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MODELING RADIATIVE TRANSFER IN A MIXTURE OF NON-GRAY GASES USING FAST APROXIMATE TECHNIQUE FOR THE CW MODEL

Carlos T. Salinas
Department of Mechanical Engineering – University of Taubaté. Rua Daniel Danelli s/n – Taubaté (SP) 12060-440 – Brazil.
csalinas_99@yahoo.com; csalinas@unitau.br

Abstract. *Determination of radiative fluxes in media containing real gases such as combustion products, atmospheric gases among others is usually a difficult task due to the strong dependence of the absorption coefficient on the wavenumber. In the CW model, we should solve the RTE in every spectral subinterval D_{ij}, for j = 1,..., n and i = 1, 2, . . .p, then it is necessary to solve n* x *p times the spectral form of the RTE for complete spectral integration. In this work the CW model is used with one numerical approximation technique based on additive properties of radiative intensity to reduce the solution of RTE to n new fractional gray gas D_J for complete spectral integration. The accuracy of the simplified technique and the algorithm was first examined for one-dimensional homogeneous media; the results are compared with line-by-line calculations and it is found that the CW model with the simplified technique is exact for the homogeneous media examined. The CW model is implemented in bi-dimensional enclosure containing real gases in isothermal cases too. The results obtained using the acceleration technique in CW model are the same as the results of original CW model. With this acceleration technique the CPU time decreases p times*.

Keywords*. Radiative transfer, Non-gray gases, Cumulative wavenumber, Discrete ordinates*

1. Introduction

Calculating radiative transport through non-gray gases at high temperature is extremely difficult due to the strong dependence of the absorption coefficient on the wavenumber and it is necessary to use some real gas model for the spectral integration of the intensity field. Research activities directed towards modeling the radiative transport of non-gray molecular gases using global methods dedicate special attention to the solution of the radiative transport problems in a high temperature gas medium (Taine and Soufiani, 1999).

The method of the weighted sum of gray gases WSGG, proposed by Hottel and Sarofim (1967), was taken as the basis for the development of methods based upon the distribution functions of the global absorption coefficient. The WSGG model (Modest, 1991) was used for the first time to solve the radiative transport equation for the case of uniform medium and for the treatment with black frontiers. The full-spectrum correlated-*K* (FSCK) model (Modest and Zhang, 2000) was introduced for treating non-homogeneous medium and later extended to include non-homogeneous gas mixtures (Modest and Zhang, 2002; Zhang and Modest, 2002). This approach was recently extended for treatment of non-homogeneous gas mixtures with absorbing particles (Modest and Riazzi, 2005). The spectral line weighted (SLW) model (Denison and Webb, 1993) is based upon detailed spectral line data. Solovjov and Webb (2000) extended the SLW method to handle non-homogeneous gas mixtures by using one cumulative distribution function of the absorption coefficient calculated over the total spectrum and weighted by the Planck function. The methods ADF, (Riviere *et al*., 1996) and ADFFG (Pierrot *et al*., 1999) are similar to the SLW method and fictitious gas weights are calculated.

Solovjov and Webb (2002) developed the CW model, which is a local spectrum correlated model. It was formulated to solve the equation of radiative transport in a medium of high temperature non-uniform gas. The spectral integration of the radiative transport equation is done by means of a new distribution function of the spectrum of gas absorption, called cumulative wavenumber. This new concept represents a local rather than the global correlation of the gas spectrum traditionally used. A local correction factor is introduced to take into account the spatial variations of the concentrations of species and the temperature of the gas that is calculated independently in each spectral interval. Later, Ismail and Salinas (2005) applied the CW model in a 2D enclosure filled with homogeneous, non-uniform and non-isothermal gases coupled with the discrete ordinates method. Recently, Solovjov and Webb (2005) presented enhancements of the CW model, formalizing a mathematical definition and extending it to handle non-homogeneous mixture of gases with non-gray particles.

It is true that the CW model is relatively simple in comparison with other models with respect to obtaining the model parameters. Still, some difficulties are found in fast and accurate numerical calculation. The present study presents an approach based on additive properties of the radiative intensity field to reduce the set of the transformed spectral radiative transfer equations generated by applying the CW model.

