17th Brazilian Congress of Thermal Sciences and Engineering
November 25th-28th, 2018, Águas de Lindóia, SP, Brazil

ENCIT-2018-0051
A STUDY OF THE INFLUENCE OF TURBULENT INLET CONDITIONS IN A NUMERICAL SIMULATION OF A CYLINDRICAL COMBUSTION CHAMBER WITH A TURBULENT NON-PREMIXED METHANE-AIR FLAME

Calisa Katiuscia Lemmertz
Felipe Roman Centeno
Francis Henrique Ramos França
Federal University of Rio Grande do Sul, Rua Sarmento Leite, nº 425, CEP 90050-170, Porto Alegre, RS, Brazil
calisalemmertz@gmail.com, frcenteno@mecanica.ufrgs.br, frfranca@mecanica.ufrgs.br

Cristiano Vitorino da Silva
Regional Integrated University of Alto Uruguai and Missions, URI, Sete de Setembro Avenue, nº 1621, CEP 99700-000, Erechim, RS, Brazil
cristiano@uricer.edu.br

Abstract. *This study analyzes the influence of turbulent inlet boundary conditions for numerical simulations of a cylindrical combustion chamber with a turbulent non-premixed methane-air flame. The problem is solved applying the finite volume method. The combustion model employed was the Eddy Break-Up-Arrhenius, with two-step global reaction mechanism. For turbulence, the standard k-ε model was considered. A mesh sensitivity study was performed to ensure the quality of the numerical results. The turbulent inlet conditions analyzed in this paper are the characteristic length of both fuel and oxidizer streams, and turbulence intensity (TI) for those same streams. The obtained results were compared to experimental data obtained by Garréton and Simonin (1994) to ensure their validity. The results showed the importance of a proper set of turbulent inlet parameters in turbulent non-premixed methane-air flame simulations, while the turbulence intensity of the oxidizer proved to be the most significant of them.*

Keywords: *turbulent combustion, characteristic length, turbulence intensity, non-premixed methane-air flame*

1. INTRODUCTION

Combustion processes are of great importance for human society. It is estimated that more than 90% of the energy used nowadays is resultant of these processes. For this reason their understanding is essential to ensure efficiency and reduction of environmental impact during energy generation.

Combustion is a phenomenon that involves complex chemical reactions, in several stages. In non-premixed flames the fuel and oxidant are initially separated, so the combustion is controlled by diffusion and turbulence (Centeno *et al.*, 2013), and reactions occur only on the interface between fuel and oxidant.

Garréton and Simonin (1994) obtained experimental results for temperature and chemical species concentration in positions of interest inside a combustion chamber with a non-premixed methane–air flame. These experimental data have been used as reference for many posterior studies. Magel *et al.* (1996) developed numerical studies on this same combustion chamber. They described the inclusion of a detailed chemical reaction mechanism and the results were compared to experimental data.

Nieckele *et al*. (2001) compared the influence of different combustion models in this same problem. Two types of models were assessed, first the generalized finite rate models (Arrhenius, Magnussen and Eddy Break-Up-Arrhenius), and then, models based on the PDF formulation (double delta and beta). The model Eddy Break-Up-Arrhenius (E-A model) showed the best results, and for this reason it was applied to the present investigation. In a later study, Nieckele *et al*. (2002) analysed two situations for the combustion process using the E-A model. First a single global reaction was used to estimate fuel burning and then a two steps reaction. The best results were obtained applying the two step reaction. In a similar line of research, Silva *et al.* (2007), through the implementation of their own code, investigated the methane-air combustion process using the Eddy Break-Up-Arrhenius model applied to this same geometry, the results obtained were very close to those described by Nieckele *et al.* (2002), confirming the importance of the thermal radiation on the heat transfer to the combustor walls. More recently, Silva *et al.* (2018) presented a comparative study between the combined Eddy Break-Up-Arrhenius model (E-A model) and the Steady Laminar Diffusion Flamelet (SLDF) model, which is based on the GRI-Mech 3.0 mechanism. This study also indicated the two step reaction (E-A model) as the most indicated for the type of problem addressed by Garréton and Simonin (1994).Centeno *et al.* (2013)

presented an analysis of the influence of the radiative heat transfer in the chamber described by Garréton and Simonin (1994). It was found that the temperature is affected by different radiative heat transfer models, while the chemical species concentration did not.

Saqr *et al.* (2010) studied the effect of increasing the turbulence intensity of the air stream on the NOx and soot formation in turbulent methane diffusion flames. They found that the increase of free stream turbulence intensity of the air supply results in a significant reduction in the NO formation and an observable reduction of the soot formation.

Cao and Meyers (2013) investigated the influence of turbulent inlet boundary conditions on indoor air-flow characteristics and pollutant dispersion in RANS simulations of an indoor ventilated enclosure at a transitional slot Reynolds number. They found that turbulent inlet boundary conditions may have an important impact over the results.

Darbandi and Ghafourizadeh (2017) studied the effects of inlet air and fuel turbulators on the thermal behavior of a combustor burning the jet propulsion (JP) (kerosene-surrogate) fuel and its resulting pollutants emission. It was found that in general the use of suitable turbulators can considerably affect the thermal behavior of a JP-fueled combustor and it also reduces the combustor polycyclic aromatic hydrocarbon (PAH) pollutants emission.

The present study intends to analyze the influence of turbulent inlet boundary conditions of numerical simulations of a cylindrical combustion chamber with a turbulent non-premixed methane-air flame. The considered turbulent inlet conditions are the turbulent characteristic length and turbulence intensity of both fuel and oxidizer streams.

2. METHODOLOGY

The increase in computational power during the past years allowed engineers to employ numerical techniques to solve complex problems, such as turbulent combustion flames. The present work makes use of the finite volume method to solve the mass conservation, momentum, energy and chemical species equations using the Eddy Break-Up-Arrhenius model for combustion combined to a two-step reaction mechanism and to the standard k-ε model for turbulence. Further information about the numerical code can be found in Centeno *et al.* (2013) and Silva *et al.* (2007).

2.1 Problem statement

The problem studied in the current investigation is the non-premixed methane-air combustion chamber described by Garréton and Simonin (1994). This cylindrical chamber consists in a concentric jet stream, with length and diameter of 1.7 m and 0.5 m, respectively, as can be seen in Fig. 1.

Natural gas and air are injected through concentric ducts in the chamber centerline. The smaller circular duct of 0.06 m diameter provides natural gas, while an external annular duct with 0.02 m spacing allows the air entrance.

Air is injected into the chamber with a mass flow rate of 0.186 kg/s at a temperature of 323.15 K, while fuel presents a mass flow rate of 0.0125 kg/s at a temperature of 313.15 K, which corresponds to air and fuel velocities of 36.29 m/s and 7.76 m/s, respectively. An fuel excess of 5% has been prescribed, following Garréton and Simonin (1994) experiment.

As suggested by Nieckele *et al.* (2002) the standard values for turbulence intensity of fuel and oxidizer streams are 10% and 6%, respectively. Concerning the characteristic length, the standard values are 0.03 m for the fuel stream and 0.04 m for the oxidizer stream. These values will be varied in the present study, to verify their influence on temperature and chemical species concentration.

The inlet air is composed of nitrogen (76%), oxygen (23%) and water vapor (1%), while the fuel is composed of methane (90%) and nitrogen (10%).

All walls were considered at 393.15 K.

As presented by Silva *et al.* (2013), buoyancy effects can be neglected, since the speed of the air and fuel at the inlet are high compared to the considerably short size of the flame, which characterize a dominant influence of the forced convection in relation to the natural convection.

As showed by Silva *et al.* (2007) the radiation heat transfer to the combustor wall has a great importance on this type of combustion problem, however, it increases in a great deal the computational time and does not affect the comparative results analyzed on this study, so the radiation heat transfer was neglected without jeopardize the outcomes.

Soot, NO_X and SO_X formation can also be neglected, once for methane combustion their molar fractions are extremely low.

