

## Investigation of Laminar Flame Speed of $\text{CH}_4/\text{N}_2/\text{O}_2$ and $\text{CH}_4/\text{CO}_2/\text{O}_2$ Mixtures Using Reduced Chemical Kinetic Mechanisms

**J. Bibrzycki\***, **T. Poinso\*\***, **A. Zajdel\***

\* Silesian University of Technology,  
Institute of Thermal Technology,  
22 Konarskiego, 44-100 Gliwice, Poland  
Corresponding author: jakub.bibrzycki@polsl.pl

\*\* Université de Toulouse,  
Institut de Mécanique des Fluides de Toulouse,  
Allée C. Soula, F-31400 Toulouse, France

The emission prevention of carbon dioxide has become an important problem recent years. In order to facilitate the sequestration of  $\text{CO}_2$  from flue gases, the combustion can be carried out in the oxidizer, which contains a mixture of  $\text{CO}_2$  and  $\text{O}_2$  without the presence of nitrogen.

The Computational Fluid Dynamics is widely used in order to design new devices and to improve existing ones. Computational costs, when detailed chemistry is employed in calculations of the flame, are too large for real applications, therefore, simplified mechanisms have to be used to solve those problems.

Because the laminar flame speed is an important parameter for a burners design and has major influence on a combustion process control, therefore, a good prediction of this quantity, using reduced mechanisms, is crucial.

The aim of the present work was to figure out the influence of oxidizer composition on the laminar flame speed and to examine simplified mechanisms in order to achieve similar laminar flame speed levels to those obtained for the detailed mechanism computations, during combustion of methane in the  $\text{CO}_2/\text{O}_2$  atmosphere. All calculations were done using the Freely Propagating 1D Laminar Premixed Flames (FP1DLPF) package coupled with the COSILAB software.

For the combustion of  $\text{CH}_4$  in the  $\text{CO}_2/\text{O}_2$  atmosphere, new reduced mechanisms were created for the oxidizer composition for which the laminar flame speed, for stoichiometric conditions, was similar to this obtained for the methane combustion in air. Similar laminar flame speed values for the conventional combustion and the oxy-combustion was obtained for the oxidizer composition of  $X_{\text{O}_2}^{\text{oxid}}=0,385$   $X_{\text{CO}_2}^{\text{oxid}}=0,615$ . Modified reduced mechanisms of methane combustion in comparison with schemes that are used for the conventional combustion, improved the accuracy of the laminar flame speed prediction with the detailed mechanism considerably, for the oxy-combustion environment.

## Nomenclature

$k_j$  – reaction rate constant,  $\text{mol}^{1-n} \cdot (\text{cm}^3)^{n-1} \cdot \text{s}^{-1}$

