وعلى مجال درجة الحرارة قد قدم في هذا البحث.

كلمات المفتاحية: CFD ، اللهب المضطرب، سرعة التدفق الجانبية ، انتشار اللهب النفاث.

Nomenclature		Greek symbols	
D	derivative	ρ	Density
$C_{\varepsilon 1}$	Constants in equation (9)	μ	Dynamic viscosity
$C_{\varepsilon 2}$	Constants in equation (9)	ν_t	Turbulent Kinematic viscosity
k	Turbulence kinetic energy	ε	Turbulence dissipation rate
g	gravity	σ_t	The turbulent Prandtl number
P_k	The production term by mean shear	Subscripts	
p	Mean pressure	t	Turbulent
t	Time	k	kinetic energy
U	Velocity		
x	distance		
Z	Mixture fraction		

1. Introduction

The need for a clean alternative energy has been paid towards hydrogen combustion which is attached more attention recently. Co-flow effect has been welcomed because it enhances the mixing of fuel and oxidizer which often leads to improve flame characteristics. Rising computer technology, software accuracy, power and realizing of combustion phenomena lead to computational analysis in the field of combustion attractive.

Dally *et.al.,* 2002, reported an investigation for the effect of concentration of oxygen in hot co-flow on H_2/CH_4 turbulent diffusion flame under MILD condition. In their experiment burner which is used in the study to investigate the heat and exhaust gas recirculation subjected to a simple jet in a hot co-flow. The obtained results refer to when the oxygen level is reducing in the hot co-flow causes the peak temperature reduces and the mean temperature increases in the reaction zone.

Experimental work to characterize the lifted flames in axisymmetric laminar co-flow jets of propane have been done by Lee *et.al.,*2003. The effect of co-flow velocity on the conditions of reattachment and blowout has been investigated. The results were showed in the linear decrease of liftoff height and jet velocity with co-flow velocity.

Experimental and simulated results on lifted flames in a hot co-flow were investigated by Cabra *et.al.,* 2005, where a lifted "CH_4 /air turbulent jet flame" in a (vitiated) co-flow of "H2/air combustion" are used. The results referred to the condition of being sensitive of the liftoff height to the jet velocity, co-flow velocity, and co-flow temperature. Also, they showed that the sensitivity to the co-flow velocity was underestimated.

The effects of co-flow air velocity on the flickering behavior of a buoyant laminar non-lifted methane diffusion flame were experimentally reported by Darabkhani *et.al.,* 2011. They reported an observation about suppression of the flame flicker. They noticed that the instable behavior of a non-lifted laminar diffusion flame was affected to the co-flow air velocity.

An experimental work done by Jonathan *et.al.,*2012, where their results focused on the stability and behavior of methane jet flame under various air co-flow velocities. They concluded that stability of oblique jet flames in co-flow, where the flame liftoff velocity is not affected by the nozzle angle. Therefore, the flame lift-off velocity is decreased with increasing co-flow air velocity. The aim of this paper is to provide information concerning the effect of low co-flow velocity on the turbulent diffusion flame for a simple type of combustor.

2. Mean Flow Equations

The numerical model of turbulent non premixed flame is formulated from the Navier-stokes equations together with RANS turbulence and an equilibrium combustion models. The Navier-stokes equations can be expressed in Cartesian notation as:

Mass conservation equation;

$$\frac{D\rho}{Dt} = 0 \qquad (1)$$

Momentum conservation equation;

$$\frac{D\rho\rho_i}{Dt} = D_i - \frac{\partial p}{\partial x_i} + \rho g_i \qquad (2)$$