2. CW model

For any fixed value of the absorption cross-section *C* and wavenumber η, the cumulative wavenumber function for a gas in the interval (η_o, η_f) is defined by the relation (Solovjov and Webb, 2002):

$$w(C,\eta)=\begin{cases}\sum_{i=1}^{L}(\beta_i-\alpha_i)+(\eta-\eta^*) & If \quad C_\eta < C \\ \sum_{i=1}^{L}(\beta_i-\alpha_i) & If \quad C_\eta \geq C\end{cases} \tag{1}$$

where, C_η is the absorption cross-section (cm^2/molecule) and C_j is the supplementary cross-section (cm^2/molecule) and α_i and β_i are the subinterval limits used in cumulative wavenumber function construction.

The intervals (α_i, β_i) are obtained from the intersection of the absorption cross-section C_η with the $C_\eta = C$. η^* is the largest wavenumber of the intersection for the case when, for the wavenumber variable η, the absorption cross-section C_η is less than the value C. L is the number of intervals where $w(C, \eta)$ is creasing. Also, according to the definition, the cumulative wavenumber is a continuous non-decreasing function of η. More formally speaking the cumulative wavenumber function can be defined by (Solovjov and Webb, 2005):

$$w(C,\eta)=\int_0^{\eta} H(C-C_\eta)d\eta \tag{2}$$

where $H(C-C_\eta)$ is the Heaviside step-function. If one differentiates Eq. (2) one has.

$$\frac{dw(C,\eta)}{d\eta}=H(C-C_\eta)=\begin{cases}1 & if \quad C_\eta < C \\ 0 & if \quad C_\eta > C\end{cases} \tag{3}$$

This formula permits changing the integration with respect to an independent variable η over the spectral region defined by the molecule absorption spectrum to integration with respect to a cumulative wavenumber.

$$\int_{\{\eta:C_\eta<C\}} d\eta=\int H(C-C_\eta)d\eta=\int_{\eta=0}^{\infty}\frac{\partial w(C,\eta)}{\partial\eta}d\eta=\int_{\eta=0}^{\infty} dw(C,\eta) \tag{4}$$

As is shown in fig (1), in the CW model the total range of the absorption cross-section $C\eta$ is subdivided into supplementary absorption cross-section of gray gases C_j, j = 1, ..., n, where n is the number of gray gases; and the range of the number of waves is subdivided in subintervals $\Delta_i = [\eta_{i-1}, \eta_i]$, i = 1, 2, . . .p, where p is the number of subintervals. Also, it is considered that H_j as the sum of all the spectral subintervals for which the real coefficient of absorption cross-section $C\eta$ lies between the supplementary absorption cross-section C_j and C_{j-1}; then it can be written as $H_J = \{\eta: C_{J-1} \leq C_\eta \leq C_J\}$, for J= 1, . . .,n. The intersection of the two spectral subdivisions is used to define the modeling of the fractional gray gas $D_{ij} = \Delta_i \cap H_J$. The sum of the fractional gray gases establishes the complete range of number of wave. In CW model, we should solve the RTE in every subinterval D_{ij}; then it is necessary to solve n x p times the spectral form of the RTE for complete spectral integration.

The consideration of local spectral correlation establishes that

$$W(C_j, s, \eta) - W(C_{j-1}, s, \eta) = u_{i,j}(s)\, \upsilon_{i,j}(\eta) \quad \text{for } \eta \in \Delta i \tag{5}$$

The integration of the spectral radiation intensity over the fraction D_{ij} of a real gas by using the accumulated wavenumber concept described by Eq. (5) yields

$$\int_{D_{i,j}} I_\eta d\eta=\int_{\{\eta:C_{j-1}<C\eta<C_j\}\cap\Delta i} I_\eta d\,\eta \quad = u_{i,j}(s)\int_{\Delta i} I_\eta d[\upsilon_{ij}(\eta)] = u_{i,j}(s)J_{i,j}(s) \tag{6}$$

Where $J_{i,j}$ is considered as a fraction of the real gas intensity and $u_{i,j}$ (s) as a local correction factor for the real gas fractional intensity. The total radiation intensity is determined from the sum of all intensities of gases with the correction factor $u_{i,j}(s)$ as a weight

$$I(s)=\int_0^{\infty} I_\eta(s)d\eta=\sum_{i,j} u_{i,j}(s)J_{i,j}(s) \tag{7}$$

where $u_{i,j}(s)$ is defined by Eq. (5).