$T$  – temperature,  $K$

$\beta_j$  – temperature exponent, -

$A_j$  – pre-exponential constant,  $\text{cgs}$

$Ea_j$  – activation energy,  $\text{cal/mol}$

$R$  – universal gas constant,  $\text{cal}/(\text{mol} \cdot K)$

$r_j$  – reaction rate progress,  $\text{mol}/(\text{cm}^3 \cdot \text{s})$

$C_i$  – specie concentration,  $\text{mol}/\text{cm}^3$

$n_i$  – reaction order, -

$S_L$  – laminar flame speed,  $\text{m/s}$

$D_{th}$  – thermal diffusion coefficient,  $\text{m}^2/\text{s}$

$Rr$  – reaction rate coefficient,  $1/\text{s}$

$\Phi$  – equivalence ratio, -

$p$  – pressure of the reaction,  $\text{MPa}$

$X$  – mole fraction, -

## 1. Introduction

Carbon dioxide emission reduction has become one of the main concern last years, due to the standpoint of most of scientists, who work on climate change that a direct connection between global temperature increase and anthropogenic greenhouse gases emission exists. Carbon dioxide is a substance, which emission cannot be avoided during combustion of the fuel containing carbon. Therefore, emission reduction can be only done through sequestration. In order to underground storage of  $\text{CO}_2$ , this specie has to be separated from flue gases, which contain mainly nitrogen, what is a very expensive process. One of the best ways to sequester  $\text{CO}_2$  is to perform combustion without the nitrogen presence in the oxidizer (oxy-fuel combustion). Nevertheless, the combustion in pure oxygen leads to dangerous temperature and flame speed escalation. In order to keep those two quantities at levels found during a conventional combustion of a fuel in air, a mixing of oxygen with part of flue gases is performed, thus, a mixture containing  $\text{O}_2/\text{CO}_2$  is used as an oxidizer.

Carbon dioxide has different heat capacity, thermal diffusivity and emissivity in comparison to molecular nitrogen. Therefore, the combustion of the fuel in the oxidizer, containing the same mole fraction of  $\text{CO}_2$  as it is found for nitrogen in air, leads to significant parameters changes in comparison with conventional fuel-air combustion [1, 2, 3, 4, 5]. Benedetto et al. [4] indicated the decrease of laminar flame speed, while nitrogen was displaced by carbon dioxide. The explanation for this behavior was the higher heat capacity of the  $\text{CO}_2$ , which decreasing the flame temperature and at the same time the combustion

rate. The reaction kinetics undergoes alterations when N<sub>2</sub> is displaced by CO<sub>2</sub> in the oxidizer.

A Computational Fluid Dynamics is an important tool for a design and a process optimization. Simulation of a full-scale geometry, with millions of cells, requires a large memory and a long computational time. In order to save time required for simulations significantly, simplified combustion mechanisms are used. Schemes containing two (WD, 2S-CM2) [6, 7], four (J-L) [8] or more [9, 10] reactions can be used to describe the combustion phenomena, however, their accuracy is limited. The mechanisms which are created for a conventional combustion of fuel in air were found not to be satisfying for an oxy-fuel combustion [1, 5], because every detailed mechanism has restricted area of usage.

The aim of the present work was to figure out the influence of the oxidizer composition on the laminar flame speed and to examine simplified mechanisms in order to achieve similar laminar flame speed levels to those obtained for the detailed mechanism computations, during combustion of methane in the CO<sub>2</sub>/O<sub>2</sub> atmosphere. All calculations were done using the Freely Propagating 1D Laminar Premixed Flames (FP1DLPF) package coupled with the COSILAB software.

## 2. Presentation of methane oxidation mechanisms

In this section particular methane oxidation mechanisms are presented, which were employed in calculations. Three different mechanisms were taken as a basis for further development of mechanisms for CH<sub>4</sub> oxy-fuel combustion: GRI Mech 3.0 [11], Jones-Linstedt (J-L) [8] and 2S-CM2 [7]. For existing as well as for new schemes the number of species involved in the flame computation was depended on the composition of the oxidizer. Simulation of methane combustion in the oxidizer composed of N<sub>2</sub>/O<sub>2</sub> or of CO<sub>2</sub>/O<sub>2</sub> limits the original GRI Mech number of reactions (325) and species (53), because argon is not present in such a mixture. In the case of oxy-fuel combustion simulation, apart from argon also nitrogen was not present, thus the reduction of species to 34 and reactions to 215, during the simulation of the flame using the detailed mechanism. Table 1 presents reactions of 2-step and 4-step mechanisms, while full specification of Arrhenius parameters (Eq. 1) for those reactions is presented in Table 2 and Table 3. The full specification of reactions for GRI Mech 3.0 is available online [11].

