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LES AND RANS OF PREMIXED COMBUSTION IN A GAS-TURBINE LIKE COMBUSTOR USING THE FLAMELET GENERATED MANIFOLD APPROACH

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ABSTRACT

Dry-low NOx gas turbine technology relies on lean premixed combustion of fuel. Additionally the accurate prediction of turbulent premixed combustion is still very difficult. In the present paper the calculation of reduced chemistry is assessed efficiently through the use of the flamelet generated manifold (FGM), which is used in conjunction with a CFD code in a RANS as well as in an LES context. In order to predict the combustion phenomena in a high swirl and high Reynolds number flow (the SimVal setup, at atmospheric pressure with elevated temperature), the present model is used concomitantly with a pre-assumed PDF for which fluctuations are completely determined in terms of an algebraic model. The mixing model for the variance has an arbitrary model constant, and the results show that the flame stabilization is not very sensitive to the model parameter present in the model. Stabilization of the combustion occurs at a location comparable to that found in experiments. In order to investigate the effects of this parameter on the numerical solutions, first RANS simulations were addressed considering arbitrary values for this parameter, defined within a certain range, and in a next step the grid resolution was changed. LES calculations were also performed showing similar features predicted in RANS. It is found that with the use of FGM combustion features in gas turbine conditions can be reproduced in a robust way.

Introduction

Gas turbines can be regarded as one of the main ways to convert energy on earth. The reason for their use can be justified mainly due to their low cost, high efficiency, and favorable environmental performances such as the inherently low emissions of NO_x, CO and unburnt hydrocarbons. This is related with generat-

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ing heat and momentum (power) in such devices by combustion processes in the lean premixed regime. There are several conflicting requirements associated with lean premixed combustion: (i) stable operations, (ii) emissions, (iii) complete combustion of fuel and (iv) fuel type.

In the future, the design of power plants will demand even more reductions in the chemical reaction pathways that produce less pollutants. Furthermore, the basic dynamics of turbulent premixed combustion are not completely understood, and should be improved.

In this paper the effectiveness of LES and RANS for modeling lean premixed methane combustion in conjunction with a reduction chemistry technique will be investigated in the context of gas turbine modeling.

The use of reduction chemistry to access combustion phenomena in gas turbine combustors is not new. In fact different kinds of strategies have been proposed in recent years, in order to provide some perspective and just to name a few, could be cited the Flame Prolongation of Intrinsic Low Dimensional Manifold (ILDM-FPI) and the presumed conditional moments with flamelets (PCM-FPI). In all the cited cases, turbulence and chemistry interaction is considered with a pre-assumed β-PDF shape.

In fact, due to the fully premixed nature related with the present combustion regime to be analyzed, several combustion modeling approaches could be used. One of them, for instance, is the Zimont model, which provides the closure of the mean reaction rate in the progress variable equation using a empirical relation.

In the present work the required reduction of the chemistry is provided by the flamelet generated manifold (FGM) approach [1]. Turbulence-chemistry interactions are considered through a presumed β-PDF in conjunction with an algebraic model, as modeled in Vreman et al. [2]. This model can be used to calculate the fluctuations necessary to determine a pre-assumed PDF. However, the model has a free parameter that is grid dependent. Typically it should take a value between 1 and 2 but it is unclear what the most correct physical/numerical value should be. This is the subject of the current investigation. At this moment, the referred algebraic model has been applied only in a more academic context, such as a Bunsen flame issuing from a slit [2]. Here its potential is addressed in a practical combustor.

To summarize, the main goal of the present work is to use the FGM method concomitantly with a pre-assumed PDF, where its respective variance is closed in terms of the cited algebraic model. The defined approach will be mostly applied in the context of RANS and LES related with a gas turbine combustor.

One of the main objectives is to predict the turbulent flame brush. Since the RANS approach is consistent with LES, also these simulations (Realizable $k-\varepsilon$) are addressed.

The outline of this paper is as follows, in the next section a short description of the FGM method and the algebraic model is exposed. Also, the description of the different simulations performed will be presented. Results of LES and RANS obtained with different values for the model parameter will be presented and discussed, and in the end a comparison between the combustion model assessed (FGM) with the Zimont model will be performed, and followed by the final conclusions.

