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ScienceDirect
C. R. Mecanique 337 (2009) 539–549
COMPTES RENDUS MECANIQUE

Combustion for aerospace propulsion

Monte Carlo method of radiative transfer applied to a turbulent flame modeling with LES

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Available online 22 July 2009

Abstract

Radiative transfer plays an important role in the numerical simulation of turbulent combustion. However, for the reason that combustion and radiation are characterized by different time scales and different spatial and chemical treatments, the radiation effect is often neglected or roughly modelled. The coupling of a large eddy simulation combustion solver and a radiation solver through a dedicated language, CORBA, is investigated. Two formulations of Monte Carlo method (Forward Method and Emission Reciprocity Method) employed to resolve RTE have been compared in a one-dimensional flame test case using three-dimensional calculation grids with absorbing and emitting media in order to validate the Monte Carlo radiative solver and to choose the most efficient model for coupling. Then the results obtained using two different RTE solvers (Reciprocity Monte Carlo method and Discrete Ordinate Method) applied on a three-dimensional flame holder set-up with a correlated-k distribution model describing the real gas medium spectral radiative properties are compared not only in terms of the physical behavior of the flame, but also in computational performance (storage requirement, CPU time and parallelization efficiency). ***To cite this article: J. Zhang et al., C. R. Mecanique 337 (2009).***

Résumé

Modélisation du rayonnement par Monte Carlo appliquée dans les flammes turbulentes simulées par LES. Le transfert radiatif joue un rôle important dans la simulation numérique de la combustion turbulente. Toutefois, à cause du fait que la combustion et le rayonnement sont deux phénomènes physiques très différents caractérisés par des échelles de temps et d'espace également différentes, l'effet du rayonnement est souvent négligé ou simplement modélisé. Le couplage entre la combustion (LES) et le rayonnement avec le solveur CORBA a été étudié. Dans le présent article, deux formulations de la méthode de Monte Carlo (méthode classique et méthode réciproque) dédiées à la résolution de l'équation de transfert radiatif ont été comparées sur un cas test de flamme 1D où l'on tient compte de l'absorption et de l'émission du milieu en utilisant un maillage 3D. Le but de ce cas test est de valider le solveur Monte Carlo et de choisir la méthode la plus efficace pour réaliser le couplage. Ensuite, deux solveurs radiatifs (Emission Reciprocity Monte Carlo Method et Discrete Ordinate Method), appliqués à une flamme Dièdre 3D avec un modèle CK de propriétés radiatives, sont comparés non seulement en termes de description physique de la flamme, mais aussi en terme de performances de calcul (stockage, temps CPU et efficacité de la parallélisation). ***Pour citer cet article : J. Zhang et al., C. R. Mecanique 337 (2009).***

Keywords: Combustion; Monte Carlo; Radiative transfer; LES; Turbulent combustion; Coupling work

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1631-0721/$ – see front matter
doi:10.1016/j.crme.2009.06.024

Mots-clés : Combustion ; Monte Carlo ; Transfer radiatif ; LES ; Combustion Turbulente ; Couplage

1. Introduction

Radiative transfer plays an important role in the numerical simulation of turbulent combustion. However, as combustion and radiation are characterized by different time scales and different spatial and chemical treatments, they require different numerical strategies for solving their governing equations. Therefore, combustion modeling, taking into account radiation, is often performed with rough models in terms of radiative transfer. Recently, with the rapid computer science development and the implementation of massively parallel architecture for computers, simulations coupling accurate models for both combustion and radiation can be performed.

Among the most popular models available to resolve the radiative transfer equation it is possible to cite: ray-tracing, discrete ordinate (DOM), the Pn and Monte Carlo methods. The principle advantage of the Monte Carlo method is that many complex physical phenomena, such as spectral dependence of surface and participating medium properties, non-isotropic scattering distributions, coupling with turbulent temperature and concentration fields, can be taken into account without simplifying assumptions and any additional increase of CPU time.

Additionally as the numerical error produced in this method is only a statistical error, statistical tests can be used to measure the results' standard deviation, which is generally not possible in deterministic methods. It is also possible to control the convergence of the solution during the simulation. Consequently, this method can be considered as a reference to validate other models, like the DOM model presented in this paper.