The reaction rate constant can be expressed according to the Arrhenius equation (Eq. 1), where  $A_j$  is a pre-exponential constant,  $\beta_j$  is a temperature exponent,  $Ea_j$  is the activation energy of the reaction [12].

$$k_j = A_j \cdot T^{\beta_j} \cdot \exp\left(\frac{-Ea_j}{R \cdot T}\right) \quad (1)$$

The reaction rate progress is described as a difference between forward and backward reaction rates (Eq. 2) [13].

$$r_j = k_f \cdot \sum_i^N C_i^{v_i'} - k_r \cdot \sum_i^N C_i^{v_i''} \quad (2)$$

**Tab. 1** Reaction number for 2-step and 4-step reduced mechanisms

Reaction number	2-step mechanisms (2S-CM2, 2S-CM2-JB1, 2S-CM2-JB2, 2S-CM2-JB3)	4-step mechanisms (J-L, J-L-JB)
1	$CH_4 + 1,5O_2 \Rightarrow CO + 2H_2O$	$CH_4 + 0,5O_2 \Rightarrow CO + 2H_2$
2	$CO + 0,5O_2 \rightleftharpoons CO_2$	$CH_4 + H_2O \Rightarrow CO + 3H_2$
3		$H_2 + 0,5O_2 \rightleftharpoons H_2O$
4		$CO + H_2O \rightleftharpoons CO_2 + H_2$

**Tab. 2** Rate constants for the 2S-CM2 scheme and for the modified versions introduced during this work: the activation energies are in *cal/mole* and the pre-exponential constants in *cgs* units. Abbreviations *ford* and *rord* mean forward and reversed order respectively

Name	2S-CM2	2S-CM2-JB1	2S-CM2-JB2	2S-CM2-JB3
$A_1$	2E15	$(-1,7172\phi^2 + 1,7503\phi + 0,9914)$ ·2E15 for $\phi > 1$ ; 2E15 for $\phi \in (0; 1)$	5,1E14	$(-1,8906\phi^2 + 3,0238\phi - 0,1302)$ ·5,1E14 for $\phi > 1$ ; 5,1E14 for $\phi \in (0; 1)$
$n_{1ford}^{CH_4}$	0,9	0,9	0,7	0,7
$n_{1ford}^{O_2}$	1,1	1,1	1,3	1,3
$E_{a1}$	35000	35000	35000	35000
$A_2$	2E9	$(-1,7172\phi^2 + 1,7503\phi + 0,9914)$ ·2E9 for $\phi > 1$ ; 2E9 for $\phi \in (0; 1)$	5,1E8	$(-1,8906\phi^2 + 3,0238\phi - 0,1302)$ ·5,1E8 for $\phi > 1$ ; 5,1E8 for $\phi \in (0; 1)$
$n_{2ford}^{CO}$	1	1	1	1
$n_{2ford}^{O_2}$	0,5	0,5	0,5	0,5
$n_{2ford}^{CO_2}$	1	1	1	1
$E_{a2}$	12000	12000	12000	12000

**Tab. 3** Rate constants for the Jones-Linstedt scheme and for the modified versions introduced during this work: the activation energies are in *cal/mole* and the pre-exponential constants in *cgs* units. Abbreviations *ford* and *rord* mean forward and reversed order respectively

J-L	$A_1$	$n_{1ford}^{CH_4}$	$n_{1ford}^{O_2}$	$E_{a1}$	$A_3$	$n_{3ford}^{H_2}$	$n_{3rord}^{H_2}$	$n_{3ford}^{O_2}$	$n_{3rord}^{O_2}$	$n_{3ford}^{H_2O}$	$E_{a3}$
	7,824E13	0,5	1,25	30000	1,209E18	0,25	-0,75	1,5	1,0	1,0	40000
	$A_2$	$n_{2ford}^{CH_4}$	$n_{2ford}^{H_2O}$	$E_{a2}$	$A_4$	$n_{4ford}^{CO}$	$n_{4ford}^{H_2O}$	$n_{4rord}^{CO_2}$	$n_{3rord}^{H_2}$	$E_{a4}$	
	3,0E11	1,0	1,0	30000	2,75E12	1,0	1,0	1,0	1,0	20000	
J-L-JB	$A_1$	$n_{1ford}^{CH_4}$	$n_{1ford}^{O_2}$	$E_{a1}$	$A_3$	$n_{3ford}^{H_2}$	$n_{3rord}^{H_2}$	$n_{3ford}^{O_2}$	$n_{3rord}^{O_2}$	$n_{3ford}^{H_2O}$	$E_{a3}$
	3,5E12	0,5	1,25	30000	3,5E17	0,25	-0,75	1,5	1,0	1,0	40000
	$A_2$	$n_{2ford}^{CH_4}$	$n_{2ford}^{H_2O}$	$E_{a2}$	$A_4$	$n_{4ford}^{CO}$	$n_{4ford}^{H_2O}$	$n_{4rord}^{CO_2}$	$n_{3rord}^{H_2}$	$E_{a4}$	
	3,0E11	1,0	1,0	30000	2,75E12	1,0	1,0	1,0	1,0	20000	