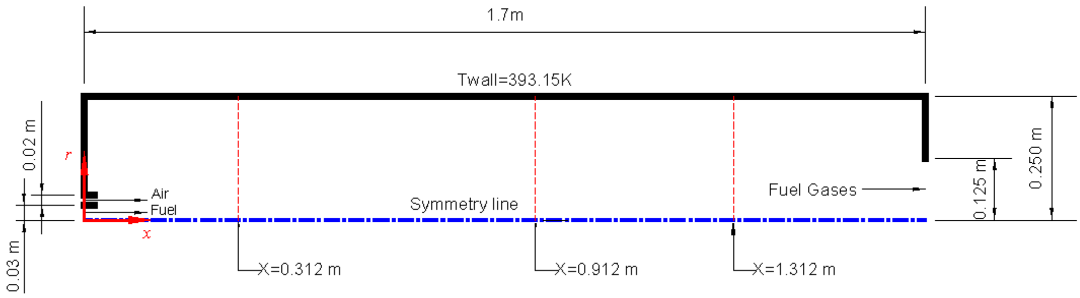

Figure 1. Combustion chamber diagram.

2.2 Mesh sensitivity

A mesh sensitivity study was performed to determine the most adequate mesh for this simulation. Five different meshes were computed. Table 1 presents the studied meshes (represented as radial control volumes × longitudinal control volumes) and computational time required by them.

Figure 2 shows the results obtained for temperature and molar fractions of CH_4, O_2 and CO_2 at the symmetry line for the different meshes.

Table 1. Mesh size and computational time

	Mesh size	Computational time (minutes)
Mesh 1	20×56	6.6
Mesh 2	24×70	27.1
Mesh 3	30×84	38.9
Mesh 4	48×140	106.5
Mesh 5	54×154	130.2

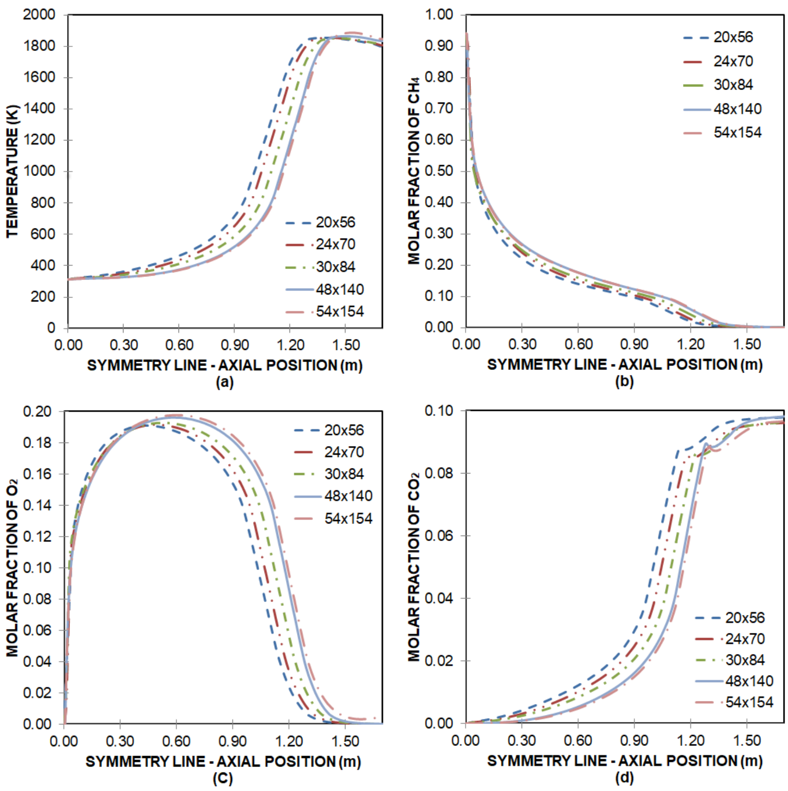

Figure 2. Mesh sensitivity result (a) Temperature (b) molar fraction CH_4 (c) molar fraction O_2 (d) molar fraction of CO_2.

As can be observed, a sensible choice is mesh 4, because the difference between the results for more refined meshes is not significant, so the increase in computational time justify this choice.

2.3 Numerical model Validation

To validate the numerical model, the results of temperature and molar fraction of CH_4 on the symmetry line and temperature in a section at *X*=0.312 m were compared to experimental data. Figure 3 shows the comparison between numerical results and experimental data.

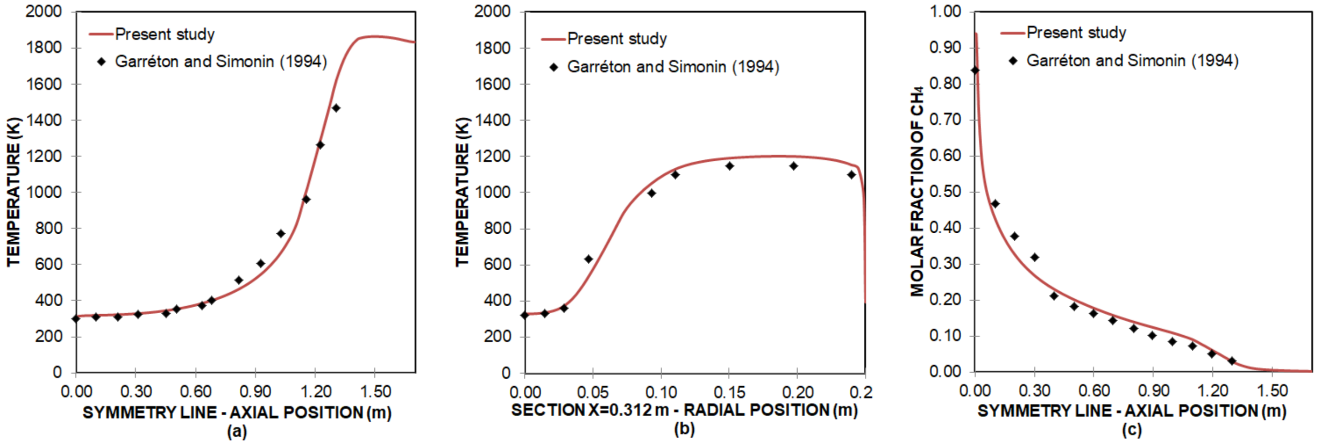

Figure 3. Validation results (a) Temperature at symmetry line (b) Temperature at *X*=0.312 m(c) molar fraction CH4 at symmetry line.

As can be seen, the numerical model can be considered adequate, once the results shown a good agreement to experimental data.

3. RESULTS AND DISCUSSIONS

The results of temperature and chemical species concentration obtained for the four inlet turbulent conditions will be presented on the symmetry line and three different radial sections at *X*=0.312m, *X*=0.912m e *X*=1.312m.

3.1 Influence of the turbulence intensity of the oxidizer stream

The standard value for the turbulence intensity of the oxidizer stream suggested by Nieckele *et al.* (2002) is 6%. This parameter was varied and compared to experimental data to verify its influence on the results.

Figure 4 presents the temperature (K) and the turbulent kinetic energy (m^2/s^2) fields for the different turbulence intensities. The turbulence intensities employed were 3%, 6% (reference), 9% 12% and 18%. Analyzing Fig. 4, it seems that the flame becomes shorter and the reaction happens earlier as the TI of oxidizers is increased, which agrees with the kinetic energy augment observed.

Figure 5 shows the influence of the turbulence intensity of the oxidizer stream on temperature and molar fractions in the symmetry line. As can be seen, the increase in the turbulence intensity of the oxidizer stream made the maximum temperature on the symmetry line shift upstream in direction to the chamber inlet, suggesting that the reaction occurs closer to the inlet, while the molar fraction of CH_4 becomes lower at all axial positions, suggesting a fuel consumption at an early stage of the chamber. The molar fraction of O_2 increases at the beginning of the chamber, and decreases rapidly and earlier when higher turbulence intensity is employed. So, a too large value for this parameter changes the O_2 molar fraction behavior, bringing a higher concentration of oxidizer to the inlet of the chamber and making it to be consumed earlier. For the molar fraction of CO_2, the variation of turbulence intensity of the oxidizer results in a production of CO_2 closer to the chamber inlet as the TI of the oxidizer stream is augmented. These results point to a general behavior of the increased air-fuel mixing occurring upstream as the TI of the air is increased, so the combustion takes place closer to the chamber inlet, then affecting the temperature gradients, CH_4 consumption, O_2 consumption and CO_2 formation.