The disadvantages of Monte Carlo method are that it is computationally expensive, huge memory demanding and slow converging. In order to improve its performance and simplify its implementation, different strategies have been proposed. For examples, some standard deviation reduction techniques have been employed in order to reduce the computational time [1–3]. Additionally, to reduce the standard deviation of Monte Carlo method, an "energy-partitioning" method proposed by Shamsundar et al. has been showed efficient in 'open' configurations [4]. Furthermore, a reverse Monte Carlo approach (called the emission path method) based on a reciprocity principle has been first presented by Walters and Buckius [5,6]. Cherkaoui and de Lataillade [7–9] are the first authors to use the reciprocity principle for one-dimensional fields from the point of view of both geometry and exchanged power (EMCM, Exchange Monte Carlo Method). Then for three-dimensional fields Tesse et al. [10] have presented and compared the conventional forward Monte Carlo (FM) with two reciprocity Monte Carlo formulations, which are called respectively ERM (emission reciprocity method) and ARM (absorption reciprocity method). These methods were applied to one-dimensional benchmark cases involving grey media and real gas-mixtures, different optical thicknesses and different thermal conditions.

For turbulent combustion simulation, the Reynolds-average Navier–Stokes (RANS) balance equations only give the mean quantities such as mean temperature, mean mass fraction of CO_2 and H_2O, directly linked to the probability to find hot burnt gases at a given location [11]. Radiative transfer is controlled by the instantaneous distribution of cold and hot gases along optical paths which can not be directly extracted from mean flow characteristics. It is possible to use probability density functions (PDF) to overcome this problem; however, PDF based methods cannot take into account the spatial correlations which are crucial in radiative transfer. This turbulence–radiation interaction problem has been addressed by several authors [12–14]. Compared to RANS, Direct Numerical Simulation (DNS) or Large Eddy Simulation (LES) gives access to the instantaneous spatial distribution of fresh and burnt gases. DNS was combined with DOM to investigate two dimension sooting flames for fires [15]. Wu et al. [16] have implemented a photon Monte Carlo method for the solution of the radiative transfer equation in a turbulent combustion DNS code to study the turbulence–radiation interaction. However, DNS computations still remain out of reach of practical industrial configurations in terms of CPU cost. Then LES appears as a very efficient alternative tool to deal with turbulent combustion radiation interaction. Indeed, this approach can be expected to provide a more accurate representation of one-point statistics and spatial correlations, a key point when dealing with radiation. The combination of LES and DOM has been performed by several authors including the consideration of soot formation and radiation [17,18]. Additionally, Goncalves has performed a simulation coupling LES and DOM solvers through a specialized framework, CORBA [19]. These results will be used later in this article.

In this article, the objective is to develop an efficient numerical tool dedicated to computing real industrial configurations based on the Monte Carlo method for radiation and LES method for turbulent combustion. Monte Carlo

method are presented in Section 2 including a brief description of the Reciprocity principle. Then in Section 3, two formulations of Monte Carlo method (Forward Method and Emission Reciprocity Method) employed to resolve RTE are compared in a one-dimensional laminar premixed flame test case in order to choose the most efficient model for the coupling application. Results obtained from Reciprocity Monte Carlo method and Discrete Ordinate Method, applied on a three-dimensional flame holder set-up with a correlated-k distribution model, are compared in terms of physical behavior of the flame and computational performance (storage requirement, CPU time and parallelization efficiency) in Section 4.

2. Numerical solvers for turbulent combustion and radiation

AVBP code [20] developed by CERFACS and IFP is the LES solver used to compute the reactive flow. It can resolve compressible equations on structured and unstructured meshes using a second order Runge–Kutta time integration and second order spatial discretization schemes and NSCBC boundary conditions [21]. This code is parallelized by domain splitting.

A 3D code developed by ONERA and EM2C is used here as radiation solver [10,22,23]. Four Monte Carlo formulations FM, ERM, ARM and ORM (optimized reciprocity method) are implemented [24] simultaneously to calculate the radiative power and the flux with unstructured grids. Additionally, many complex physics phenomena can also be treated as the diffusion or the effect of soot. Concerning the gas radiative properties, the CK model, SBPM model or line by line model have been described.

Another 3D Monte Carlo solver has been also developed at EM2C for this study. This solver is dedicated to LES simulations. It only includes ERM model and CK model for the gas properties in order to save memory and CPU time.

The algorithm of the Monte Carlo method can be described briefly as follows: a large number of random optical paths characterized by three independent sets of parameter, the random departure point, the random spectral frequency and the random direction of the propagation, are generated. They carry power qualities. Then each path crosses cell by cell in the selected optical direction, when the optical path goes through a cell, the power absorbed in this cell is computed with the local crossed length absorptivity and the remained power in the path leaving from this cell can be computed with the local transmissivity. In this way, the power carried along the path will be extinguished gradually until the amount of power becomes less than a cutoff value or until the path leaves the enclosure.