### 3. Calculation method of the laminar flame speed

In Cosilab it is possible to calculate laminar flame speed from freely propagating laminar one-dimensional flames package (1DFPLF). For this kind of the flame, the laminar flame speed is equal to the propagation speed of the fresh mixture provided far enough from the flame front [13]. Freely propagating flames are found far from combustion chamber walls or from burner nozzles that the disturbance of the flow is not present. In the industry, this type of flames rarely exists. However, some quantities, which are calculated thanks to 1DFPLF, can be used for better understanding and advanced modeling of the combustion phenomena (flamelet turbulent model [14, 15]) in real applications.

The laminar flame speed is defined generally as the speed of the flame front, in a normal direction to the surface of this flame during the combustion of a homogenous mixture [16]. According to Eq. (3) the laminar flame speed depends on the square root of diffusion coefficient of heat and reaction rate coefficient [12].

$$S_L \sim (D_{th} \cdot Rr)^{0,5} \quad (3)$$

In the 1DFPLF, four main equations are employed in calculations of laminar flame speed as well as other parameters (the continuity equation, the species-mass conservation equations, the energy equation and the ideal-gas equation of state). The additional equation, which is solved simultaneously to above-mentioned ones, is the momentum equation, which allows calculating the pressure variation through the flame [13]. Boundary conditions that had to be declared to solve the problem are temperature and composition of the fresh, unburned mixture and the pressure of the process.

### 4. Simulation results for CH<sub>4</sub>/air flames

The composition of the oxidizer was chosen to imitate the air in a simple way, thus the mole fractions of O<sub>2</sub> and N<sub>2</sub> were equal respectively to 21% and 79%.

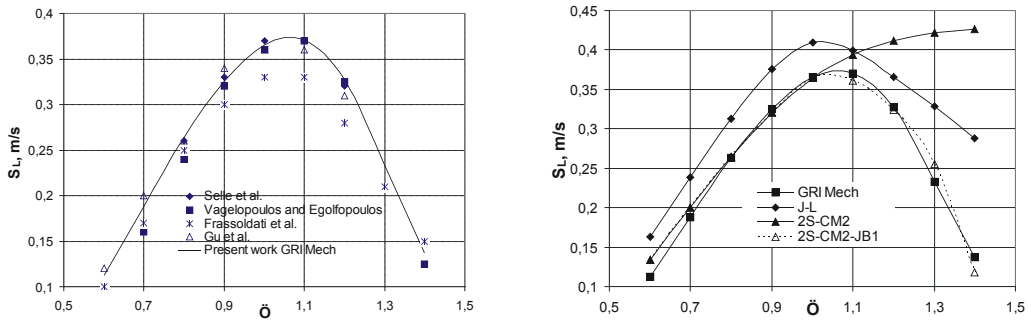
Determining laminar flame speeds of methane-air mixtures, for various equivalence ratios, can be done experimentally or numerically [5, 17, 18, 19].

Figure 1(a) presents a comparison of results from different publications and from present calculations using the Cosilab software with the GRI Mech 3.0. Tendencies as well as values obtained experimentally or numerically by different researchers are similar. The laminar flame speed attains a maximum value for slightly fuel-rich mixture at equivalence ratio approximately 1,05 and achieves value circa 0,37 m/s.