An Algebraic Model for the Variance

To take into account turbulence-chemistry interactions, the flamelet approach can be combined with a pre-assumed PDF in order to proper define the mean chemical source term, which is necessary to close the turbulent transport equation for the mean progress variable, $\tilde{c}$.

$$\left[\frac{\partial \bar{\rho}\tilde{c}}{\partial t}+\vec{\nabla}.\left(\bar{\rho}\tilde{\vec{u}}\tilde{c}-\bar{\rho}\left(D+D_T\right)\vec{\nabla}\tilde{c}\right)\right]=\bar{\dot{\omega}}_c \tag{1}$$

where $\bar{\rho}$ is the Reynolds averaged density, $\tilde{c}$ is the Favre averaged reaction progress variable, and $\bar{\dot{\omega}}_c$ is the mean value of the source term computed through the integration of the laminar database in terms of the presumed density probability function. $D=\frac{\nu}{Sc_L}$ and $D_T=\frac{\nu_T}{Sc_T}$ are the diffusion transport coefficients for the laminar and turbulent transport respectively.

For the reaction progress variable, the laminar and turbulent Schmidt numbers are considered to be constant and equal to Sc_L=0.7 and Sc_T=0.85, respectively.

It is assumed for the present case, that the reactants and products distribution can be described by the commonly used β-PDF function. In practical terms, the β-PDF function is used to perform an integration over the laminar manifold generated with FGM, resulting in a turbulent database after integrating the laminar realizations. In the laminar realizations, all the information about the thermo-chemistry variables were previously stored as a function of the progress variable, c.

After performing the referred integration, now the thermo-chemistry average values can be defined. With this systematic approach the new manifold is extended, and redefined using two control variables, namely the reaction progress variable, $\tilde{c}$, and its respective variance, $var(\tilde{c})$. As an example, in Eqn. (1), the average value for the source term, $\bar{\omega}_c=\omega_c\left(\tilde{c},var(\tilde{c})\right)$ can be defined as:

$$\bar{\omega}_c=\int_0^1 \omega_c\left(c\right)P_{\tilde{c},var(\tilde{c})}\left(c\right)dc \tag{2}$$

where $\omega_c\left(c\right)$ is the source term value from the laminar manifold, and $P_{\tilde{c},var(\tilde{c})}$ is the presumed β-PDF density probability function.

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Nevertheless, to generate this new turbulent manifold, some model must be considered to define the variance to compute the β-PDF distribution.

Concerning this definition, there are several options to close the variance of the reaction progress variable, $var(\tilde{c})$. For instance, some studies treat the closure problem with a mixing model, e.g., [2]:

$$var(c) \approx \frac{a^2 \Delta_k^2}{12} \left(\frac{\partial \tilde{c}}{\partial x_k} \right)^2 \quad (3)$$

where a is a parameter and the definition of Δ_k for RANS simulations is related with the grid size and for LES simulations, Δ_k can be regarded as the filter width length.

The dependence of $var(\tilde{c})$ on the parameter a imposes restrictions for the values that can be used for this parameter. For example, the upper-bound limit of a can be determined considering that the β- PDF requires a limitation for the variance of $\tilde{c}$, in this case $\tilde{c}(1-\tilde{c}) \leq \frac{1}{4}$ [2]. This limitation for $var(\tilde{c})$ implies that the parameter, a, can be only consistely varied in the range, $1 \leq a \leq 2$, as can be seen in [2].

Within this range, it has been found that the optimal choice for the parameter, a, is dependent on the grid resolution. For instance, in the grid related with the academic cases studied, the optimal value for a, was found to be $a \approx 1.4$ for the coarse grid and $a \approx 2.0$ for a more refined grid [2].

Its expected that in the present numerical investigation the model parameter tends to show similar dependence for the grid to be considered, which is more complex than in [2] as will be shown further. Actually, due to this dependence the best option would be to consider a dynamic procedure for the parameter, a. However, in the present analysis it is assumed that the model coefficient is constant throughout the domain.

Assuming the cited restriction, in the end the main task is to verify the capability of the algebraic model to simulate turbulent premixed combustion of high swirl flows using LES or RANS models coupled with the flamelet generated manifold technique, FGM.

Premixed Combustion Modeling - The Flamelet Generated Manifold

Due to the non-linear nature intrinsically related with combustion phenomena, and the several restrictions imposed to model the associated transport physics in a proper way, many chemical kinetics reduction strategies were developed. Actually, the situation becomes more problematic when turbulence and chemistry interactions must be taken into account. In fact, considering the computational capabilities, Direct Numerical Simulations (DNS) of reactive flows are restricted to specific purposes.

One strategy to overcome this situation, is based in the application of LES to understand the relevant physics and combustion models in which stretch effects on the flame front and turbulence-chemistry interactions are properly considered. In this paper, as already pointed out, combustion will be modeled with a flamelet tabulated chemistry technique, namely the flamelet generated manifold, FGM [1]. The FGM technique makes use of correlations of species to reduce the set of transport scalar equations. Within this approach, the combustion process is described in terms of a few control variables. The strength of the FGM reduction technique is that the number of independent control variables, starting with a single reaction progress variable c, can be increased for a better description of the combustion phenomena. An important advantage of FGM is the capability to predicted minor species in a consistent way.