In the Forward Monte Carlo method (FM), a path defined from point A to point B is only used to compute the power emitted from A and extinguished at point B, but in the reciprocal method (ERM), the same path is used for the power exchanged between A and B, that means radiative transport from A to B and from B to A are associated. Mathematically, a statistical estimation of the exchanged power between cell q and other cells for FM (radiative power calculated in cell q) can be expressed by the following equation:

$$\tilde{P}_q^{FM} = \sum_{i=1}^{N_v+N_s} \tilde{P}_{iq}^{ea} - P_q^e \tag{1}$$

where the computation domain is divided into N_v elementary volumes and N_s elementary surfaces. $\tilde{P}_{iq}^{ea}$ is the statistical estimation of the power per unit volume emitted by cell i and absorbed by cell q. P_q^e is the energy per unit volume emitted by cell q calculated in a deterministic manner:

$$P_q^e = 4\pi V \int_0^\infty k_{\nu,q} L_\nu^0(T_q)\,\mathrm{d}\nu \tag{2}$$

For the Reciprocal Monte Carlo method, a reciprocity principle proposed in Ref. [25] is used: the ratio of the spectral power emitted by a cell i and absorbed by a cell j to the spectral power emitted by cell j and absorbed by cell i is equal to the ratio of the equilibrium spectral intensities of cell i and j, which is expressed:

$$\frac{P_{ij}^{ea}}{P_{ji}^{rea}} = \frac{L_\nu^0(T_i)}{L_\nu^0(T_j)} \tag{3}$$

P_{ij}^{ea} is the power emitted by cell i and absorbed by cell j in the forward direction and P_{ji}^{rea} is the reciprocal power emitted by cell j and absorbed by cell i associated with the same optical path.

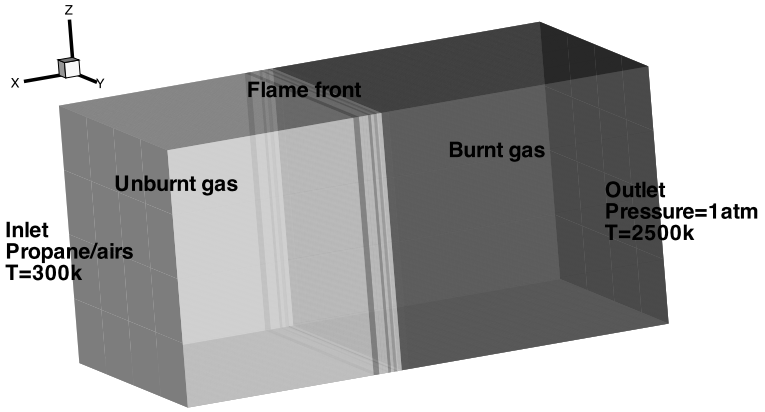


Fig. 1. Geometry of the 1D flame with grid size 0.1 mm.

Now using above principle to calculate the exchanged power in cell i with the Emission Reciprocity Method (ERM), the energy emitted by i is computed in deterministic manner and the energy absorbed by i is computed with the reciprocal optical path using above formulation.

$$P_i^{ERM} = \sum_{j=1}^{N_v+N_s} P_{ji}^{rea} - P_i^e \tag{4}$$

with Eq. (3), we have

$$P_{ji}^{rea} = P_{ij}^{ea} \cdot \frac{L_\nu^0(T_j)}{L_\nu^0(T_i)} \tag{5}$$

and P_{ij}^{ea} can be written as:

$$P_{ij}^{ea} = P_i^e \cdot \tau_{\nu,i-j} \cdot \alpha_j \tag{6}$$

where α_j is the absorptivity of the crossed length of cell j, and $\tau_{\nu,i-j}$ is the total transmissivity between cell i and cell j; here it is just a simplified symbolic expression, more details can be found in Ref. [22].

In conclusion, for the ERM method, the radiative power in a given cell can be calculated by only using the information from this cell, which allows to compute the radiative power of each cell of the computational domain independently. This approach can also be applied on some complex configurations to decrease the storage requirement.

3. Validation of Emission Reciprocal Monte Carlo method with flame 1D

3.1. Description of the test case

To compare the FM and ERM Monte Carlo models [24] in the context of combustion processes, simulation of a one-dimensional premixed laminar flame are performed using the ASTRE solver developed by ONERA and EM2C.

The simulated configuration is displayed in Fig. 1. The benchmark was defined by a non-isothermal, emitting and absorbing medium between two parallel infinite isothermal semi-reflecting opaque walls which are perpendicular to the x-axis and the computation slab is a cube of 0.1 m × 0.0004 m × 0.0004 m (x, y, z) with 16 000 hexahedron cells. The grid size of this mesh is constant and equal to $\Delta = 0.1$ mm. To simulate the infinite transverse dimension of the 1D benchmark along the y- and z-axis, four lateral faces of this cube are considered as four symmetry conditions.

A premixed propane/air flow is injected from the inlet at the location of $x = -0.05$ m with an upstream mean velocity of about 0.48 m/s and an equivalence ratio $\phi = 1.0$. The outlet boundary downstream with imposed pressure is retained at the end of the computation domain and the flame front is defined artificially near the center of this cube.