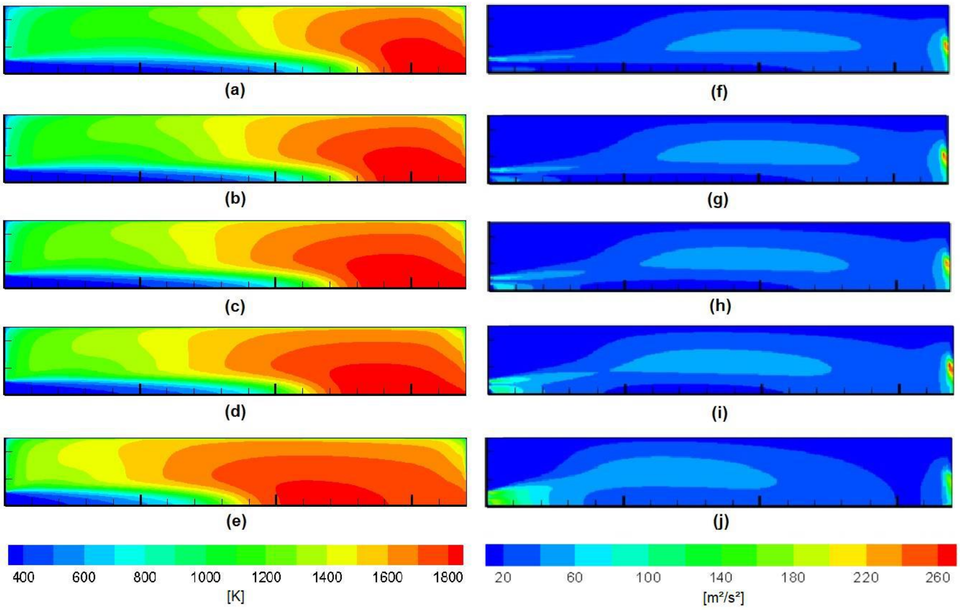

Figure 4. Temperature (left) and turbulent kinetic energy fields (right) varying turbulence intensity of oxidizer stream (a) (f) 3% (b) (g) 6% (Standard) (c) (h) 9% (d) (i) 12% (e) (j) 18%.

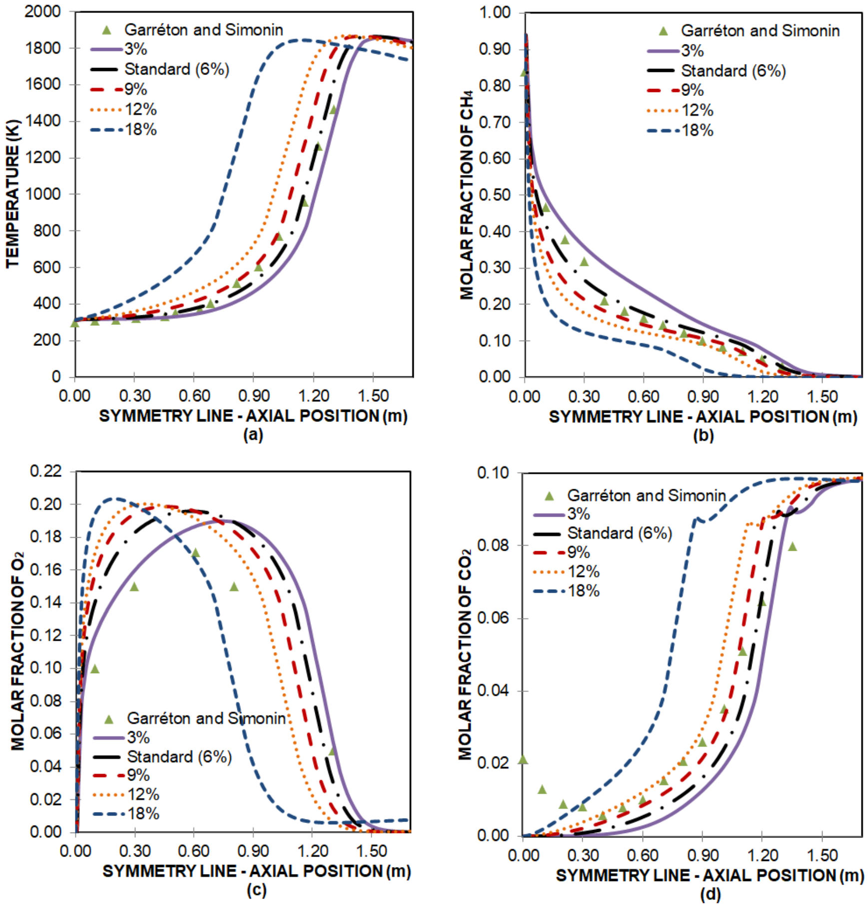

Figure 5. Results varying turbulence intensity of oxidizer stream (a) Temperature (b) molar fraction of CH_4 (c) molar fraction of O_2 (d) molar fraction of CO_2.

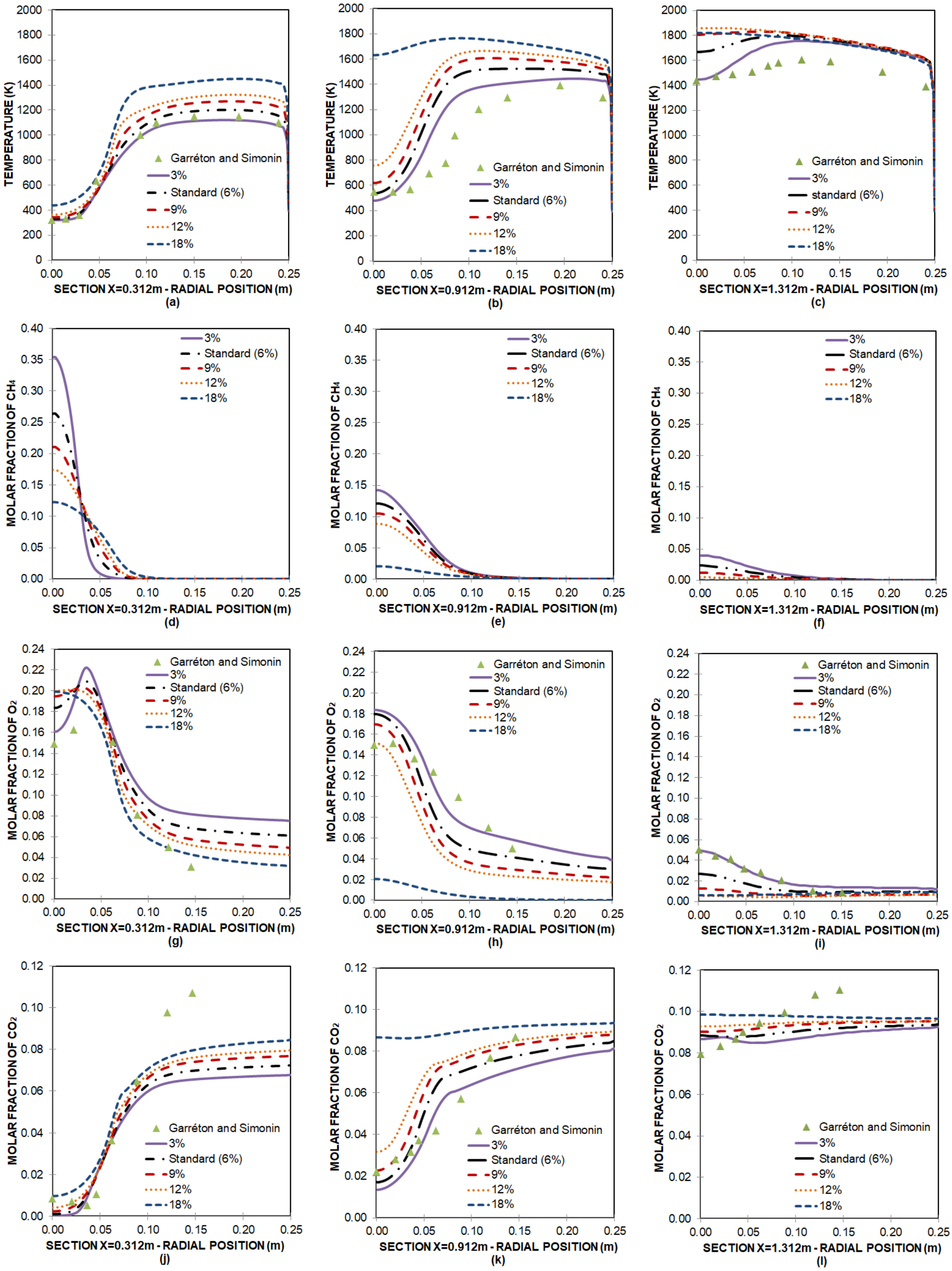

Figure 6. Results of temperature, molar fraction of CH_4, molar fraction of O_2 and molar fraction of CO_2 at sections X=0.312m, X=0.912m and X=1.312m varying turbulence intensity of oxidizer stream.