In the FGM technique the real source term can be used, instead of its definition based on empirical correlations [4]. The flamelet generated manifold uses a physical laminar source term directly retrieved from a laminar flamelet database generated from a one-dimensional flamelet calculation. Also, an estimation related with the computational time between the reactive turbulent flow modeled with the current method (FGM) and cold flow simulations, gives an expectation of comparable computing times since only one additional transport equation will be solved. More information about the FGM procedure can be found in [1].

Generation of the FGM database

It must be mentioned last that in the FGM approach chemistry is tabulated *a priori* aside the flow solution. Then a look-up procedure to retrieve the thermo-chemical variables, from the integrated database, can be effectively done due to the known structured nature of the database.

In order to generate the flamelet table database for the present case, in a first step the governing laminar unstretched free methane premixed flame is calculated using the package CHEM1D, developed at Eindhoven Technology University [3]. For this case, complex chemistry and transport are applied to generate pre-heated 1D flamelets at inlet temperature, $T_{inlet} =$ 530K and equivalence ratio $\phi = 0.6$. The laminar flame speed, S_L was calculated using the GRI3.0 mechanism which contains 325 elementary reactions between 53 species. It was found that $S_L = 44.5$ cm/s, which is higher than the value found by other authors [4].

In a second step, turbulence-chemistry interactions are taken into account by integrating the laminar database using the β-PDF function. At this point, the full database consists of a structured array where all thermo-chemistry variables are tabulated in an equidistant grid as a function of the progress variable and its variance. In this structured database, the informations about the mean source term and additional mean thermo-chemistry variables are completely allocated. The results from the referred

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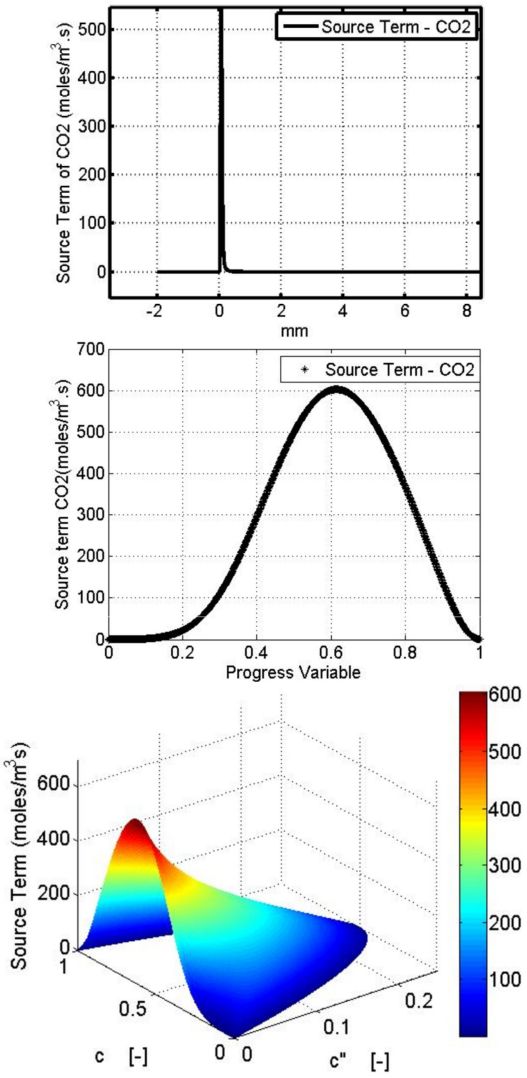

FIGURE 1. UPPER: SOURCE TERM OF CO_2 AT PRESSURE OF 1 BAR AS A FUNCTION OF POSITION X IN THE PHYSICAL SPACE. MIDDLE: SOURCE TERM OF CO_2 AS A FUNCTION OF C, $1D$ MANIFOLD FOR THE LAMINAR FLAME (FGM). BOTTOM: $2D$ TURBULENT MANIFOLD DETERMINED FROM THE PRESUMED β-PDF, MEAN SOURCE TERM OF CO_2 AS A FUNCTION OF C AND $VAR(C)$.

steps are shown in Fig. 1, and defines the use of FGM in the present case. For both steps, the manifold generation process and its integration in terms of β-PDF, Eqn. (2), the routines used were developed by Vreman *et al.* [2].

The requirement for the choice of the progress variable, c, determines that it must be monotonously increasing from the initial state to the equilibrium state. At the present lean condition, it is assumed that the progress variable can be described by carbon dioxide, CO_2. To check this assumption, thermo-chemistry variables were plotted as function of CO_2 and indeed these variables can be described without ambiguity using just carbon dioxide as the reaction progress variable. Due to the limited space, these plots will not be shown here.