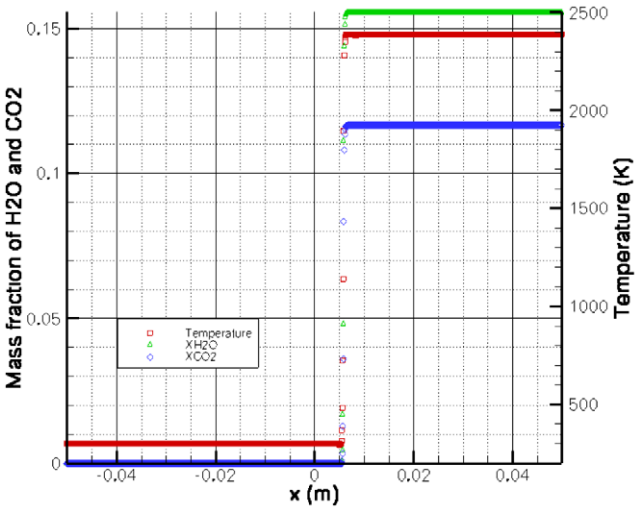


Fig. 2. Temperature, Y_{CO_2} and Y_{H_2O} profiles of 1D flame with AVBP.

Concerning the chemical aspect, a one-step global chemical mechanism is chosen to represent the reaction between propane and air [20].

$$C_3H_8 + 7/2O_2 \longrightarrow 3CO + 4H_2O \tag{7}$$

The corresponding reaction rate is given by:

$$\dot{\omega} = A[C_3H_8]_\alpha[O_2]_\beta \exp(-E_a/RT) \tag{8}$$

where $[C_3H_8]$ and $[O_2]$ denote the molar concentration of species C_3H_8 and O_2, the corresponding exponents α and β are separately 0.856 and 0.503, the pre-exponential factor A_i is 3.162×10^{10} (cgs), the activation energy E_a is 31126 cal mol^{-1} and T is the absolute local gas temperature. With these chemical parameters, a laminar flame speed $S_L^0 = 0.48$ m/s can be obtained for a equivalence ratio $\Phi = 1.0$. Fig. 2 shows the converged results of combustion obtained by AVBP.

Gas radiative properties are treated in a correlated manner by a correlated-k (CK) model which was firstly generalized for reactive application by Rivière et al. [26] and the database was developed by Soufiani and Taine [27]. 44 spectral bands are considered for H_2O and 17 spectral bands for CO_2, due to the correlation between the spectral bands of CO_2 and H_2O (they have 17 bands superimposed), 1022 spectral bands are used:

$$(44 - 17) \times 7 + 17 \times 7 \times 7 = 1022 \tag{9}$$

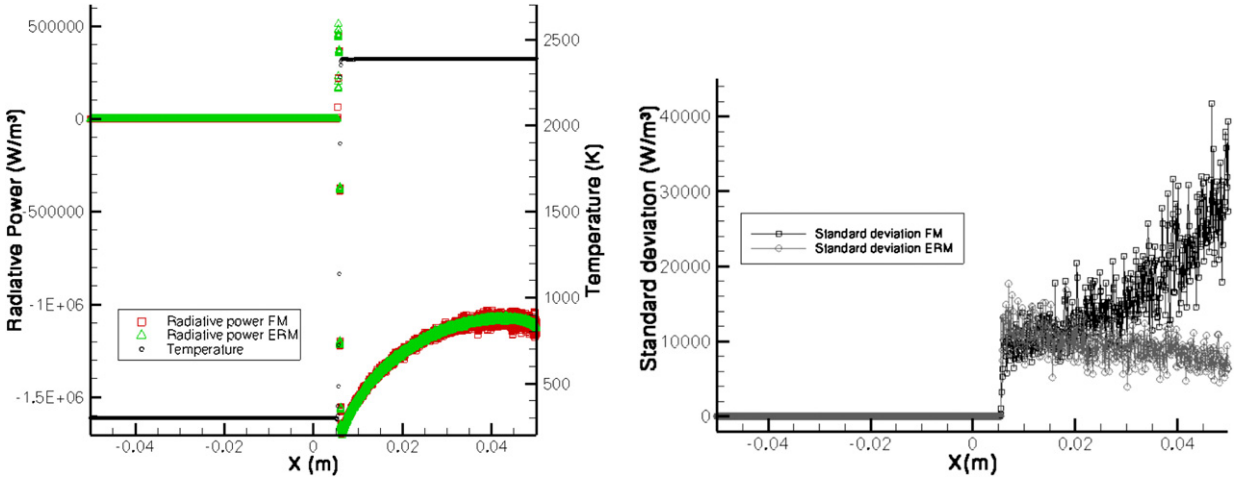
To simplify the computation, the emissivity is set to be equal to 1 both at the inlet and outlet, that means all of the radiative rays arriving will be totally absorbed. And the temperature of outlet is equal to $T_{burntgas}$, $T_{inlet} = 300$ K. Furthermore, all of the cases tested here have been approved to correspond to an optically thin medium.