Mixture fraction equation;

$$\frac{D\rho\rho}{Dt} = Dz \qquad (3)$$

where the total derivative is defined as:

$$\frac{D}{Dt}=\frac{\partial}{\partial t}+U_i\ \frac{\partial}{\partial x_i} \qquad (4)$$

$$D_i=\frac{\partial}{\partial x_i}\left(\mu\ \frac{\partial U_i}{\partial x_i}-\rho\overline{u_i u_j}\right) \qquad (5)$$

$$Dz=\frac{\partial}{\partial x_i}\left(\frac{\mu}{\sigma_z}\ \frac{\partial Z}{\partial x_i}\right) \qquad (6)$$

where μ and σ_t are the fluid viscosity and turbulent Prandtl number respectively. The turbulent kinetic energy and its dissipation rate transport equations are;

$$\frac{D(\rho(\rho}{Dt}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_t}\right)\frac{\partial k}{\partial x_i}\right]+\rho P_k-\rho\left[\varepsilon+2\nu(\frac{\partial k^{1/2}}{\partial x_i})^2\right] \qquad (7)$$

where P_k, is the production term created by mean shear, defined as :

$$P_k=\nu_t(\frac{\partial U_i}{\partial x_i}) \qquad (8)$$

$$\frac{D(\rho\varepsilon)}{Dt}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_i}\right]+C_{\varepsilon 1}\rho\frac{\varepsilon}{k}P_k-C_{\varepsilon 2}\rho\frac{\varepsilon}{k}P_k \qquad (9)$$

3. Combustion modeling approach

The equilibrium chemistry model has been used in this work. The model assumes that the chemical reaction is taken place at infinitely fast rate which is sufficiently for the chemical equilibrium. The chemical species are expressed in terms of mixture fraction by using the minimization of Gibbs of the free enthalpy. Therefore the thermodynamic properties of the reactive and productive species at equilibrium are depend on the mixture fraction only. The instant values of mass fractions for the reactive scalars are to be expressed as functions of the mixture fraction as,

$$Y_i=Y_i^e(Z) \qquad (10)$$

where (e) refers to an equilibrium state. Similarly, the above equation can be written for the thermodynamic properties at equilibrium conditions such as the temperature and density, etc. In order to link between the turbulence and chemistry, the probability density function (PDF) approach is used. Where the instantaneous values in the chemical reaction state and the mixture fraction values are accounted as;

$$Y_i=\int Y_i^e(Z)\ f(Z)dZ \qquad (11)$$

The theoretical shape of f(Z) can be approximated by a mathematical model which assumes beta-function distribution, in the form as;

$$Y_i=\frac{Z^{a-1}(1-z)^{b-1}}{\int Z^{a-1}(1-z)^{b-1}dZ} \qquad (12)$$

Where;

$$a = Z\left[\frac{Z(1-Z)}{Z^2} - 1\right] \qquad (13)$$

And;

$$b = (1-Z)\left[\frac{Z(1-Z)}{Z^2} - 1\right] \qquad (14)$$

4. Description of Experimental Study:

The experiments were carried out by Barlow and Carter, (1994). The design of the jet- in-cold co-flow burner is based on that of injected pure hydrogen jet-in-cold co-flow burner. The configuration examined in this study is a vertical turbulent diffusion hydrogen-air jet flame with different values of co-axial air stream as shown in Figure1. Experimental data for the temperature and species concentrations were presented by Flury and Schlatter,(1997). The recent boundary and initial conditions, which used in this study, are to be taken as referenced. The inner diameter of the tube was 3.75 mm, the outer diameter 4.8 mm. The co-flowing air velocity is varied at [1, 10 and 20 m/s]. The hydrogen mean inlet velocity is 296 m/s and the Reynolds number of the flame is 10000.

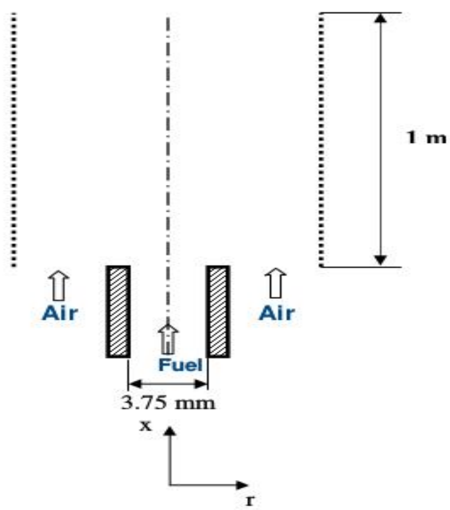

Figure 1: Description of the experimental schematic configuration.