Figure 6 shows the influence of the turbulence intensity of the oxidizer stream in the temperature and molar fractions on three different sections, X=0.312 m X=0.912 m and X=1.312 m. As can be observed, temperature at the first two sections increases considerably over all radial positions as the TI of oxidizer is increased, presenting lower values near the symmetry line (flame region), which agrees with the temperature fields presented on Fig. 4. A different behavior is observed at section X=1.312 m, where the temperature increases near the symmetry line and become stable, showing less dependence, away from it. This increase on temperature at chamber center for the outlet section occurs until the turbulence intensity of 12%, after this value a slight decrease is observed, as can be better observed on Fig. 4. At section X=0.312 m the molar fraction of CH_4 decreases at the chamber symmetry line, but this decrease becomes less sudden as the TI of the oxidizer is augmented. It seems that the fuel spreads more radially at the inlet as this turbulator is increased. As the sections become farther from the inlet the CH_4 concentrations become smaller, as expected, and at sections X=0.912 m and X=1.312 m the increase on turbulence intensity results in even smaller concentrations. It means that the turbulence intensity of the oxidizer affects significantly the fuel concentration along the chamber. So, a higher turbulence intensity of oxidizer makes the fuel to be consumed in an early stage of the chamber. Since the air is injected at the external annular duct shown in Fig. 1, the inlet section, as expected, presents a lower concentration of O_2 on the symmetry line where the fuel is injected and a higher concentration at the annular region where the oxidizer is injected. The oxidizer concentration becomes smaller as you move away from this region. In the same way as the CH_4 concentration, as the sections become farther from the inlet part of the chamber, the O_2 concentration becomes lower, so it seems the combustion reaction is happening at an earlier part of the chamber, as was suggested before by Fig. 4. As expected, the molar fraction of CO_2 augments, since more fuel and oxidizer are consumed. With the increase on turbulence intensity of the oxidizer the reaction happens earlier in the chamber, as well as the CO_2 formation, as a result of the enhanced mixing between fuel and air. As the sections become farther from the inlet, higher the molar fraction of CO_2 become, been almost uniform at all radial positions on the outlet of the chamber.

As can be observed the inlet and middle parts of the chamber are more affected by the turbulence intensity of the oxidizer, while the outlet part shows smaller differences.

3.2 Influence of the turbulence intensity of the fuel stream

The standard value for the turbulence intensity of the fuel stream suggested by Nieckele *et al.* (2002) is 10%. This parameter was varied and compared to experimental data to verify its influence on the results.

Figure 7 presents the temperature and turbulent kinetic energy fields for the different turbulence intensities of fuel stream. The turbulence intensities employed were 5%, 10% (reference), 15% 20% and 30%. The flame length does not depend on the TI of fuel, but the temperature at the flame surroundings does. As the TI of fuel stream is augmented, the peak temperature shifts to the upstream portion of the chamber. The kinetic energy field does not present significant variation.

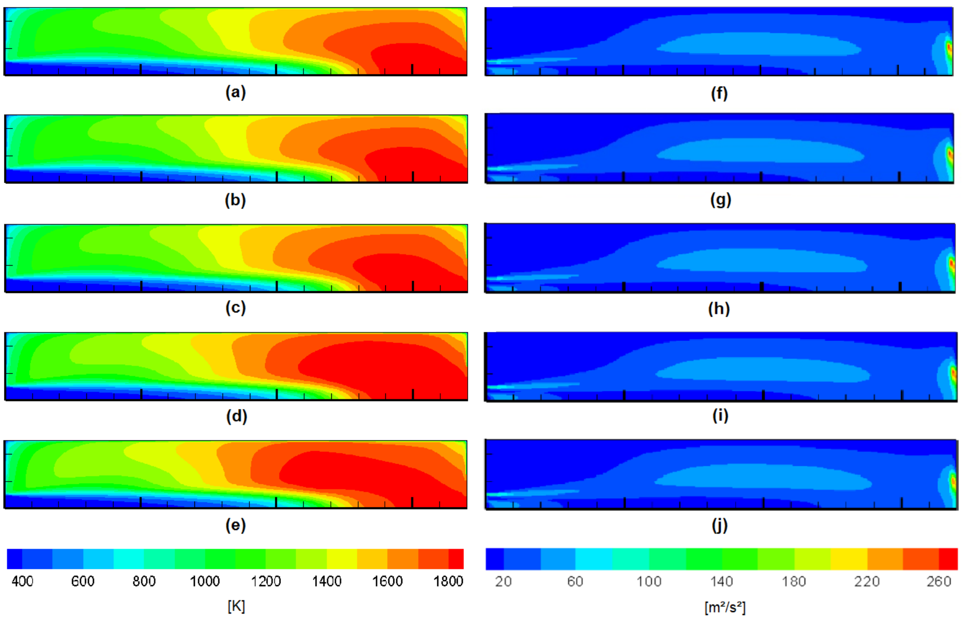

Figure 7. Temperature (left) and turbulent kinetic energy (right) fields varying turbulence intensity of fuel stream (a) (f) 5% (b) (g) 10% (Standard) (c) (h) 15% (d) (i) 20% (e) (j) 30%

Figure 8 shows the influence of the turbulence intensity of the fuel stream in the temperature and molar fractions in the symmetry line. As can be seen, the increase in the turbulence intensity of the fuel stream has no significant influence on the temperature or molar fractions at the symmetry line, except by the temperature and CO_2 concentration at the outlet stage of the chamber, where the temperature decreases and the molar fraction of CO_2 increases, both significantly.

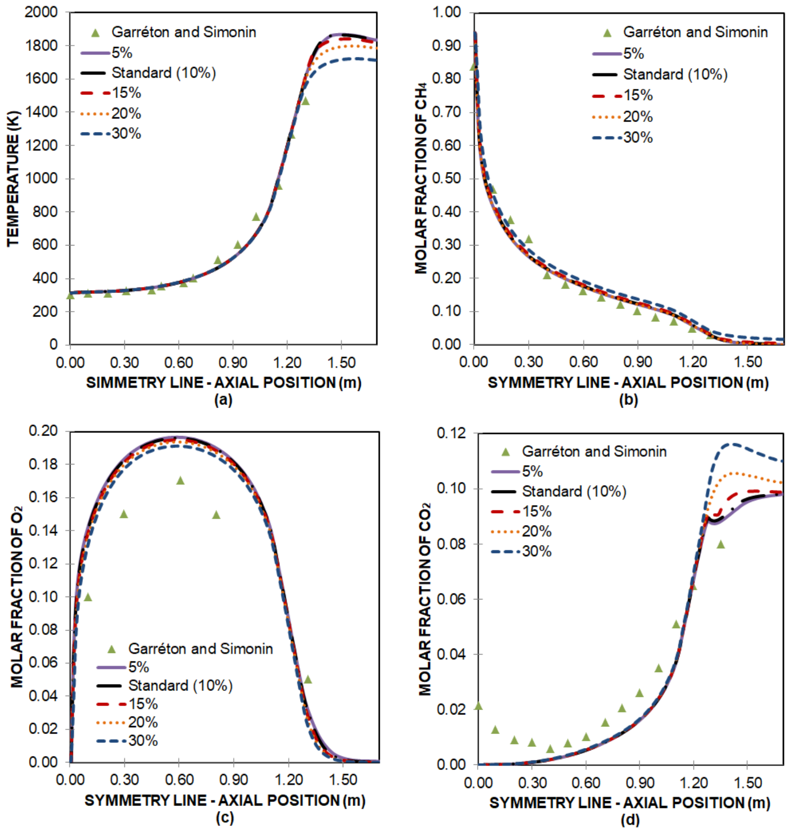

Figure 8. Results along symmetry line varying turbulence intensity of fuel stream (a) Temperature (b) molar fraction of CH_4 (c) molar fraction of O_2 (d) molar fraction of CO_2

Figure 9 shows the influence of the turbulence intensity of the fuel stream in the temperature and molar fractions on three different sections, X=0.312 m X=0.912 m and X=1.312 m. As can be observed, temperature at the inlet and middle sections increases outside the flame region as the TI is increased, presenting lower values near the symmetry line (in the flame), which agrees with the temperature fields shown in Fig. 7. A different behavior is observed at section X=1.312 m, where the temperature increases over almost all radial positions. This increase on temperature at the outlet section occurs until the turbulence intensity of 20%, after this value a decrease is observed from the symmetry line until half the chamber radius, as can be better observed in Fig. 7, once the temperature seems to migrate to the earlier parts of the chamber. The molar fraction of CH_4 increases slightly near the symmetry line (flame region) as the TI of the fuel is augmented. It is possible to observe the fuel radial spread and its consumption as the sections are moved away from the inlet section. The augment of the TI of fuel decreases the concentration of O_2 over all radial positions, especially outside the flame region, away from the symmetry line and at the outlet region, which appoints for a larger consume of oxidizer. The molar fraction of CO_2 augments as the TI of fuel stream is increased, particularly outside the flame region, which indicates a larger formation of CO_2.