3.2. Results and discussions

Using the ASTRE code the radiative power of this 1D flame has been computed. Besides of the mean results for each quantity at each cell, the Monte Carlo method gives also access to the standard deviation σ which shows and controls the convergence:

$$\sigma(i) = \sqrt{\frac{\sum_{j=1}^{N_b}(\overline{A_i} - A_{ij})^2}{N_b}} \tag{10}$$

Here the total optical rays generated from cell i was divided into N_b beams; for each beam j, a mean radiative power A_j has been computed, then the variance of this Monte Carlo calculation was obtained by computing the standard



(a) Mean radiative power (b) Standard deviation

Fig. 3. The results of the test case 1D flame computed by the Monte Carlo method, grid size = 0.01 mm, number of the optical paths = 2000/cell, $N_b = 5$.

deviation of the radiative power of all these rays' beams. A more detailed description of this technique has been presented in Ref. [22]. $\overline{A_i}$ is the mean value among these N_b beams, being written as:

$$\overline{A_i} = \frac{\sum_{j=1}^{N_b} A_i j}{N_b} \tag{11}$$

According to the law of large numbers (LLN) in probability theory, the influence of the optical paths' number on the convergence of Monte Carlo method has been studied; finally the minimum ray number to get the computation convergence was determined as 10^3/cell for a 16 000 cell mesh, with a Uniform spatial Distribution (UD) of the optical path in the calculation domain [10].

The comparison between these two models FM and ERM has been studied through the mean radiative power and the standard deviation, as illustrated in Figs. 3(a) and 3(b). In the isothermal fresh gas zone, where the mass fraction of CO_2 and H_2O is equal to 0, there is no absorption energy. Near the low temperature side of the flame front, absorption energy appears dominant due to the CO_2 absorption bands at 600 K. Because of the large temperature gradient, the modulus of the radiative power has a maximum value in the high temperature part of flame front, before decreasing in the isothermal burnt gas zone. In the present simulation the outlet temperature has been set equal to 2500 K and the related emissivity equal to 1, so the boundary condition can be considered as an infinite extension of the burnt region. Furthermore, it is important to noticed that the mean radiative power calculated with FM and ERM completely superposes in all of the computation domain except that FM presents more fluctuations near the boundary.

Since the performance of Monte Carlo method is defined as the product of the computation time t and the variance σ^2 [28], the comparison of the standard deviations σ obtained from the different approaches is then significant. In our test, the effect of σ has been observed with the same simulation time. Obviously, ERM and FM have nearly the same level in the flame front, then ERM converges more quickly than FM in the burnt gas region which corresponds to the fact that reciprocal model is more efficient in isothermal medium.

To summarize, ERM has been considered as the most suitable model for the following computations. Using this result a new original dedicated Monte Carlo solver has been developed by EM2C including only the ERM model, the CK parameters to describe the radiative properties and a real time convergence control.

4. Comparison between DOM and Monte Carlo applied to "Diedre_3d"

In order to check the new EM2C Monte Carlo solver for LES simulations, a comparison with the Discrete Ordinate Method (DOMASIUM code [29,30]) already used for coupled simulations [19], was performed on a three-dimensional configuration "Diedre_3D" in terms of physical behavior of the flame and computational aspects (storage

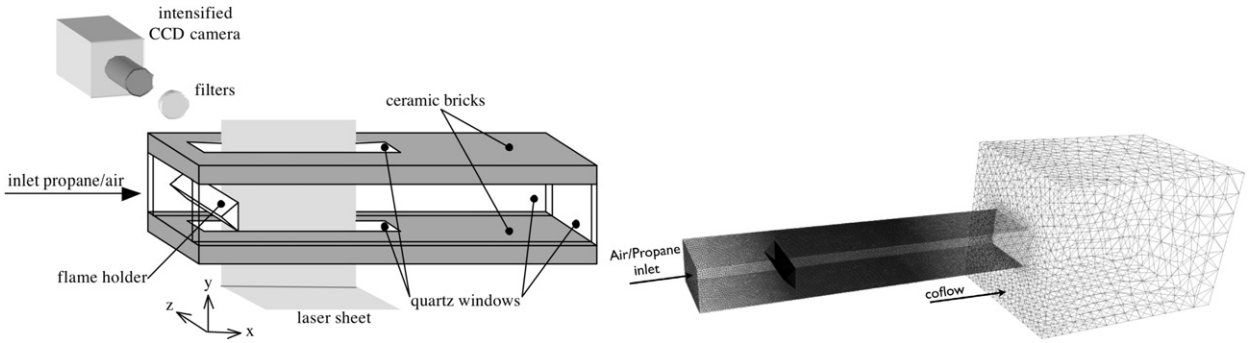


Fig. 4. Experimental set-up of "diedre_3d" retained for numerical simulations investigated by Knikker et al. and "Diedre_3d" mesh used by AVBP code with 4.7 million tetrahedral cells.

requirement, CPU time and parallel efficiency). Furthermore, as the statistic Monte Carlo method is more precise than the Discrete Ordinate Method (DOM), it is also considered as a reference to validate the DOM model.