5. Computational algorithm

The studied case of the hydrogen-air turbulent diffusion flame is simulated using non-premixed combustion model of FLUENT package,(2006). A steady solution of the mean transport equations is computed. In the solution of the mean transport equations for continuity, axial and radial momentum and the standard k-epsilon model is known for its shortcomings in predicting the turbulent flow. The SIMPLE-PRESTO! Algorithm is used for pressure- velocity coupling. The second order upwind convection scheme is consistently used for all the terms. The resulting computational domain consists of 18530 cells, 37381 faces and 18851 nodes, as shown in Figure 2.

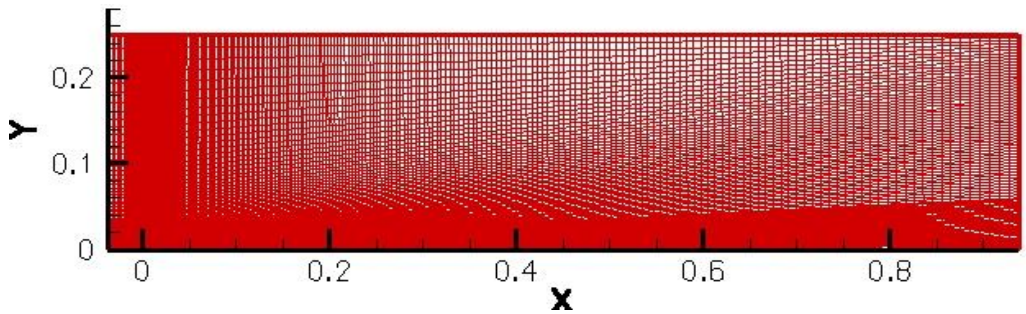

Figure 2: Two dimensional view of the computational domain.

6. Results and discussions

First of all, in order to validate the simulation accuracy of the proposed technique, a comparison has been performed with the experimental data,(1997). Figure 3 shows a comparison of mean temperature profile predicted from the lookup table which is prepared before the combustion simulation. The comparison expresses a good agreement with the experimental data. This section contains the results of the simulations.

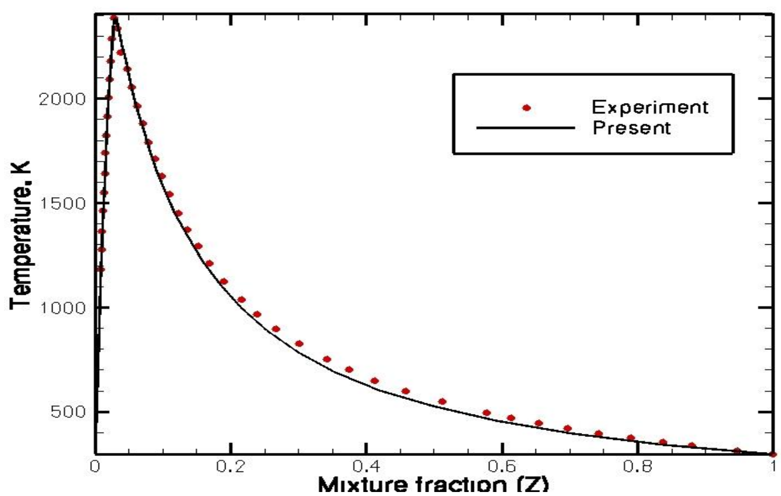

Figure3: Comparison the predicted and measured temperature.

All figures are extracted at the centerline which all profiles provide information on the evolution of the flow field that can be used to evaluate the turbulence-reaction models. For a fixed hydrogen flow rate and increasing values of co-flow air flow velocities, the turbulent flame temperature distribution is shown in Figure 3. Figure 4a represents a comparison between co-flow velocity (1 m/sec) and (10 m/sec) for the spatial temperature distribution. It can be seen that, for a co-flow (1 m/sec), the flame temperature is high and extended into a large zone in a computational domain. But, the flame becomes, a less in temperature, thinner and higher when the co-flow increases as shown in Figure 4b, where the figure shows a contour plots to compare between co-flow velocity (10 m/sec) and (20 m/sec).