As can be observed, the flame region is little affected by the turbulence intensity of fuel stream variation, except by the CH_4 concentration. An augment of temperature and CO_2 formation is observed, as well as a reduction of O_2 concentration inside the combustion chamber.

Comparing the influence of the TI variation for the air stream with the influence of the TI variation of the fuel stream, it is noticed that the TI of the air stream affects strongly the thermal field and species concentrations predictions inside the combustion chamber. This may be caused due to the higher inlet velocity of the air stream (36.29 m/s, while the fuel stream inlet velocity is 7.76 m/s), since the turbulence intensity is a percentage scale that characterizes a relationship between the turbulent fluctuations of the velocity and the mean velocity, so a higher mean velocity (and a higher turbulence intensity) means higher velocity turbulent fluctuations at the inlet, which provides enhancements to the mixing process between the air stream and the fuel stream. While the fuel stream at the inlet has smaller velocity, its velocity turbulent fluctuations are smaller (in comparison with the inlet air stream), so the variation of its turbulence intensity affects the flow and thermal fields and reaction process, but in a reduced way (when comparing to the variation of the inlet air stream turbulence intensity).

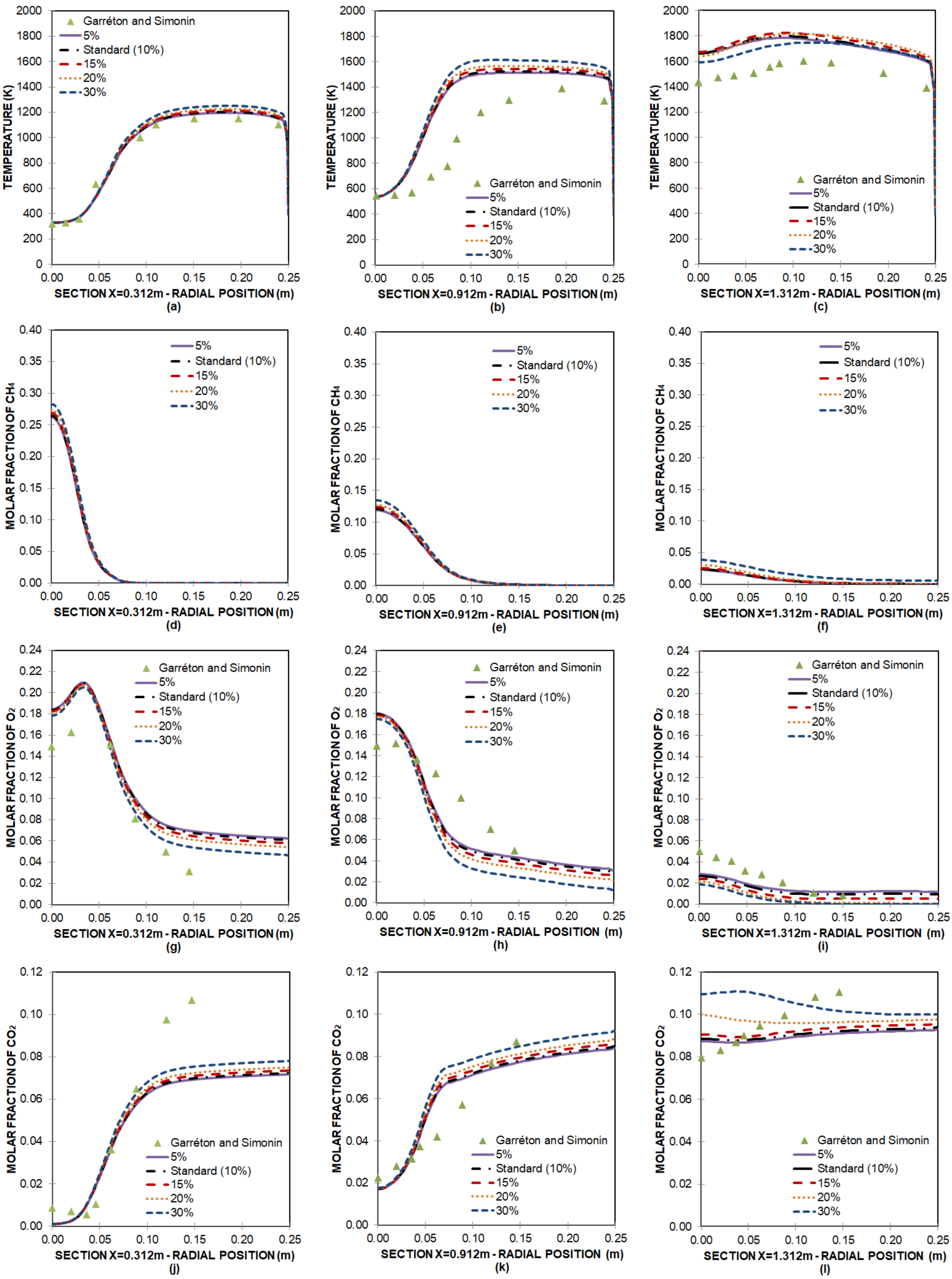

Figure 9. Results of temperature, molar fraction of CH_4, molar fraction of O_2 and molar fraction of CO_2 at sections X=0.312m, X=0.912m and X=1.312m varying turbulence intensity of fuel stream

3.3 Influence of the turbulent characteristic length of the oxidizer stream

The standard value for the turbulent characteristic length of the oxidizer stream at the inlet suggested by Nieckele *et al.* (2002) is 0.04 m. This parameter was varied and compared to experimental data to verify its influence on the results.

Figure 10 presents the temperature and turbulent kinetic energy fields obtained for the different turbulent characteristic lengths of oxidizer stream at the inlet. The turbulent characteristic length employed were 0.01 m, 0.04 m (reference), 0.08 m, 0.16 m and 0.20 m. As can be observed, the flame length, temperature and kinetic energy field does not depend on the turbulent characteristic length of the oxidizer stream at the inlet. A qualitative comparison does not show great differences.

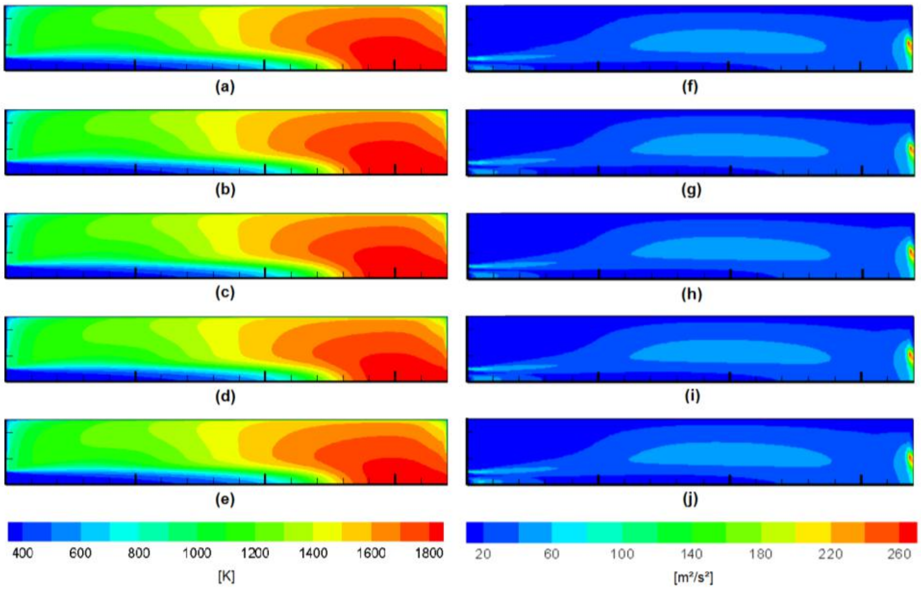

Figure 10. Temperature (left) and turbulent kinetic energy (right) fields varying the turbulent characteristic length of the oxidizer stream (a) (f) 0.01 m (b) (g) 0.04 m (Standard) (c) (h) 0.08 m (d) (i) 0.16 m (e) (j) 0.20 m