Turbulence and flame parameters

An estimation of the turbulent length scales for the present flow, gives an estimate value for the Kolmogorov scale, $\eta \approx 0.01$ mm and for the integral scale $l \approx 2.5$ mm [4]. The flame thickness based on the maximum temperature gradient value, computed from the previous $1D$ laminar flamelet calculations, is around $l_F \approx 0.6$ mm. This gives a high value for the Karlovitz number, meaning that the turbulent flame will be in the thin reaction zone regime [6].

In particular in the thin reaction zone regime Kolmogorov scales can in principle penetrate into the pre-heated zone, also strong wrinkling effects are observed due to the kinematic interaction between the turbulent length scales and the flame front. Therefore, in an LES approach of such combustion regime the filter width should be tuned in a such way that the referred effects are explicitly solved or properly modeled using a sub-grid model that take them into account.

When the LES approach is considered to be used in situations involving more complex geometries, as in the present case, it should be considered that the high grid resolution necessary to include such effects implies that we have simulations with a high computational cost. When such effects are not fully considered and directly solved, sub-grid effects can play a significant role in the LES simulations to be performed. In fact depending on the grid resolution, these sub-grid effects can introduce several difficulties in modeling turbulent premixed combustion using LES [6].

The main issue in LES is to circumvent spurious sub-grid effects on the flame front propagation [7]. Therefore, the key parameter in LES will be the size of the flame front thickness (based in the thickness of the thermal layer), l_F, when compared with the filter width size, Δ_k. If the ratio of flame thickness to the LES filter width is of the order of 1, it is possible to conclude that sub-grid wrinkling effects could be in principle neglected [6].

In the present work, the filter width, Δ_k, is based on the grid resolution. This approach should be handled with care, because in some situations it cannot be the best option to consider, especially when $\Delta_k > l_F$. In this situation, the flame may occur entirely in the sub-filter scale and local changes from the unburnt state to burnt state are prone to numerical errors [6].

In the next section a more detailed description of the grid and the numerical simulations performed will be addressed.

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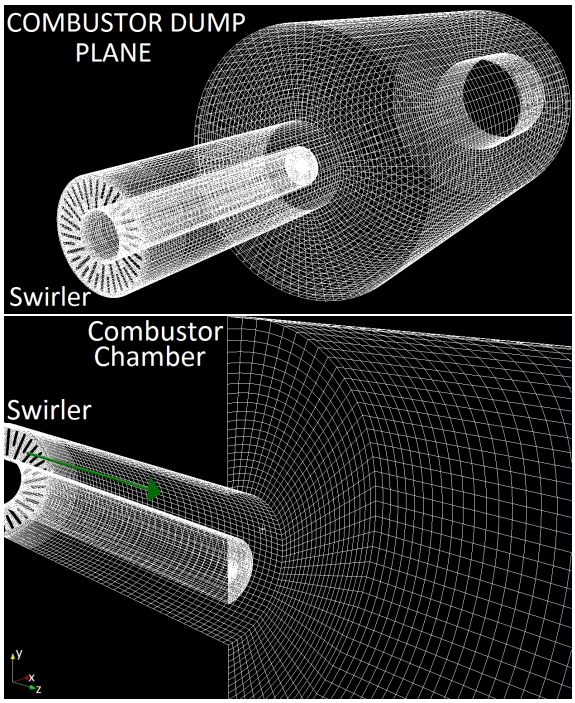

FIGURE 2. TOP: ENTIRE GRID DOMAIN OF THE SIMVAL COMBUSTOR. BOTTOM: HALF SECTION OF THE SIMVAL COMBUSTOR SHOWING THE 3*D* STRUCTURED GRID. THE GREEN ARROW SHOWS THE FLOW AXIAL DIRECTION. THE COMBUSTOR DUMP PLANE AND THE SWIRLER COMPONENTS ARE SHOWN.

Description of numerical methods

The objective is to simulate a gas turbine like combustor with Fluent 12.0, considering the coupling between the CFD solver with the FGM implementation. To simulate the flow field for the reacting flow case, the turbulence models used were the Reynolds-averaged Navier-Stokes, RANS (Realizable $k-\varepsilon$), and LES with sub-grid terms modeled using the dynamic Smagorinsky model.

The case is defined by the SimVal combustor, developed by Strakey and Yip [5]. The entire grid section is shown in the upper figure of Fig. 2, also a more detailed view of the nozzle section region from the swirler until the combustor dump plane, and the beginning of the combustor chamber are pointed out in the lower figure. The green arrow shows the flow axial direction. Further details about the geometry can be found in [5].