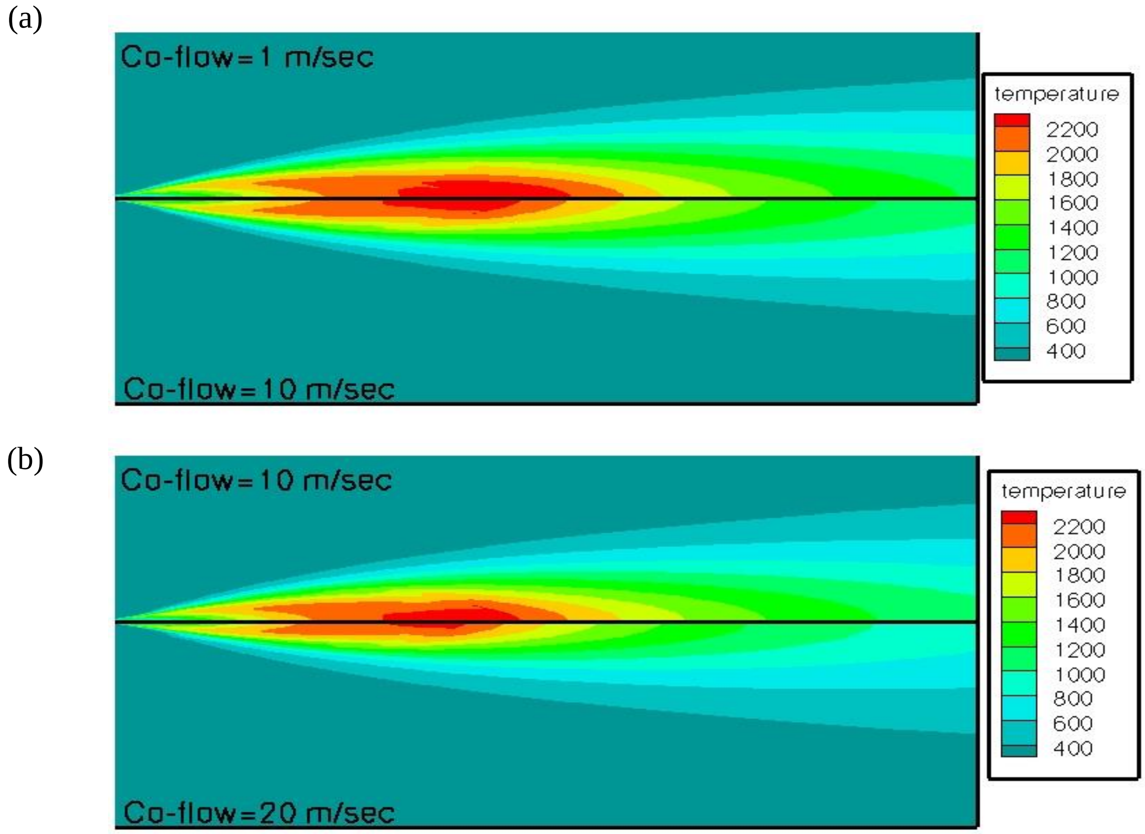

Figure 4: Contours of static temperature.

To illustrate that, Figure 5 shows the axial distribution for flame temperature at the centerline. For example, besides the decrease in the peak flame temperature with decreasing there is even more drastic reduction in temperature in the centerline region.