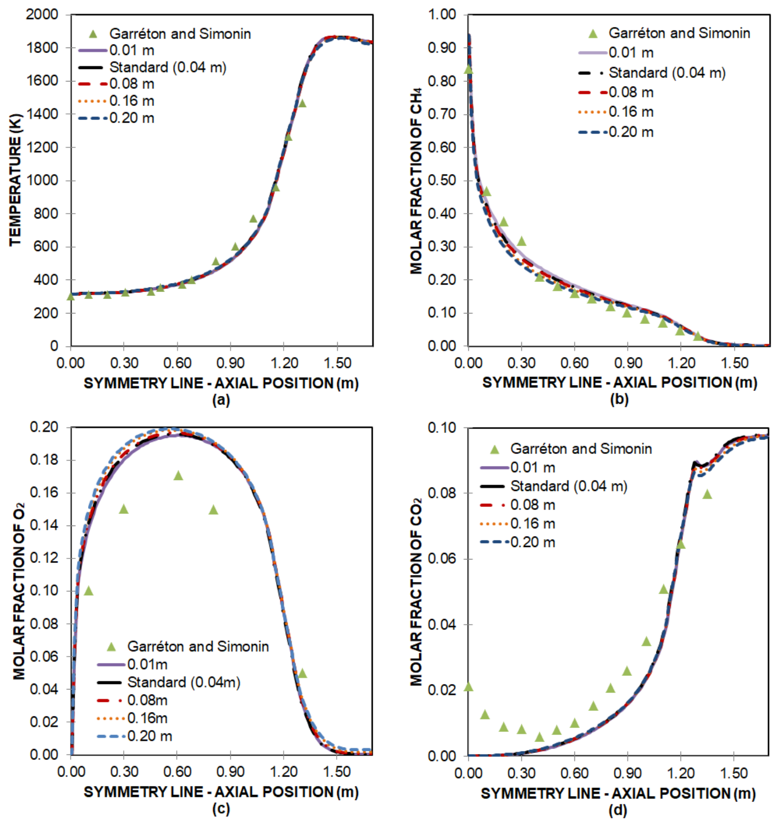

Figure 11. Results along symmetry line varying the turbulent characteristic length of the oxidizer stream (a) Temperature (b) molar fraction of CH_4(c) molar fraction of O_2 (d) molar fraction of CO_2

Figure 11 shows the influence of the turbulent characteristic length of the oxidizer stream at the inlet on the temperature and molar fractions in the symmetry line. As can be seen, the increase in the turbulent characteristic length of the oxidizer stream at the inlet has no significant influence on the temperature at the symmetry line. At the first part of the chamber, a slight reduction on CH_4 concentration and a slight augment on the O_2 concentration are observed when the characteristic length of the oxidizer is increased. As well as a little decrease on CO_2 formation at the end part of the chamber.

Figure 12 shows the influence of the turbulent characteristic length of the oxidizer stream in the temperature and molar fractions on three different sections, X=0.312 m X=0.912 m and X=1.312 m. As can be observed, the turbulent characteristic length of oxidizer has no significant influence over temperature at all sections, as shown before by Fig. 10. Some reduction on CH_4 concentration can be seen at sections X=0.312 m and X=0.912 m near the symmetry line, at flame region. A little augment on the O_2 molar fraction can be observed at the inlet section near the symmetry line. The variation of the turbulent characteristic length of oxidizer has not showed any significant influence on CO_2 formation.

So, it is possible to conclude that the turbulent characteristic length of the oxidizer stream has no important influence over temperature and species concentration. The turbulent characteristic length is inversely proportional to the dissipation rate of the turbulent kinetic energy, and can be considered as a rough scale of the larger eddies at the entrance of the combustion chamber. Since the oxidizer inlet annulus pipe is relatively small, it limits the sizes of the turbulent eddies in a real chamber, so it does in its numerical modelling. This could explain the weak relation between the results obtained by imposing different turbulent characteristic lengths to the oxidizer stream at the chamber inlet and the numerical results for the thermal and reactive fields.

3.4 Influence of the turbulent characteristic length of the fuel stream

The standard value for the turbulent characteristic length of the fuel stream suggested by Nieckele *et al.* (2002) is 0.03 m. This parameter was varied and compared to experimental data to verify its influence on the results.

Figure 13 presents the temperature and turbulent kinetic energy fields for the different turbulent characteristic lengths of fuel stream at the chamber inlet. The turbulent characteristic lengths employed were 0.01 m, 0.03 m (reference), 0.05 m, 0.10 m and 0.15 m. As can be observed, the flame length does not depend on the turbulent characteristic length of the fuel at the inlet, however the temperature field presents a considerable change as this parameter is augmented, showing an increase on chamber temperature at the upstream region of the chamber (shifting the highest temperatures towards the chamber inlet, and reaching the middle region of it). No significant variation on kinetic energy fields can be observed.

Figure 14 shows the influence of the turbulent characteristic length of the fuel stream on the temperature and molar fractions in the symmetry line. As can be seen, the increase on the turbulent characteristic length of the fuel stream imposed as inlet boundary condition has no significant influence on the temperature at the symmetry line for values until 0.05 m, and showed a considerable reduction of temperature at the outlet region for values above that. A slight increase on the molar fraction of CH_4 can be observed as the turbulent characteristic length of fuel is augmented, as well as a slight reduction on O_2 concentration. An increase in CO_2 concentration at the outlet region of the chamber occurs as the turbulent characteristic length of fuel is augmented.

Figure 15 shows the influence of the turbulent characteristic length of the fuel stream on the temperature and molar fractions on three different sections, X=0.312 m, X=0.912 m and X=1.312 m. As can be observed, the augment on the turbulent characteristic length of fuel causes a considerable increase on temperature at sections X=0.312 m and X=0.912 m, while it causes a reduction of temperature at section X=1.312 m, this fact has already been pointed out at Fig. 13. An increase on CH_4 concentration can be seen at the inlet and middle sections near the symmetry line (at flame region), as well as an increase on this concentration at all radial positions of the outlet section, which suggests an incomplete combustion reaction when the value for the turbulent characteristic length of the fuel is too high. A decrease on O_2 molar fraction is observed at all radial position of every studied section, particularly outside the flame. The increase of this characteristic length represented a considerable increase on CO_2 formation.

So, unlike the turbulent characteristic length of oxidizer, the turbulent characteristic length of fuel has a more important influence over temperature and species concentration. This can be related to the fuel inlet diameter, which is larger than the oxidizer inlet annulus pipe size, allowing larger turbulent eddies at the chamber inlet which then carry more turbulent kinetic energy into the chamber, affecting more importantly both thermal and reaction fields.