4.1. Experimental set-up and numerical configuration

The numerical geometry studied here corresponds to an experimental set-up investigated by Knikker [31–33] as displayed in Fig. 4. A premixed propane/air flow is injected into a rectangular combustion chamber which is 300 mm long (x) and 50 mm × 80 mm in cross section (y, z) and the flow rate is imposed as 20 g s^{-1} corresponding to an upstream mean velocity of about 5 m s^{-1} (a turbulence level of about 5%); the equivalent ratio of this premixed gas is chosen as $\phi = 1.0$ and the temperature is imposed as 300 K. A stainless steel triangular flame holder (height 25 mm), corresponding to a 50% blockage ratio, is embedded in the lateral windows. A V-shaped turbulent flame stabilized by the hot gases recirculating behind the flame holder is studied. In order to visualize the whole chamber, the transparent artificial quartz windows are used to make the lateral walls. The upper and lower walls are made of thick ceramic material for thermal isolation including two narrow windows used to introduce laser sheets.

The mesh of the computational domain starts from 10 cm upstream of the flame holder and continues up to 60 cm downstream as displayed in Fig. 4. The LES mesh for the combustion code contains about 4.7 million tetrahedral cells, and the grid size has a minimum value $\Delta = 1.0$ mm in the zone near the flame holder, where the recirculation zone is. This zone should be well described, because it is responsible for flame stabilization. Then the grid size is geometrically increased from the end of the recirculation zone up to the exit. On the other hand, the radiation code uses a different mesh with less cells in order to reduce the computational time and required memory. By using a connectivity table, the physical properties (temperature, mass fraction, etc.) can be transferred from one mesh to another in both directions. The radiation mesh contains about 3.4 million tetrahedral cells and the mesh of the recirculation zone is the same as the LES one.

For combustion simulation, a dynamically thickened flame model (DTFLES) [34,35] is applied. In this formulation, the thickening factor F is not a constant as in TFLES but goes to F_{max} in flame zones and remains at 1 in non-reactive zones. This model is more adapted to the calculation of the radiative power because it does not change the species and thermal diffusions outside the flame region. The chemical reaction is that described previously. About the boundary condition in AVBP code, both the static pressure at the outlet and the velocity components (the statistic temperature and the species mass fractions) at the inlet are imposed in a soft way by the Navier–Stokes Characteristic Boundary Conditions (NSCBC). The four lateral walls are defined as the heat-loss walls using a wall-function approach with zero normal velocity (slip wall). All of other walls are supposed to be adiabatic slip walls. The instantaneous field of the stabilised flame, such as the temperature, is displayed in Fig. 5, which will be loaded into both Monte Carlo and DOM radiation codes to compute and compare the radiative power and flux.

All details of the Discrete Ordinate Method computation with code DOMASIUM can be found in the dissertation of R. Goncalves [19] and Joseph [30]. The correlated-k (CK) distribution method is used with a reduced number of spectral bands (28 for H_2O and 8 for CO_2), corresponding the wavelengths having the most important contributions to the global radiative power. The diamond mean flux scheme (DMFS) and a quadrature of 4th order have been adopted resulting in 24 spectral directions, no sub-grid scale radiation model is taken into account.

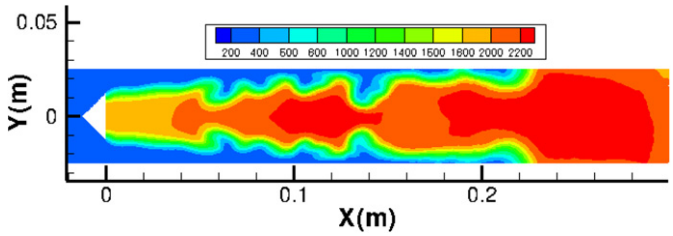


Fig. 5. Cut at $z = -0.002$ m of the instant temperature, result of AVBP code, "diedre_3d".

Table 1
Comparison of the computational performance between DOM and Monte Carlo.