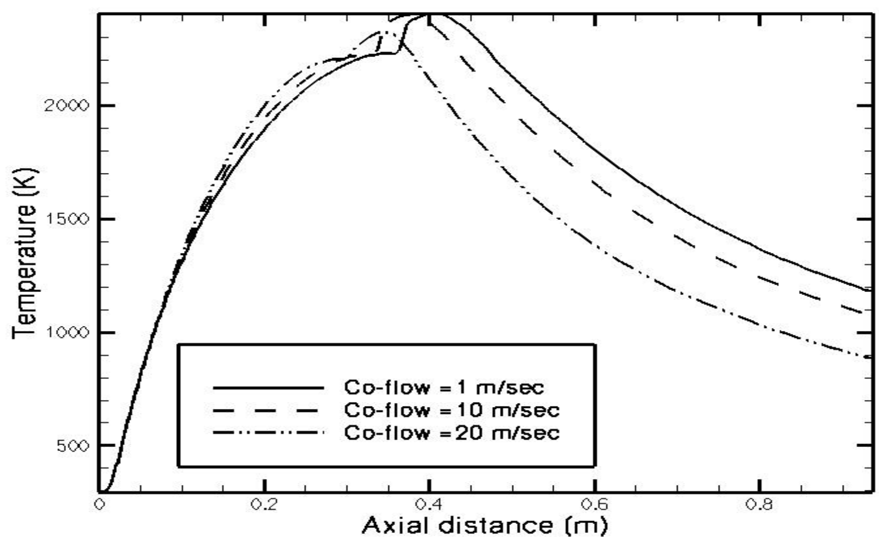

Figure 5: Effect of variations of co-flow velocity on central temperature.

Figure 6 shows contour plots for the axial velocity distributions at the three co-flow velocity values. Note that different flame height are observed for each plot owing to the variation in the axial velocity. The axial velocity express qualitatively similar trend for both free jet and the co-flow. That means increases the axial velocity as the co-flow increases because they are in the same direction.

(a)

(b)

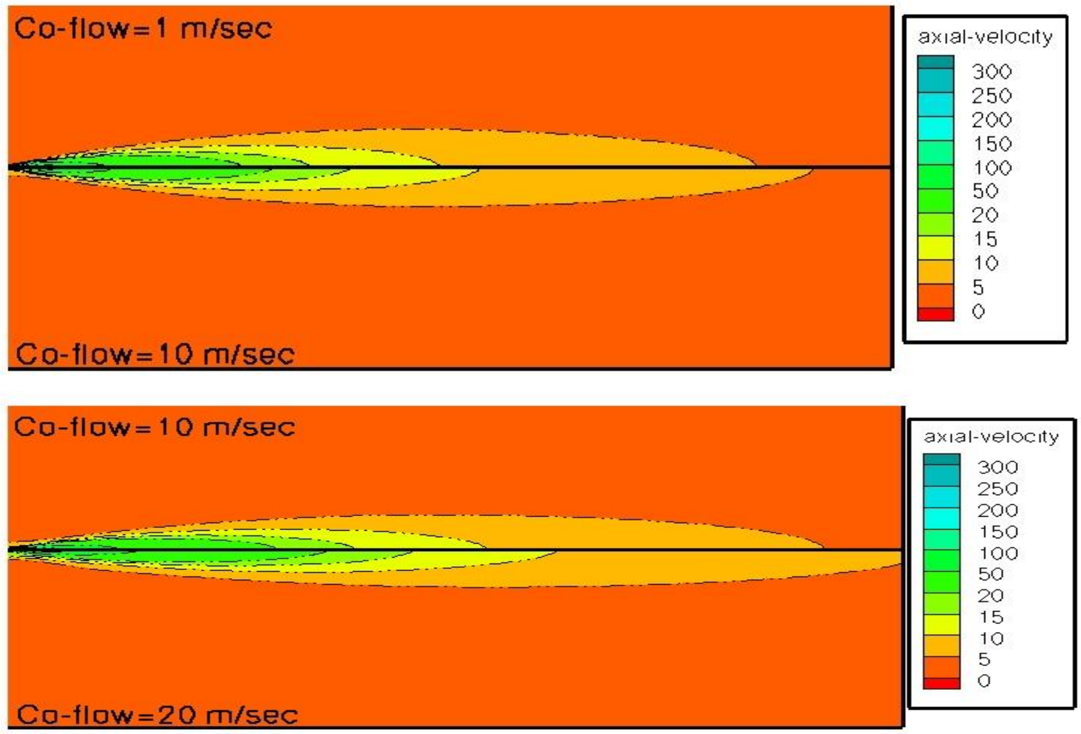

Figure 6: Contours of axial velocity.