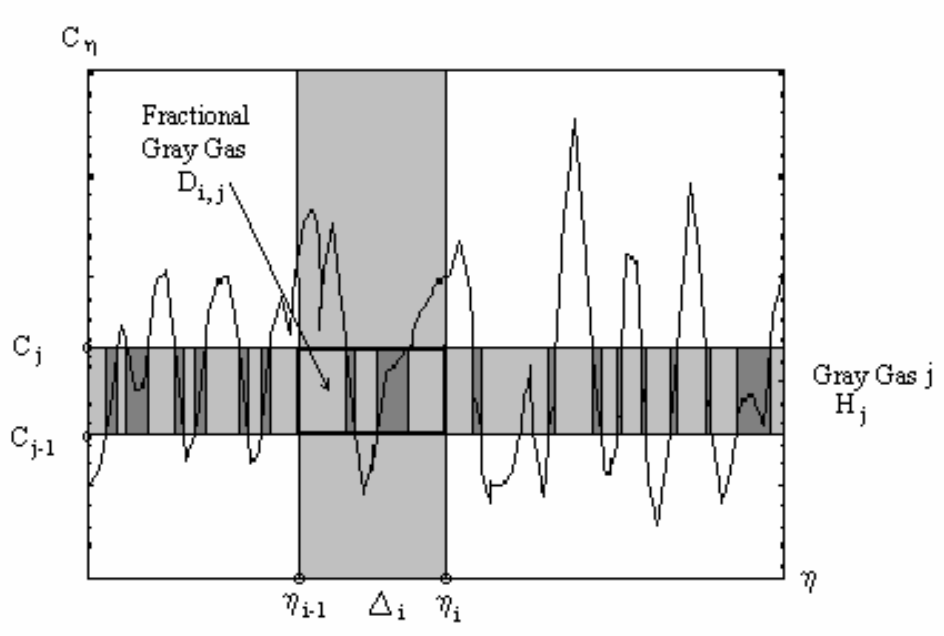

Figure 1. CW modeling by fractional gray gases.

3. The radiative transport equation (RTE)

3.1 The radiative transport equation (RTE) in gray media

The radiative transport equation for an absorbing, emitting gray gas medium can be written as (Siegel and Howell, 1992)

$$(\boldsymbol{\Omega}.\nabla)\boldsymbol{I}(\boldsymbol{r},\boldsymbol{\Omega}) = -\kappa\boldsymbol{I}(\boldsymbol{r},\boldsymbol{\Omega}) + \kappa\boldsymbol{I}_b(\boldsymbol{r}) \tag{8}$$

where $\boldsymbol{I}(\boldsymbol{r},\boldsymbol{\Omega})$ is the radiation intensity in $\boldsymbol{r}$, and in the direction Ω; $\boldsymbol{I}_b(\boldsymbol{r})$, is the radiation intensity of the blackbody in the position **r** and at the temperature of the medium; κ is the gray medium absorption coefficient. For diffusely black surfaces the radiative boundary condition for Eq. (8) can be written as

$$\boldsymbol{I}(\boldsymbol{r},\boldsymbol{\Omega}) = \boldsymbol{I}_{bwall}(\boldsymbol{r}) \tag{9}$$

where $\boldsymbol{r}$ lies on the boundary surface Γ, and the Eq. (9) is valid for $\boldsymbol{n}.\Omega > 0$. $\boldsymbol{I}(\boldsymbol{r},\boldsymbol{\Omega})$ is the radiation intensity leaving the surface at the boundary condition.