The three-dimensional computational domain encompasses the region from the exit of the swirl plate to 9 cm into the exhaust section. Results were obtained for three different grids, a coarse grid comprised of approximately 5.8×10^5 hexahedral cells, a middle grid of 1.63×10^6 hexahedral cells, and a refined grid with 3.8×10^6 hexahedral cells. The time steps in LES simulations was 5μs and the LES simulations were run for a total time larger than 20 flow through times, which was found to obtain good statistical results.

TABLE 1. MATRIX THAT SUMMARIZES THE SIMULATIONS PERFORMED WITH THREE DIFFERENT GRID RESOLUTIONS. THESE SIMULATIONS ARE REFERRED TO FGM AS THE COMBUSTION MODEL USED.

Parameter - a	Coarse Grid $5.8\times10^5\Rightarrow$ cells	Middle Grid $1.63\times10^6\Rightarrow$ cells	Refined Grid $3.8\times10^6\Rightarrow$ cells
$a=1.0$	LES and RANS	LES and RANS	RANS
$a=1.2$	RANS		
$a=1.4$	LES and RANS		
$a=1.8$	RANS		
$a=2.0$	RANS		

The boundary conditions were considered through the same conditions described in [4]. For the kinematic viscosity a simple Sutherland law was assumed to include the dependence on the temperature. And at the wall, non-slip boundary conditions for velocity and adiabatic boundary conditions for temperature and progress variable were used. The scalar equations for the reaction progress variable, Eqn. (1), were discretized with a second-order upwind scheme.

In order to check how the variance, $var(c)$, depends on the constant, a, the referred parameter was varied in the RANS and LES context. The simulations were performed according with the conditions described in Table 1.

Results

In order to see the capability of the algebraic model associated with FGM to simulate combustion in gas turbines, some first results were obtained for the turbulent reactive flow field. It is modeled using the dynamic Smagorinsky model. The simulations with the dynamic Smagorinsky model is referred from now on as LES/FGM and for the RANS case (Realizable $k-\varepsilon$), RANS/FGM. For both approaches a reference value of $a=1.0$ is chosen.

1 Typical results

The first result is obtained with a coarse grid. This result shows a comparison between the flow field contours provided by the mean LES/FGM field and the RANS/FGM. In Fig. 3, these contours for the axial velocity of the reactive flow are given. These results related to the vortex breakdown occurring in the

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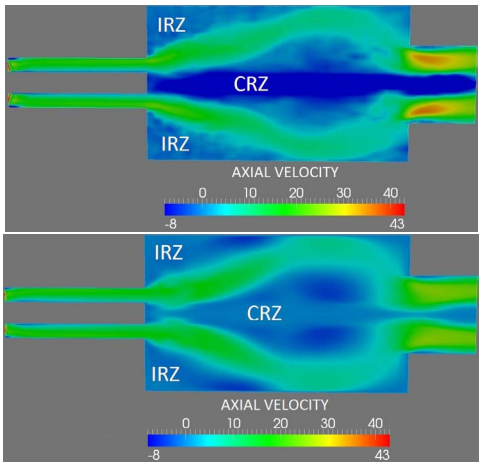

FIGURE 3. LES/FGM AND FGM/RANS RESULTS: 2D CONTOURS OF AXIAL VELOCITY. TOP: RESULTS FOR THE MEAN AXIAL VELOCITY LES/FGM. BOTTOM: RESULTS FOR RANS/FGM.

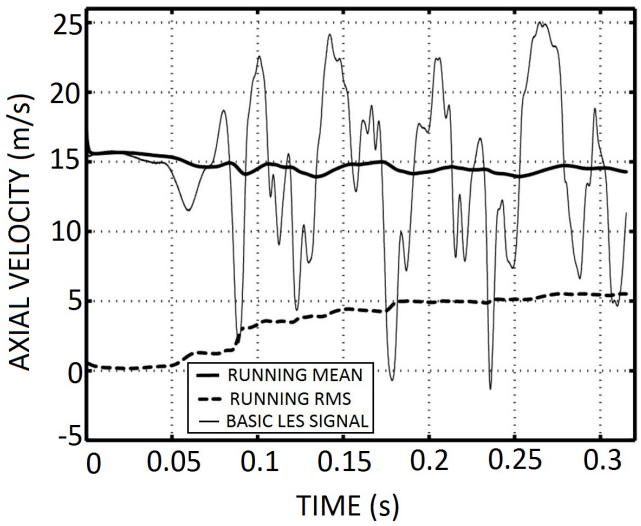

FIGURE 4. LES/FGM RESULTS ON THE COARSE GRID: AXIAL VELOCITY MONITORED AT THE COMBUSTOR DUMP PLANE IN THE COARSE GRID.

present high swirl flow is observed in both the LES/FGM and the RANS/FGM results. Also the inner recirculation zone (IRZ) is present, which means that standard expectations regarding the flow field can be recovered when the model parameter is set to $a = 1.0$, in both approaches.