The axial velocity profiles are shown in Figure 7. They are having a maximum values at the inlet and then decrease slowly. From the figure the magnitude of axial velocity is sensitive to the co-flow velocity. In order to see the better effect of the co-flow air velocity on the radial velocity,

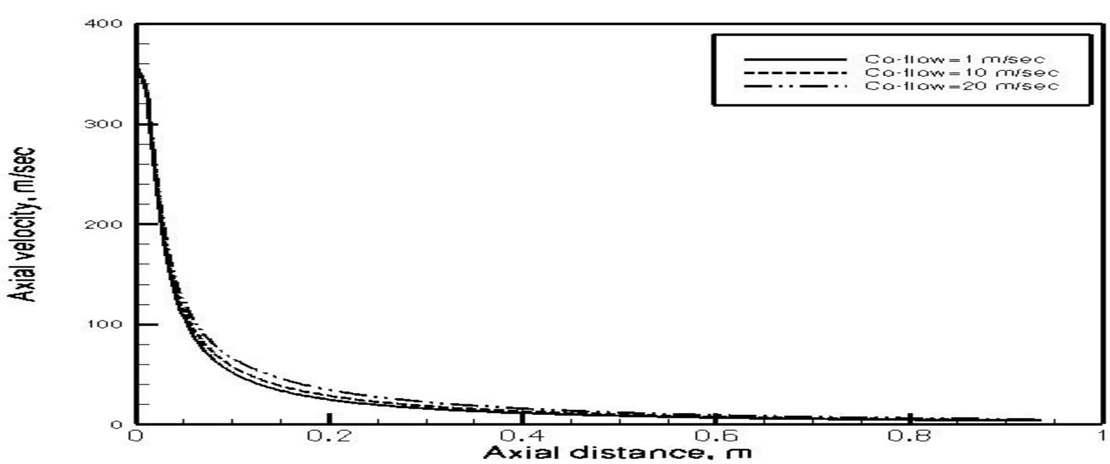

Figure 7: Effect of variations of co-flow velocity on axial velocity.

Figure 8 shows contour plots of radial velocity distribution at three different air co-flow velocity. It is important to mention that the radial velocity component starts with an initial value of (1 m/sec). From these plots, it can be found that there is two regions with positive and negative values. These two regions are separately by the nearly distance from the nozzle. Due to highly injected velocity for the hydrogen (296 m/sec), the positive region is increased with the increase of the co-flow velocities. Similarly the negative region is increased with the increasing of co-flow velocities. The high Reynolds number (10000) causes vortex for the flow to be turbulent near the nozzle.