Two different simplified chemical kinetics mechanisms (J-L, 2S-CM2) existing in the

literature were investigated. Results using those two reduced mechanisms were compared to GRI Mech computations. The full specification of the reaction parameters of reduced mechanisms is presented in Tables 1, 2 and 3.

The capacity of reduced schemes to predict flame speeds for various equivalence ratios was tested. Figure 1(b) shows a systematic overestimation of  $S_L$  by 0,045 m/s for the J-L mechanism, for fuel-lean and nearly stoichiometric flames, in comparison with the GRI Mech calculations. When the 2S-CM2 mechanism is employed to calculate the laminar flame speed, for fuel-lean conditions, the accuracy is good. Nevertheless,  $S_L$  for fuel-rich conditions is seriously overestimated comparing with the GRI Mech. Even the curve tendency does not preserve a proper shape and it is necessary to employ the pre-exponential factor adjustment (PEA) for fuel-rich conditions, in order to cover the full scheme data. The two-step mechanism, which utilizes PEA, is 2S-CM2-JB1 (Table 2). A good agreement between outcomes for the detailed mechanism and 2S-CM2-JB1 was found.



**Fig. 1** Laminar flame velocities for  $\text{CH}_4/\text{N}_2/\text{O}_2$  plotted against equivalence ratio for  $p_0 = 1 \text{ MPa}$  and  $T_0 = 300 \text{ K}$ : (a) obtained by various researchers, (b) present work simulation results for four different mechanisms

#### 4. Simulation results for $\text{CH}_4/\text{O}_2/\text{CO}_2$ flames

The different diffusivity and thermal capacity of carbon dioxide and molecular nitrogen modify the combustion of  $\text{CH}_4$ . According to the dependency of the laminar flame speed on the diffusion coefficient (Eq. (3)), lower thermal diffusivity in the  $\text{CO}_2$  atmosphere influences the laminar flame speed. Different oxidizer compositions have effects on the chemistry itself. The dissociation of  $\text{CO}_2$  affects the production of carbon monoxide for higher temperatures ( $>1300 \text{ K}$ ) [1]. Nevertheless, a thermal effect on a laminar flame speed decrease was found as the major one by Benedetto et al. [4]. Carbon dioxide has a higher specific heat capacity than  $\text{N}_2$ , so that the flame has much lower temperature comparing to the conventional combustion in air, for the same mole fraction of diluents in the oxidizer. Lower temperatures also have an impact on the combustion rate, which in conjunction

with a lower thermal diffusivity and changes in chemistry cause a big difference in laminar flame speed values (Table 4).

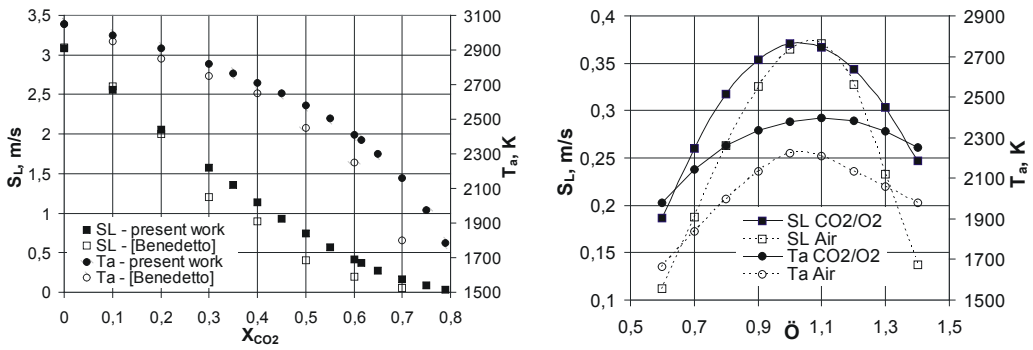
**Tab. 4** Summary of laminar flame speed values obtained during present work for methane oxidation simulation in O<sub>2</sub> = 21%/N<sub>2</sub> = 79% and O<sub>2</sub> = 21%/CO<sub>2</sub> = 79% for various equivalence ratios, GRI Mech