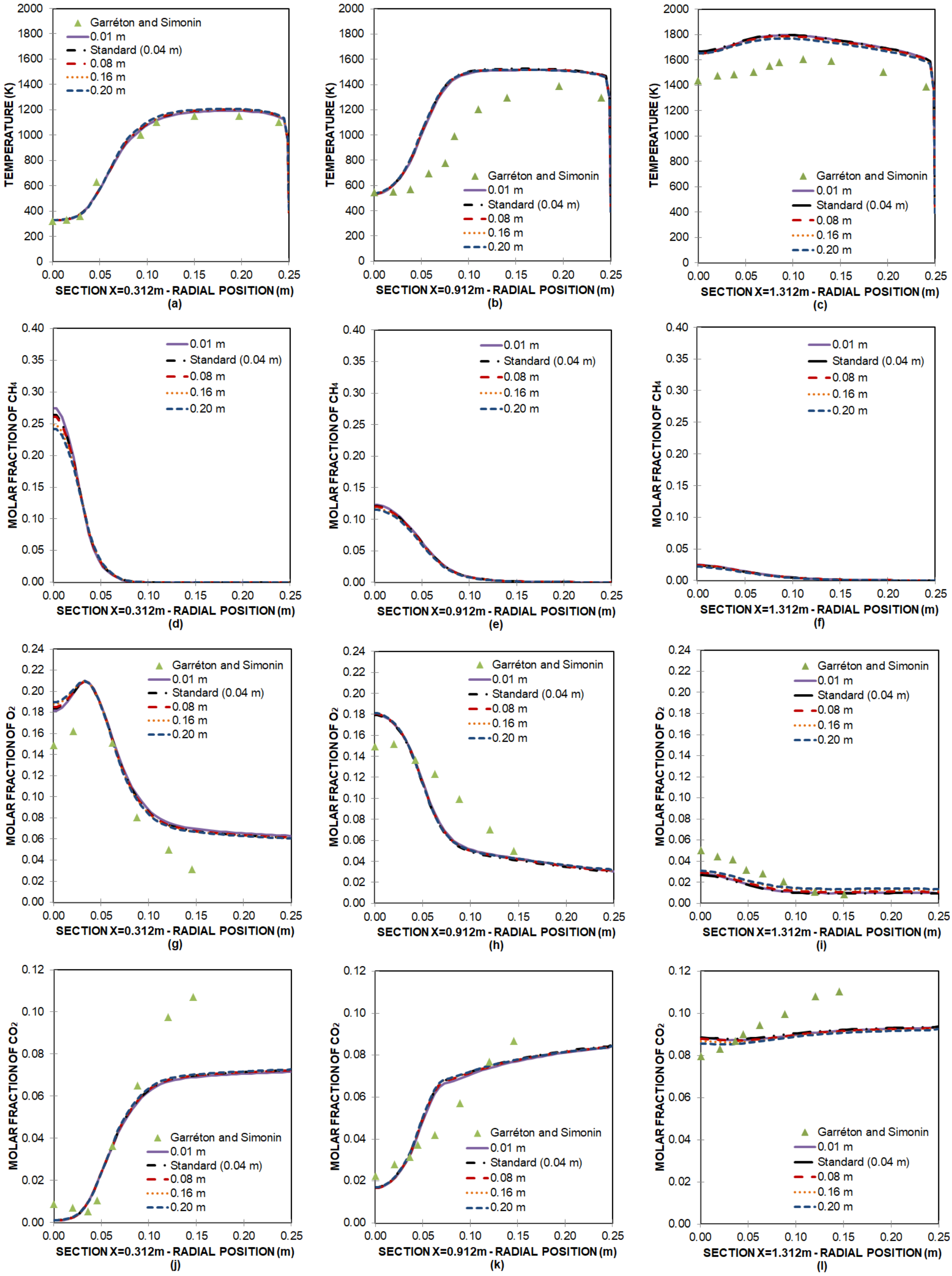

Figure 12. Results of temperature, molar fraction of CH_4, molar fraction of O_2 and molar fraction of CO_2 at sections X=0.312m, X=0.912m and X=1.312m varying the characteristic length of the oxidizer stream

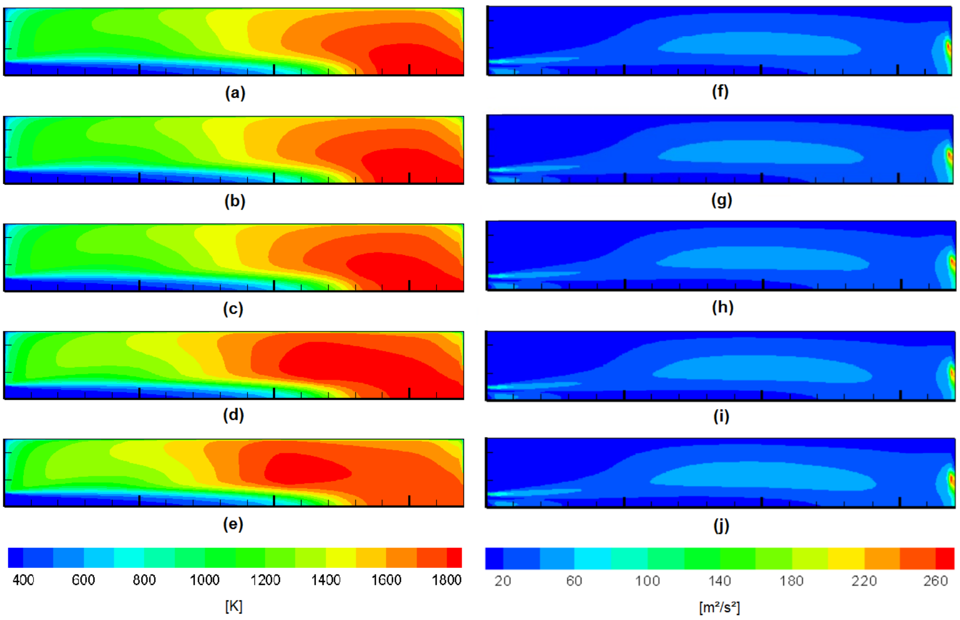

Figure 13. Temperature (left) and turbulent kinetic energy (right) fields varying the turbulent characteristic length of the fuel stream (a) (f) 0.01 m (b) (g) 0.03 m (Standard) (c) (h) 0.05 m (d) (i) 0.10 m (e) (j) 0.15 m

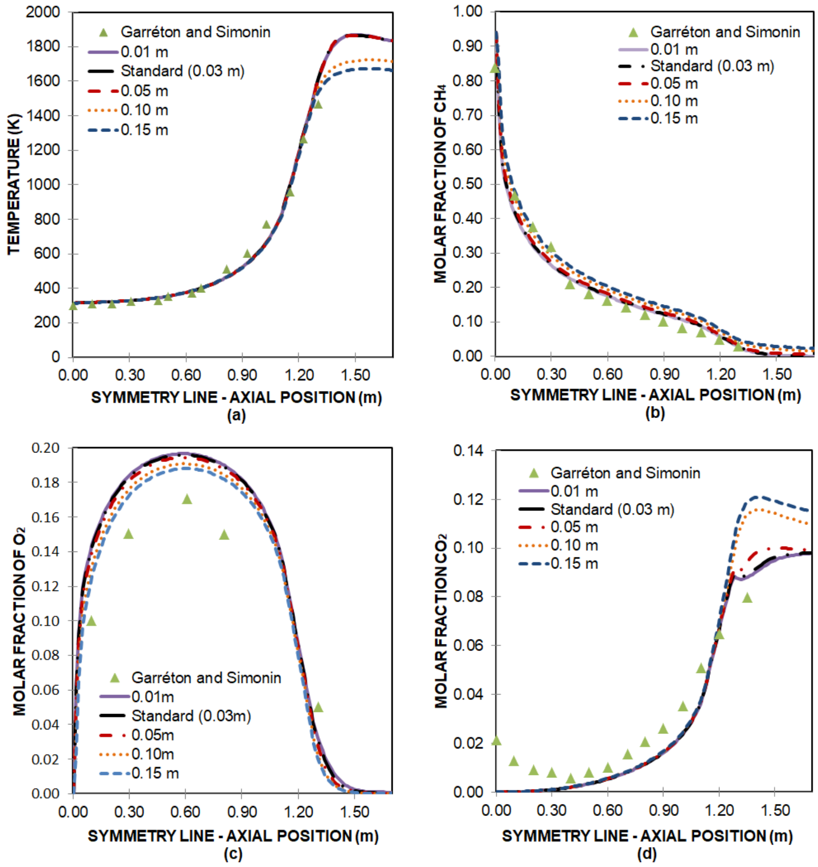

Figure 14. Results along symmetry line varying the turbulent characteristic length of the fuel stream (a) Temperature (b) molar fraction of CH_4(c) molar fraction of O_2 (d) molar fraction of CO_2