Method	Proc. number	Optical paths	Spectral bands	CPU time	Memory
DOM	72	–	36	2 min	2 G
Monte Carlo	72	1000_max	1022	18 min	0.48 G
DOM_bis	72	–	1022	56 min	2 G

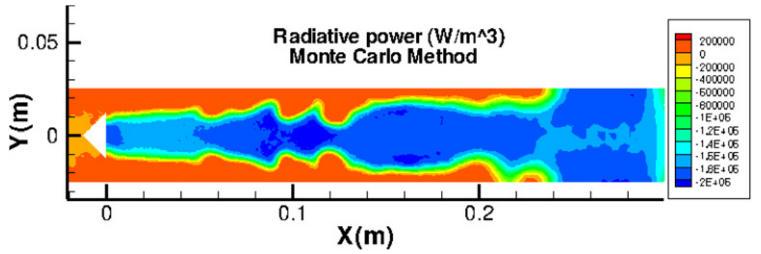
As the objective of this part is to compare the results between Monte Carlo code and DOM solver, the same computation conditions are requested. The four lateral walls and the flame holder are considered to be hot black body with an emissivity equal to 0.9 and inlet and outlet are assumed to be cold black body. The impact of the boundary conditions and the computation with the real wall emissivities and temperature will be studied later.

4.2. Results and discussions

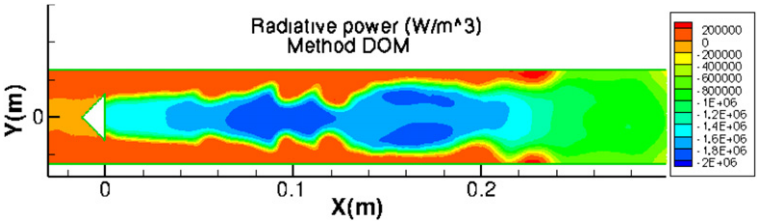
Fig. 6(a) presents the radiative power at $z = -0.002$ m computed by the Monte Carlo ERM model. Here the ray number generated from each cell is not a priori imposed but is determined during the simulation through convergence tests performed every N rays departure from one cell, leading to a local convergence control. If the ratio of the local standard deviation to the local radiative power is less than a criterion fixed (0.01 in this test case), then the calculation is converged and the ray generation is stopped. Fig. 6(c) shows the distribution of ray number for a converged result. Obviously it is more difficult to be converged in the flame front zone than in others, so more optical paths are requested, while in the hot gases zone, which is homogeneous, the optical path number is reduced. In Fig. 6(d), the local standard deviation is presented showing that the simulation is fully converged. This local error control greatly improves the performance of our computations in term of CPU time.

The result of DOM is illustrated in Fig. 6(b). Compared with radiative power of the Monte Carlo method displayed in Fig. 6(a), these two results are nearly the same except for a small difference near the outlet. That difference might come from the influence of the outlet boundary condition. In general, we can conclude that these two methods match well in this three-dimensional flame holder computation. To make the comparison more quantitative, two cuts have been extracted at $x = 0.11$ m and $x = 0.15$ m. In the fresh gas zone, the difference is small, while the maximum difference appears in the hot zone rather than in the flame front. This could be due to the fact that in the Monte Carlo method 1022 spectral bands of CK model have been used while in the DOM simulation only 36 spectral bands were taken into account. The error between these two methods is about 7% which is acceptable.

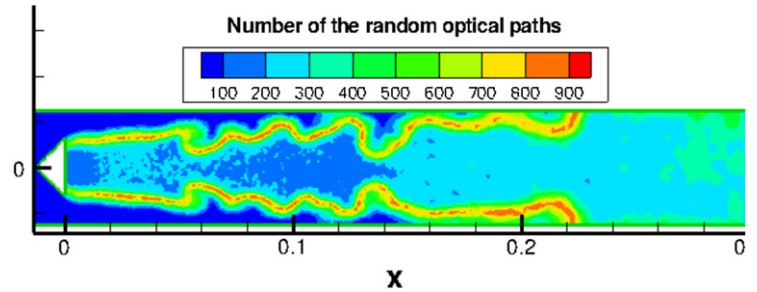
The comparison of the computational performance between these two methods are presented in Table 1. These computations are carried out on the EM2C Laboratory SUN cluster. With 72 processors, the DOM solver takes about 2 minutes and 2 G of memory using 36 spectral bands while the Monte Carlo solver takes about 56 minutes and 0.48 G of memory using 1022 spectral bands. Evidently the use of 1022 bands is more precise than 36 bands and also asks for more CPU time, so if we consider the DOM_bis case which does not use simplifications in terms of the spectral bands, Monte Carlo will not be more expensive. In conclusion, the Monte Carlo method spent less time and memory compared with DOM if both of them take into account the same complex parameters. Furthermore, our new original Monte Carlo solver can run well with a machine having about 500 MB of memory, like all the Blue Gene supercomputers, while DOM needs at least 2 GB memory which is not always available in massively parallel computers.