$S_L$ [m/s] for	$\phi = 0,8$	$\phi = 0,9$	$\phi = 1,0$	$\phi = 1,1$
N <sub>2</sub> /O <sub>2</sub>	0,263	0,326	0,365	0,370
CO <sub>2</sub> /O <sub>2</sub>	0,026	0,033	0,036	0,033

Calculations for different mole fractions of CO<sub>2</sub> and O<sub>2</sub> in the oxidizer were performed in order to find the laminar flame speed, which was obtained during a detailed chemistry simulation of methane combustion in the environment similar to air. Adiabatic flame temperature and laminar flame speed variations with CO<sub>2</sub> mole fractions in the oxidizer are presented in Fig. 2(a). Both parameters are decreasing with the CO<sub>2</sub> mole fraction in the oxidizer. The correlation of the laminar flame speed with the CO<sub>2</sub> mole fraction in the oxidizer is almost linear with a negative tangential factor, while the adiabatic flame temperature is more likely to be a parabolic function of CO<sub>2</sub> in the oxidizer. A good agreement between present work and CH<sub>4</sub> combustion simulation in Chemkin-Premix [4] can be observed. For both adiabatic temperature and laminar flame speed, compatibility is much better for higher mole fraction of oxygen in the oxidizer. For pure oxygen-methane flame the temperature reaches value at about 3050 K and laminar flame speed is in the order of 3,1 m/s.

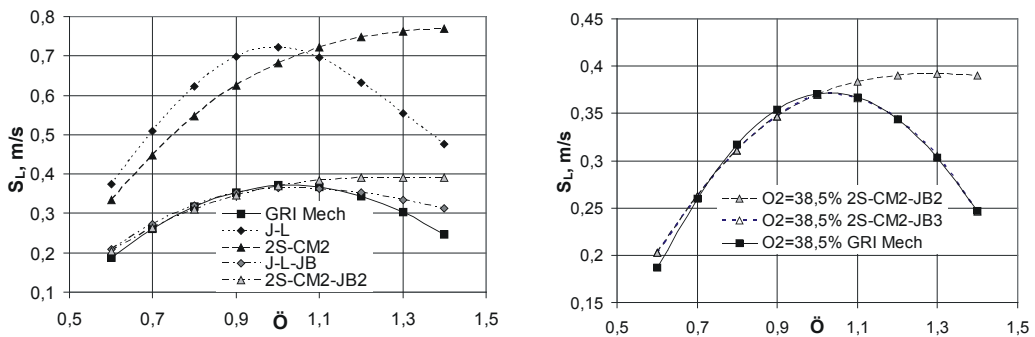
Due to the flame stabilization, when an oxidizer is shifted from an air to a mixture of CO<sub>2</sub>/O<sub>2</sub>, achieving similar laminar flame speeds, for an oxy-fuel and a conventional combustion, is important. Carbon dioxide mole fraction in the oxidizer, for which values of the laminar flame speed is approximately equal to the values obtained during combustion simulation in N<sub>2</sub>/O<sub>2</sub> environment, is equal to  $X_{CO_2}^{oxid} = 0,615$ , for the equivalence ratio around one (Fig. 2(b)). The further the mixture is from stoichiometric conditions the  $S_L$  value disagrees more. The adiabatic temperature is elevated for the CO<sub>2</sub>/O<sub>2</sub> case at about 250 K roughly.