To analyze the dynamics related with the LES/FGM simulations performed on the coarse grid, time series for the axial velocity were monitored at the combustor dump plane. With the purpose of just giving indication, the respective cumulative temporal mean and rms of the axial velocity, for the LES/FGM model are shown in Fig. 4. The LES results are at the convergence region with respect to the mean and rms of the axial velocity at the dump plane. By analyzing the autocorrelation function of the LES basic signal, the Taylor micro scale was found to be 0.014 s and the integral scale to be 0.137 s.

To check the effects of such scales on the flame front, the grid resolution was increased in the LES/FGM simulations. For the middle grid resolution, the flame topology and the wrinkling of the flame front due to the turbulence scales are better resolved. The 3D progress variable contour of the flame anchored at the combustor dump plane, is shown in Fig. 5. With this resolution, the particular effect of the unsteadiness related to the shear layer in the flame region can be captured.

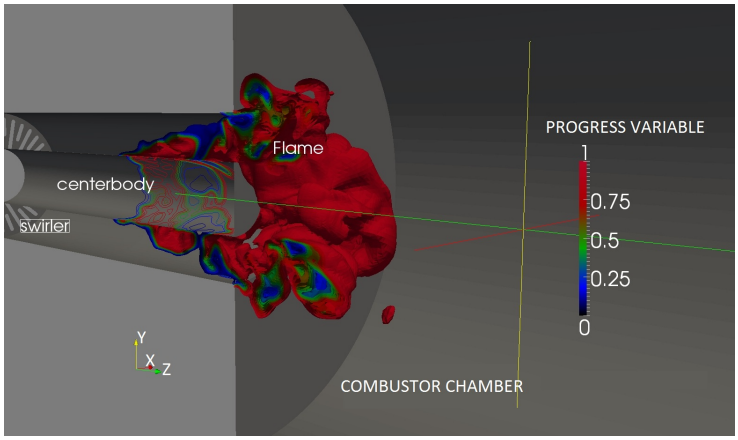

FIGURE 5. LES/FGM RESULTS FOR THE MIDDLE GRID: CUTTING PLANE OF A 3D INSTANTANEOUS FLAME FRONT SHOWING ISO-SURFACES OF MEAN PROGRESS VARIABLE. THE FLAME ZONE LOCATION AND THE COMBUSTOR COMPONENTS ARE SHOWN.

2 Grid convergence study

A more profound analysis over the grid-refinement was performed in the RANS/FGM case, the purpose was to check the grid convergence considering the three grids resolutions described in Table 1. In Fig. 6, the results for the axial velocity components are shown, similar effects were also found for the other two velocity field components. In principle, it seems that already some grid independence can be related with the coarse grid. From this study, the coarse grid was selected to perform the analysis about the generality of the model parameter, i.e, how the results are affected selecting different values of the parameter a, also summarized in Table 1.

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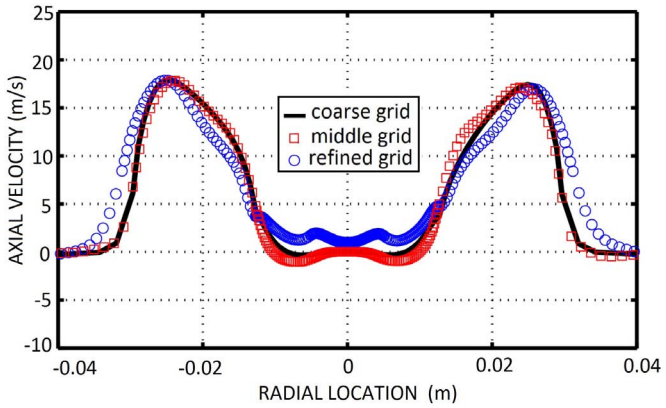

FIGURE 6. RANS RESULTS FOR THE AXIAL VELOCITY PROFILE, WITH $a = 1.0$. AT Z=3mm.