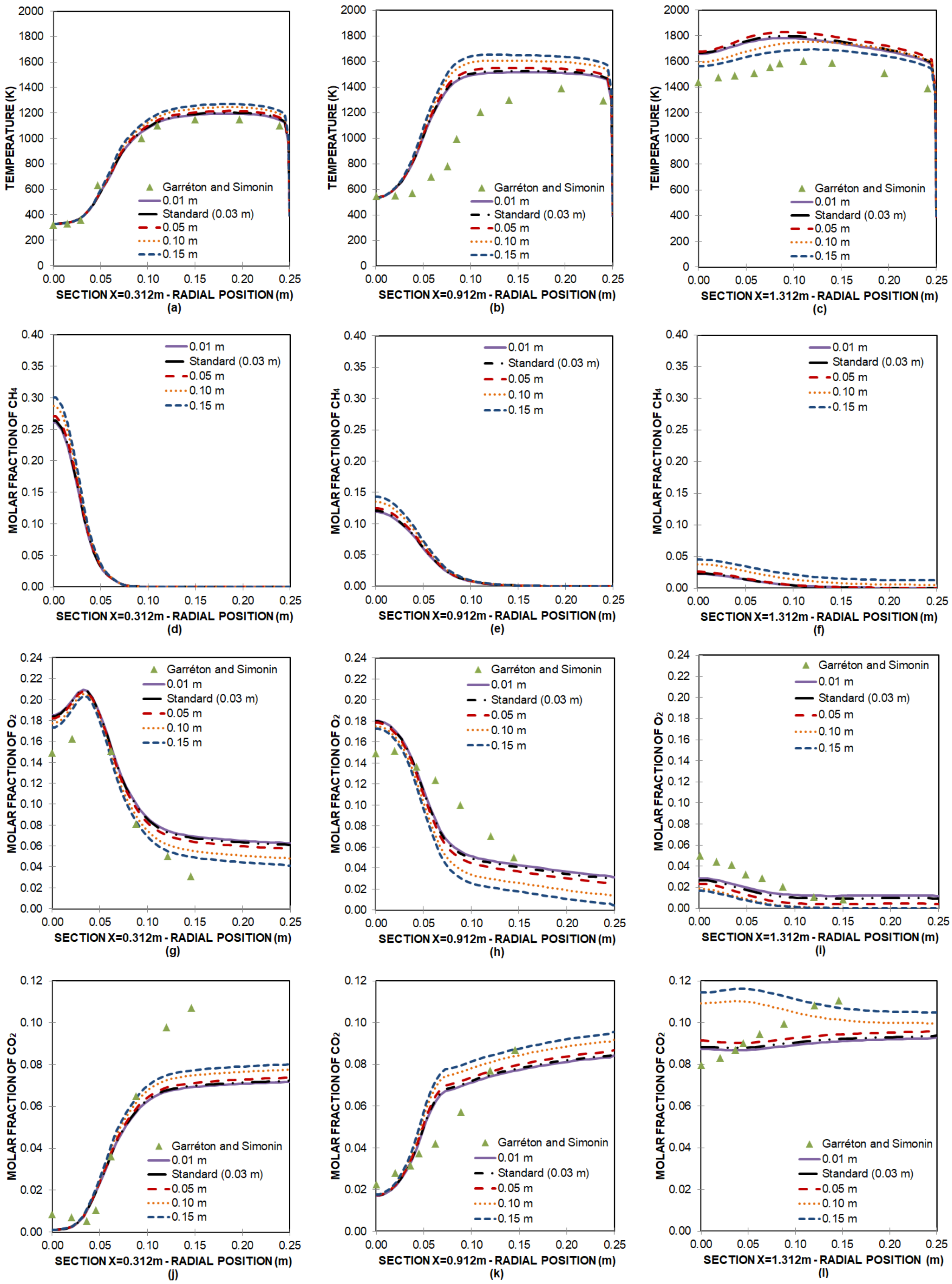

Figure 15. Results of temperature, molar fraction of CH_4, molar fraction of O_2 and molar fraction of CO_2 at sections X=0.312m, X=0.912m and X=1.312m varying the characteristic length of the fuel stream

4. CONCLUSIONS

The comparison of the numerical results generally provided a good agreement with the experimental data, while some differences are explained by the relatively simplistic two-step reaction mechanism employed.

The specification of different turbulence intensities of the oxidizer stream at the chamber inlet showed a great influence over both temperature and species concentration, changing even the behavior of the flame, turning it shorter as this parameter was increased. With the increase of this turbulator, the temperature augmented inside the chamber, CH_4 concentration was reduced and O_2 concentration augmented on the inlet part of the chamber but was consumed in an earlier part and decreased more rapidly. These observations, as well as the higher kinetic energy on the chamber inlet characterize the combustion reaction happening closer to the inlet of the chamber, which explains the reduction on flame length. An increase on CO_2 formation was observed too. These important differences presented, make this parameter the most relevant turbulent boundary condition to be specified for the present turbulent non-premixed flame simulation.

The turbulence intensity of the fuel stream at the chamber inlet had no influence at the flame length, but its increase augmented the temperature on the earlier part of the combustion chamber. An augment of temperature and CO_2 formation was observed inside the chamber, as well as a reduction of O_2 concentration.

The turbulent characteristic length of the oxidizer stream at the chamber inlet was the parameter which showed the less important influence over both temperature and molar fractions, being its variation influence negligible.

The turbulent characteristic length of fuel stream, on the contrary, showed a significant influence over temperature and species concentration, again demonstrating an augment on temperature in the beginning of the combustion chamber. An increase on CH_4 concentration was observed at the flame region, as well as an increase on this concentration on the outlet region. The obtained results suggest an incomplete combustion reaction when the value for the turbulent characteristic length of the fuel is too high. A decrease on O_2 molar fraction was observed, particularly outside the flame. The increase of this turbulent characteristic length represented a considerable increase on CO_2 formation.

Finally, it is concluded that the correct selection of the inlet turbulent boundary conditions has a great influence on the numerical simulation results for a turbulent non-premixed flame, while the turbulence intensity of the oxidizer stream is the most important one.

5. REFERENCES

Cao, S. and Meyers, J., 2013.“Influence of turbulent boundary conditions on RANS simulations of pollutant dispersion in mechanically ventilated enclosures with transitional slot Reynolds number”. *Building and Environment*, V. 59, p. 397-407.

Centeno, F.R., Cassol, F., Vielmo, H.A., França, F.H.R. and da Silva, C.V., 2013. “Comparison of different WSGG correlations in the computation of thermal radiation in a 2D axisymmetric turbulentnon-premixed methane–air flame”. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, V. 35, p. 419–430.

Darbandi, M. and Ghafourizadeh, M., 2017.“Numerical study of inlet turbulators effect on thermal characteristics of a JP-fueled combustorand its hazardous pollutants emission”.*ASME Journal of Heat Transfer*, V. 139(6), p. 061201.

Garréton, D. and Simonin, O.,1994.“Final results”. *First Workshop of Aerodynamics of Steady State Combustion Chambers and Furnaces*, V. 25, p. 29-35.

Magel, H.C. Schnell, U. and HEIN, K.R.G., 1996.“Simulation of detailed chemistry in a turbulent combustor flow.”*Twenty-Sixth Symposium (International) on Combustion/The Combustion Institute*, V.26, p. 67–74.

Nieckele, A.O.,Naccache, M.F.,Gomes, M.S.P., Carneiro, J.E. and Serfaty, R., 2001.“Models evaluations of combustion processing a cylindrical furnace.”*ASME International Mechanical Engineering Congress and Exposition*, New York, USA.

Nieckele, A.O., Naccache, M.F., Gomes, M.S.P., Carneiro, J.E. and Serfaty, R., 2002. “Predição da combustão de gás natural m uma fornalha utilizando reações em uma e duas etapas.”*CONEM - Congresso Nacional de Engenharia Mecânica*, João Pessoa, Brazil.

Saqr, K.M., Aly, H.S., Sies, M.M. and Wahid, M.A., 2010. “Effect of free stream turbulence on NOx and soot formation in turbulent diffusion CH4-air flames.”*International Communications in Heat and Mass Transfer*, V. 37, p. 611–617.

Silva, C.V., França, F.H.R. and Vielmo, H.A., 2007. “Analysis of the turbulent, non-premixed combustion of natural gas in a cylindrical chamber with and without thermal radiation.” *Combustion Science and Technology*, V.179, p. 1605-1630.

Silva, C.V., Segatto, C. A., de Paula, A. V., Centeno, F.R. and França, F.H.R., 2013. “3d analysis of turbulent non-premixed combustion of natural gas in a horizontal cylindrical chamber.” *Proceedings of 22st Brazilian Congress of Mechanical Engineering, Ribeirão Preto*, SP, Brasil.

Silva, C.V., Deon, D. L., Centeno, F.R., França, F.H.R and Pereira, F. M., 2018. “Assessment of combustion models for numerical simulations of a turbulent non-premixed natural gas flame inside a cylindrical chamber”. *Combustion Science and Technology*, V. 190 p. 1528-1556.