Figure 3(a) presents laminar flame speed results for different basic oxidation mechanisms described in this report. A significant disagreement of this quantity is observed between the detailed mechanism and the J-L or the 2S-CM2 mechanisms (Fig. 3(a)). These reduced mechanisms were evaluated for fuel-air flames and this probably explains such a big divergence, when they are employed in oxy-fuel combustion calculations. Likewise, in the conventional combustion simulation with reduced mechanisms (Fig. 1(b)), the oxy-fuel calculation of  $S_L$  using the J-L mechanism preserves proper curve shape for different equivalence ratios, as well for the 2S-CM2 mechanism laminar flame speed is overestimated for fuel-rich mixtures.



**Fig. 2** Laminar flame speed and adiabatic flame temperature for  $p_0=0,1 MPa$ ,  $T_0=300 K$  plotted against: (a)  $CO_2$  mole fractions in oxidizer; results obtained by Benedetto et al. [4] (open symbols) and gained in present work during simulation of flame with GRI Mech (solid symbols);  $\Phi=1,0$ , (b) equivalence ratio for conventional and for oxy-fuel combustion; GRI Mech

To improve the precision of reduced mechanisms, parameters from the Arrhenius equation (Eq. (1)) were readjusted (Tables 2, 3). For the J-L mechanism, two reactions have a major impact on the laminar flame speed: reactions 1 and 3 in Table 1. For both 2S-CM2-JB2 and J-L-JB mechanisms, the agreement was improved considerably. However, for a fuel-rich mixture the difference between the detailed mechanism and reduced ones is still relatively big, especially for the 2S-CM2-JB2 mechanism. Therefore, a new 2-step scheme with PEA was created (2S-CM2-JB3). For oxidizer with 38,5% of oxygen mole fraction, a very good agreement between the GRI Mech and 2S-CM2-JB3 is achieved, after employing PEA, for a fuel-rich conditions (Fig. 3(b)).



**Fig. 3** Comparison of the laminar flame speed results obtained for 38,5% of  $O_2$  in the oxidizer and  $p_0=0,1MPa$ ,  $T_0= 300 K$  for: (a) GRI Mech, J-L, 2S-CM2 and two new mechanisms (J-L-JB and 2S-CM2-JB2); (b) GRI Mech, 2S-CM2-JB2 and for mechanism that using PEA (2S-CM2-JB3).

## 5. Conclusions

Two reduced mechanisms (2S-CM2 and J-L) have been tested for conventional air-methane combustion. Whereas, found in the literature schemes (2S-CM2 and J-L) and refined ones (2S-CM2-JB2 and J-L-JB) were verified using detailed chemistry computations, for specified oxy-fuel conditions.

The oxidizer composition, which allows to achieve similar values of the laminar flame speed to those obtained for the conventional methane-air combustion, was evaluated to  $X_{O_2}^{oxid}=0,385$ ,  $X_{CO_2}^{oxid}=0,615$ .

A large disagreement between values of the laminar flame speed obtained using the detailed mechanism (GRI Mech) and obtained for J-L and 2S-CM2 global schemes, for the oxy-fuel combustion, was found for freely propagating 1D laminar premixed flames.

The prediction of laminar flame speeds were improved significantly, when new schemes (2S-CM2-JB2 and J-L-JB), created for specified oxidizer composition, were employed in simulations of methane combustion in CO<sub>2</sub>/O<sub>2</sub>.

## Acknowledgments

The work presented in this article has been performed at CERFACS (The European Center for Research and Advanced Training in Scientific Computation) and at IMFT (Institut de Mécanique des Fluides de Toulouse) in Toulouse, in France. The research activity was supported by the Marie Curie Host Fellowships for Early Stage Research Training within the framework of the ECCoMET (Efficient and Clean Combustion Experts Training).