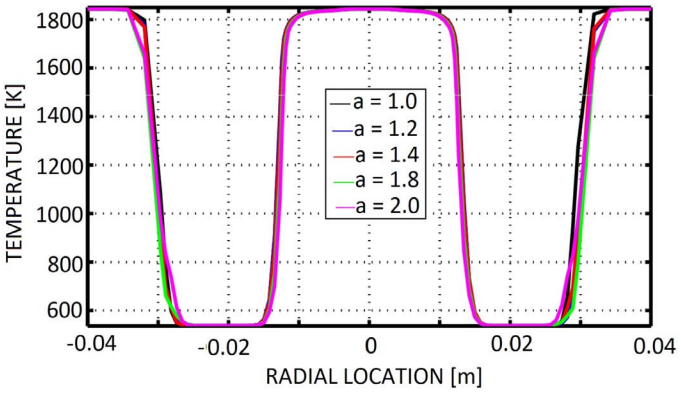

FIGURE 7. TEMPERATURE AS A FUNCTION OF THE RADIAL LOCATION, AT Z=3mm.

3 Influence of the value of a

In order to verify the impact of the value for the parameter a on the thermo-chemistry variables prediction, it was systematically varied for the coarse grid for the RANS/FGM case. The related results for the temperature field are shown in Fig 7, and no significant differences can be pointed out for the temperature profiles related with different values of a.

A more quantitative comparison between the LES/FGM and RANS/FGM results are shown in Fig 8 for the axial velocity profiles. Clearly, the axial velocity profiles show the standard expectations of an expanding swirl jet [5], which are found in both approaches. Naturally, the maximum values are different when the approaches are directly compared. An important conclusion is that great differences in principle cannot be pointed out when each approach is compared directly with the other respective case associated with different values of a.

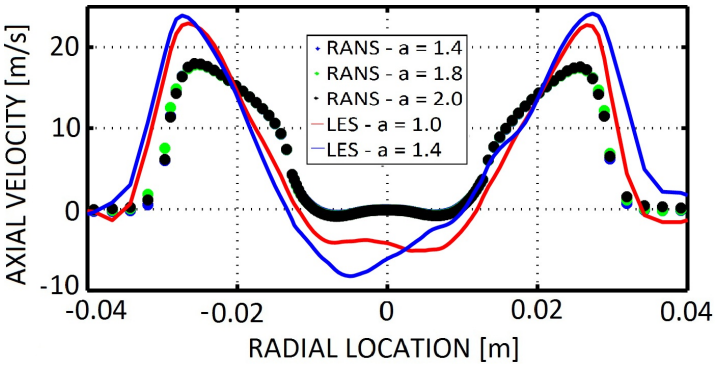

FIGURE 8. COMPARISON BETWEEN LES AND RANS SIMULATIONS OBTAINED WITH THE FGM MODEL FOR DIFFERENT VALUES OF a.

4 OH results

As a result of the FGM approach, all the information about the intermediate species can be directly accessed from the stored turbulent table. From the CFD data, the values for the progress variable, $\tilde{c}$, and for the variance, $var(\tilde{c})$, are known in the whole domain, thus the data for intermediate species like OH, can be directly accessed through the scalar values. The CFD code interpolates the table during the solution of the premixed combustion problem.

From this approach and the fact that the flame front can be related with intermediate species, such as OH, some results obtained with the RANS/FGM approach are shown for this radical in Fig. 9. This result shows the relative difference between the integrated quantity of OH mass fraction as a function of the model parameter.

This difference is relative to the amount of OH mass fraction associated with the profile results for the parameter set to $a = 1.0$. As can be verified, the integration of OH mass fraction over the entire structure leads to a maximum difference of 3.5% when the parameter is set to $a = 1.8$, which supports the previous conclusion about the relative independence of the mixing model with respect to the model parameter. Results for OH contours over the domain are shown in Fig 10.

5 Comparison with the Zimont model

After presenting the results related with the two different approaches, LES/FGM and RANS/FGM, and addressed the discussion about the role of the algebraic model based on the adjustable model constant, the last results show a comparison between the RANS/FGM model with the parameter set to $a = 1.4$ and another reference case namely the so-called Zimont model as in [4]. This comparison is presented in Fig. 11, from which it is possible to conclude that in both cases, the flame structure is symmetric, although its structure is distinct when the results are directly com-

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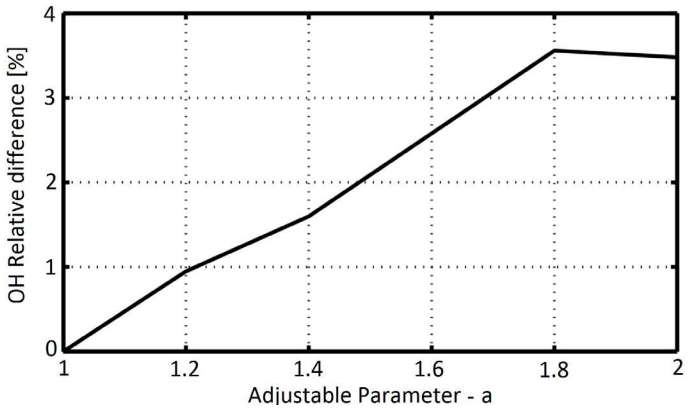

FIGURE 9. RELATIVE DIFFERENCE BETWEEN INTEGRATED OH MASS FRACTIONS AS A FUNCTION OF a. RESULTS FOR THE COARSER GRID OBTAINED WITH THE RANS/FGM APPROACH.