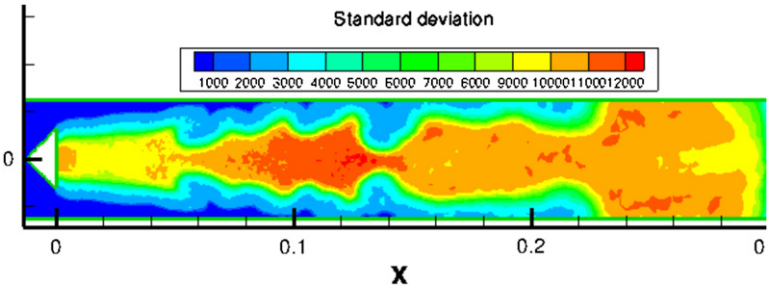
(a) Radiative power obtained by Monte Carlo Method



(b) Radiative power obtained by Discrete Ordinate Method



(c) Optical path number, maximum value fixed as 1000, result of Monte Carlo Method



(d) Standard deviation, result of Monte Carlo Method

Fig. 6. Presentation of the results of the test case "diedre_3d", cut at $z = -0.002$ m.

5. Conclusions

In order to take into account the radiative transfer for the turbulent combustion simulation more precisely, a quasi-exact method Monte Carlo has been investigated for radiation computation and a LES solver has been used for combustion modeling in this paper. To overcome the disadvantage of Monte Carlo – huge CPU time and memory – some optimization work has been performed to improve the numerical performances and a new original Monte Carlo code has been developed. After the comparison of two different formulations of the Monte Carlo method (Forward Method, Emission Reciprocity Method) applied on a one-dimensional flame test case, ERM was considered as the most efficient model both in terms of physical behavior and computational aspects. Then this ERM method was used to resolve a three-dimensional flame holder set-up with a correlated-k distribution model and compared with Discrete Ordinate Method solvers. The results of these two RTE solvers matched well in terms of the physical behavior, which

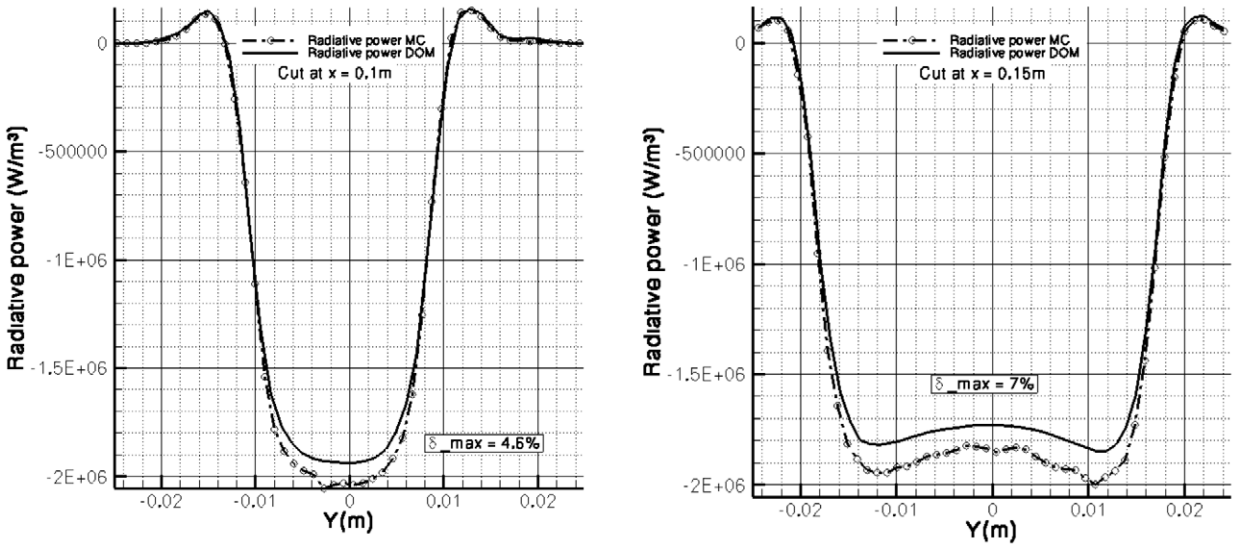


Fig. 7. Comparison of the radiative power between DOM and Monte Carlo, at $z = -0.002$ m and $x = 0.11$ m, $x = 0.15$ m.

validates the coupling work previously carried out with DOM. Comparison of computational performance displays that if both of them take into account the same complex parameters, the Monte Carlo method spent less time and memory compared with DOM.

Acknowledgements

We would like to thank ONERA for providing us the ASTRE solver to performed the one-dimensional laminar flame simulation. This work has been financially supported by the ANR "Calcul intensif" Project CORAYL.

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