## References

- [1] T. Giselsson, J. Andersen, Ch. L. Rasmussen and P. Glarborg, Global combustion mechanisms for use in CFD modeling under oxy-fuel conditions, *Energy & Fuels*, 23:13791389, 2009.
- [2] K. Andersson and Filip Johnsson, Flame and radiation characteristics of gas-fired O<sub>2</sub>/CO<sub>2</sub> combustion, *Fuel*, 86:656668, 2007.
- [3] I. Gokalp, D. F. Kurtulus, C. Cohea, Ch. Chauveau, CO<sub>2</sub> addition and pressure effects on laminar and turbulent lean premixed CH<sub>4</sub> air flames, *Proceedings of the Combustion Institute*, 32:18031810, 2009.
- [4] E. Salzano F. Cammarota G. Russo A. Di Benedetto, V. Di Sarli, Explosion behavior of CH<sub>4</sub>/O<sub>2</sub>/N<sub>2</sub>/CO<sub>2</sub> and H<sub>2</sub>/O<sub>2</sub>/N<sub>2</sub>/CO<sub>2</sub> mixtures, *International Journal of Hydrogen Energy*, 34:6970 6978, 2009.
- [5] T. Faravelli, E. Ranzi, C. Candusso, A. Frassoldati, A. Cuoci and D. Tolazzi, Simplified kinetic schemes for oxy-fuel combustion, In 1<sup>st</sup> International Conference on Sustainable Fossil Fuels for Future Energy, 2009.
- [6] C. Westbrook and F. Dryer, Simplified reaction mechanism for the oxidation of hydrocarbon fuels in flames, *Combust. Sci. Tech.*, 27:31–43, 1981.
- [7] G. Boudier, Methane/air flame with 2-step chemistry: 2S-CH<sub>4</sub>-CM2, CERFACS technical report, 2007.
- [8] W. P. Jones and R. P. Lindstedt, Global reaction schemes for hydrocarbon combustion, *Combust. Flame*, 73:222–233, 1988.

- 
- [9] A. C. Zambon and H. K. Chelliah, Explicit reduced reaction models for ignition, flame propagation and extinction of  $C_2H_4/CH_4/H_2$  and air systems, *Combustion and Flame*, 150:71–91, 2007.
- [10] C. K. Law, C. J. Sung and J. Y. Chen, An augmented reduced mechanism for methane oxidation with comprehensive global parametric validation, In *Twenty-Seventh Symposium (International) on Combustion*, The Combustion Institute, 1998.
- [11] M. Frenklach, N. W. Moriarty, B. Eiteneer, M. Goldenberg, C. T. Bowman, R. K. Hanson S. Song, W. C. Gardiner Jr., V. V. Lissianski, G. P. Smith, D. M. Golden and Z. Qin, GRI Mech 3.0, <http://www.me.berkeley.edu/gri-mech/>.
- [12] T. Poinsoot and D. Veynante, *Theoretical and Numerical Combustion*, R.T. Edwards, 2<sup>nd</sup> edition, 2005.
- [13] COSILAB Combustion Simulation Laboratory Manual, version 2.0.
- [14] B. Rogg, R. S. Cant and K. N. C. Bray, On laminar flamelet modelling of the mean reaction rate in a premixed turbulent flame, *Combustion Science and Technology*, 69:53–61, 1990.
- [15] J. F. Driscoll, Turbulent premixed combustion: flamelet structure and its effect on turbulent burning velocities, *Progress in Energy and Combustion Science*, 34:91134, 2008.
- [16] Ryszard Petela, *Paliwa i ich spalanie cz. II Spalanie*, Dział Wydawnictw Politechniki Śląskiej, 1982.
- [17] T. Boushaki, B. Ferret, L. Selle, Y. Dhue and T. Poinsoot, Experimental and numerical study of the accuracy of flame-speed measurements in Bunsen burner, In *Sixth Mediterranean Combustion Symposium MCS 6*, 2009.
- [18] X. J. Gu, M. Z. Haq, M. Lawes and R. Woolley, Laminar burning velocity and Markstein lengths of methane-air mixtures, *Combust. Flame*, 121:41–58, 2000.
- [19] C. M. Vagelopoulos and F. Egolfopoulos, Direct experimental determination of laminar flame speeds, In *27th Symp. (Int.) on Combustion*, The Combustion Institute, pages 513–519, Pittsburgh, 1998.