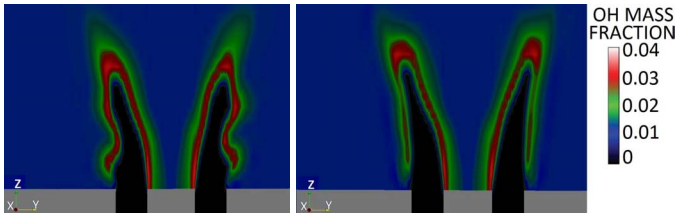

FIGURE 10. RANS/FGM RESULTS: 2D SLICE CONTOURS OF OH FOR THE RANS SIMULATIONS OBTAINED WITH $a = 1.0$ (LEFT) AND $a = 1.4$ (RIGHT).

pared.

The main difference with the Zimont model is that the RANS/FGM model does not define the mean source term in the same way. In the Zimont model [4], the combustion source term is derived from an empirical expression for the turbulent flame speed, which in turns can be directly computed through empirical relations based on the turbulent kinetic energy, whereas in FGM the real value of the source term is used.

One additional advantage is that the FGM model gives information about the intermediate species, which information can not be directly provided by the Zimont model. To conclude, convergence analysis shows that both models have approximately the same convergence rate, and it has been observed that using in a proper way the model RANS/FGM for the present simulations, the computational time per iteration is decreased by almost a factor 1.5 when compared with the Zimont model.

Conclusion

Results concerned with LES and RANS simulations were obtained for the reactive flow in a gas turbine burner. These simulations considered the use of FGM as the combustion model coupled with an algebraic model to determine turbulence and chemistry interaction through a pre-assumed probability function. In the analyzed case, the parametrization provided by FGM defines the combustion process in terms of two control variables, namely $\tilde{c}$ and $var(\tilde{c})$. For turbulence-chemistry interactions the presumed β-PDF was considered to close the mean source term, which definition implies in a proper choice for a model to close the variance, $var(\tilde{c})$, including an unknown model constant.

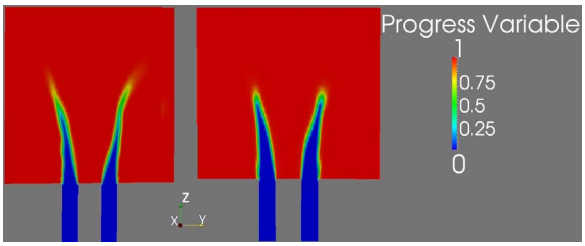

FIGURE 11. 2D SLICE CONTOURS FOR THE PROGRESS VARIABLE RESULTS: (LEFT) ZIMONT MODEL, (RIGHT) RANS/FGM RESULTS WITH $a = 1.4$.

In order to verify the impact of the algebraic model on the results, an evaluation of the constant was performed. It was expected that the numerical solution would be noticeably dependent on this parameter. Nevertheless, the results show no significant dependences on the parameter a, neither in the RANS/FGM or in the LES/FGM case.

LES/FGM results gives much more insight compared to the results provided by the RANS/FGM. In fact, the unsteady effects and the associated coherent large turbulent scale interactions with the flame front were only captured within the LES/FGM formalism with increasing grid resolution. As cited in [4], in the LES context the computational time of other models was found to be three times more expensive than models that also use the progress variable approach, e.g., the Zimont model. Since FGM computational time is comparable with the one provided by the progress variable approach, it is expected that LES/FGM will be less expensive than, for instance, the finite rate chemistry, with the advantage to take turbulence and chemistry interactions into account, and that all the information about intermediate species can be directly retrieved from the table.

As an overall conclusion, the use of the β-PDF approach can be justified considering that in the major part of the grid wrinkling occurs mostly at the sub-grid scale, and that no significant dependence was found in the present test case for the sub-grid variance in terms of the parameter a.

Some results [2] give the expectation that the best option is to filter the flame front directly in the physical space and not in the reaction progress variable space, c-space, as the β-PDF performs.

Furthermore, the simulations performed with FGM in both

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RANS and LES approaches shows that through an appropriate look-up procedure, combustion features in gas turbine conditions can be reproduced with a reasonable computational effort. In the future non-ideal premixing and heat-loss can be taken into account.

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