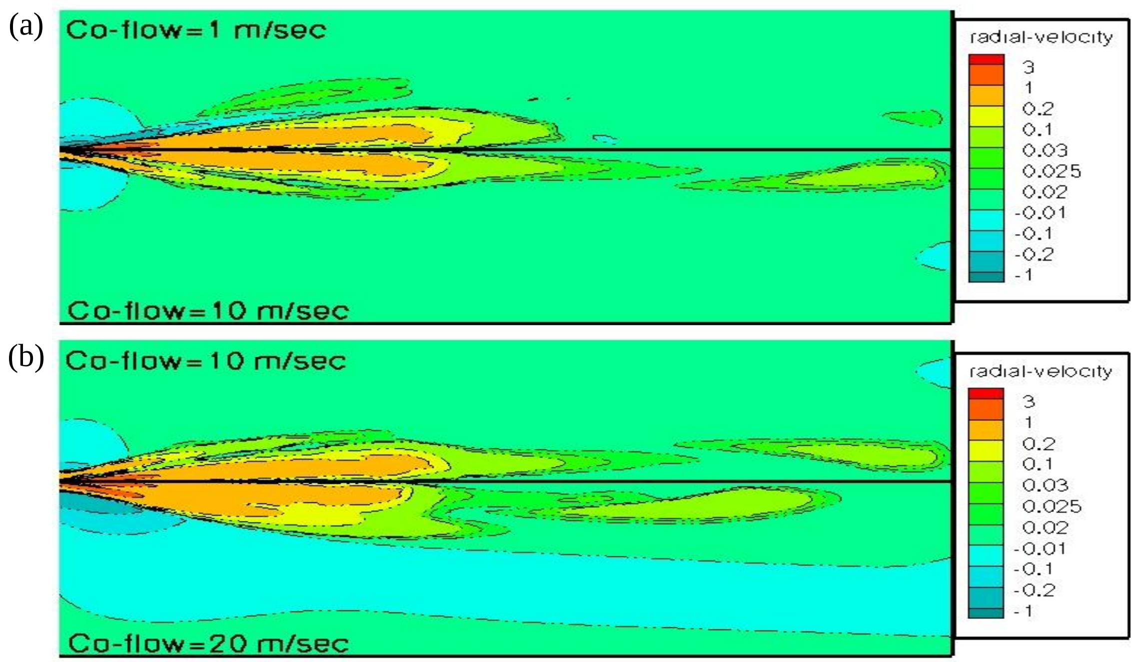

Figure 8: Contours of radial velocity.

Figure 9 shows these fluctuations where both axes are implemented with logarithmic values. Now, the next part of investigations are related with the effect of co-flow velocity on the chemical reaction.

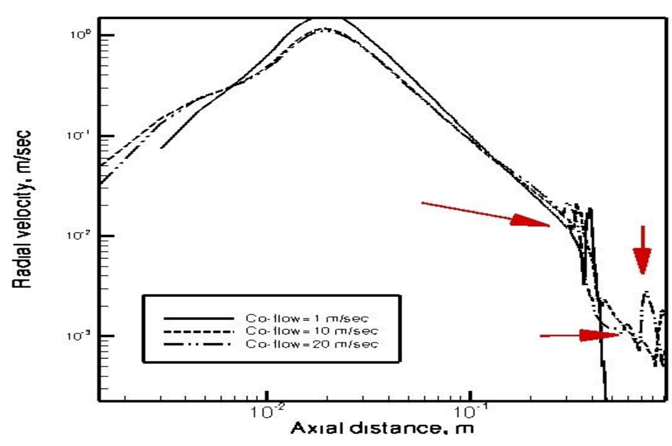

Figure 9: Effect of variations of velocity on mixture

Figure 10 shows the axial profiles of mixture fraction at the center of symmetry with different co-flow velocities. At the beginning, before the interactions, the mixture fraction is equal to unity, where the initial value of the mass fraction for the fuel is equal to one. When the chemical reaction has been started a change, has been in this profile. That is referring to the onset change in thermal and diffusive species interactions. The effect of co-flow velocity on the mixture fraction is by decreasing the mixture fraction as the co-flow velocity is increased. This due lean mixture (that there is more air present than stoichiometry requires).

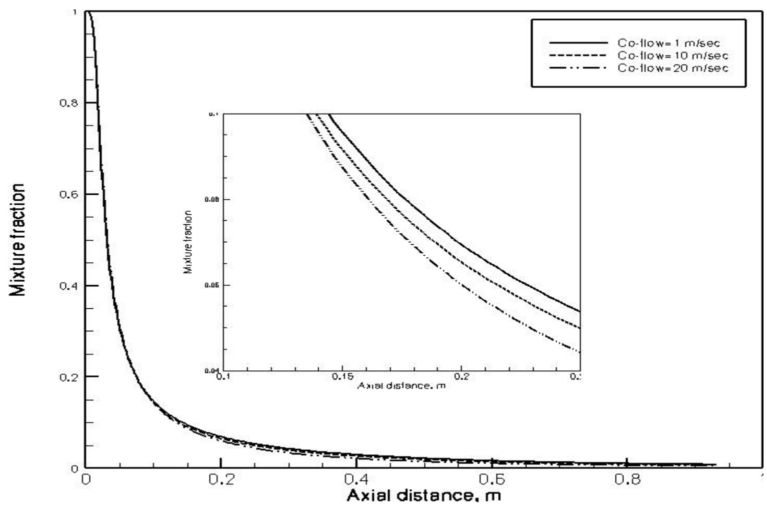

Figure 10: Effect of variations of co-flow velocity on radial velocity.

Figures 11 and 12 show the mean turbulent kinetic energy distributions and its turbulent dissipation rate at the centerline with the three co-flow velocities.

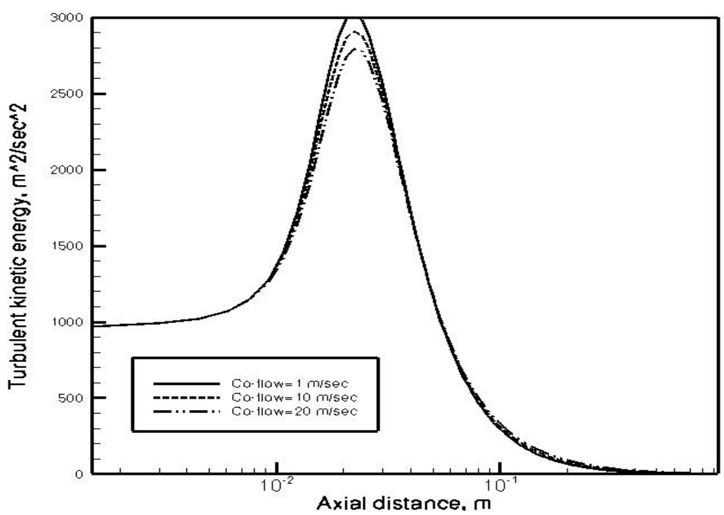

Figure 11: Effect of variations of co-flow velocity on turbulent kinetic energy.

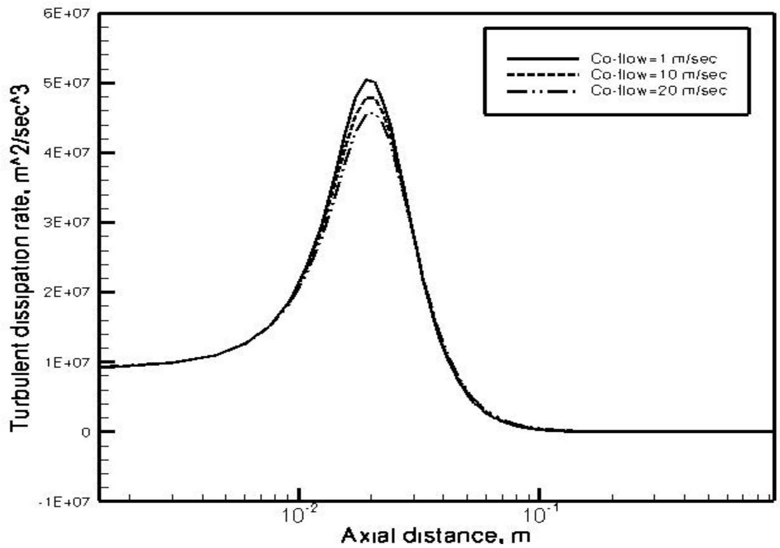

Figure 12: Effect of variations of co-flow velocity on rate of turbulent dissipation of kinetic energy.

It is easy to notice that both profiles are decreased as the co-flow velocity is increased. The turbulent kinetic energy profiles exhibits different trends to the axial velocity profiles. That is because modeling the turbulence characteristics in the region with strong density gradient due to the combustion. The high velocities cause a noticeable differences where the preferential diffusion is occurred in the reaction zone.

7. Conclusions

Numerical simulation of a co-flow turbulent, non-premixed hydrogen-air flame at atmospheric pressure by using a detailed chemical and kinetics of the gas-phase reaction mechanism through a complex transport and thermal properties. Numerical simulations results show that, the simulation captured most of the main features of the turbulent diffusion flame under effect of different co-flow velocities.

1. As the co-flow velocity is increased, the decrease in the peak flame temperature and also there is even more drastic reduction in temperature in the centerline region.
2. The results refer that axial velocity magnitude is sensitive to the co-flow velocity.
3. The effect of co-flow velocity on the mixture fraction is by decreasing the mixture fraction as the co-flow velocity is increased.

8. References

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