3.2 Additive properties consideration

For an absorbing, emitting gray gas medium a set of radiative intensity fields can be described by the following equations:

$$(\boldsymbol{\Omega}.\nabla)\boldsymbol{I}_A(\boldsymbol{r},\boldsymbol{\Omega}) = -\kappa\boldsymbol{I}_A(\boldsymbol{r},\boldsymbol{\Omega}) + \kappa\boldsymbol{I}_{Ab}(\boldsymbol{r}) \tag{10.a}$$

$$(\boldsymbol{\Omega}.\nabla)\boldsymbol{I}_B(\boldsymbol{r},\boldsymbol{\Omega}) = -\kappa\boldsymbol{I}_B(\boldsymbol{r},\boldsymbol{\Omega}) + \kappa\boldsymbol{I}_{Bb}(\boldsymbol{r}) \tag{10.b}$$

$$(\boldsymbol{\Omega}.\nabla)\boldsymbol{I}(\boldsymbol{r},\boldsymbol{\Omega}) = -\kappa\boldsymbol{I}(\boldsymbol{r},\boldsymbol{\Omega}) + \kappa\left(\boldsymbol{I}_{Ab}(\boldsymbol{r}) + \boldsymbol{I}_{Bb}(\boldsymbol{r})\right) \tag{10.c}$$

With the correspondent radiative black boundary conditions

$$\boldsymbol{I}_{Awall}(\boldsymbol{r},\boldsymbol{\Omega}) = \boldsymbol{I}_{Abwall}(\boldsymbol{r}) \tag{11.a}$$

$$\boldsymbol{I}_{Bwall}(\boldsymbol{r},\boldsymbol{\Omega}) = \boldsymbol{I}_{Bbwall}(\boldsymbol{r}) \tag{11.b}$$

$$\boldsymbol{I}_{wall}(\boldsymbol{r},\boldsymbol{\Omega}) = \boldsymbol{I}_{Abwall}(\boldsymbol{r}) + \boldsymbol{I}_{Bbwall}(\boldsymbol{r}) \tag{11.c}$$

It can be demonstrated that

$$\boldsymbol{I}(\boldsymbol{r},\boldsymbol{\Omega}) = \boldsymbol{I}_{A}(\boldsymbol{r}) + \boldsymbol{I}_{B}(\boldsymbol{r}) \tag{12}$$

This additive property is easily verified invoking the superposition principle for non-homogeneous linear equations. Also, it can be easily extended to the mixture of homogeneous gases. This additive property is the key for utilizing a fast approximation technique to reduce the number of transformed spectral radiative transport equations that is generated by application of CW model for the complete integration of the radiative transport in real gas media. Also, if one can reduce the number of transformed spectral RTEs using the additive property, one can reduce the amplitude of the subintervals Δ_i.

3.3 The RTE in the fast CW model approximation

The radiative transport in an absorbing and emitting medium along trajectory s in the direction Ω is given by Siegel and Howell (1992)

$$\frac{\partial \boldsymbol{I}_{\eta}}{\partial s} = -\kappa_{\eta}\boldsymbol{I}_{\eta} + \kappa_{\eta}\boldsymbol{I}_{b\eta} \tag{13}$$

According to the CW spectral model, the spectral RTE, Eq. (13), is integrated over fractional gray gas wavenumbers $D_{ij} = \{\eta: C_{j-1} < C_{\eta} < C_j\} \cap \Delta_i$

In a similar manner as Eq. (13) the RTE in the CW model (Solovjov and Webb, 2002)

$$\frac{\partial \boldsymbol{J}_{i,j}}{\partial s} = -\kappa_j \boldsymbol{J}_{i,j} + \kappa_j \boldsymbol{J}_{bi,j} \tag{14}$$

where κ_j is the absorption coefficient of gray gas determine as in Denison and Webb (1993).

The term $\boldsymbol{J}_{bi,j}$ in Eq. (14) is the radiative source term at the black body fractional intensity which by using Eq. (4) can be written as (Ismail and Salinas, 2005)

$$\boldsymbol{J}_{bi,j}(s) = \frac{(W(C_j,s^*,\eta_i) - W(C_j,s^*,\eta_{i-1})) - (W(C_{j-1},s^*,\eta_i) - W(C_{j-1},s^*,\eta_{i-1}))}{\eta_i - \eta_{i-1}} \int_{\eta_{i-1}}^{\eta_i} \boldsymbol{I}_{b\eta}(T(s),\eta)d\eta \tag{15}$$

Or finally by putting

$$\boldsymbol{f}_{wi,j} = \frac{(W(C_j,s^*,\eta_i) - W(C_j,s^*,\eta_{i-1})) - (W(C_{j-1},s^*,\eta_i) - W(C_{j-1},s^*,\eta_{i-1}))}{\eta_i - \eta_{i-1}} \tag{16}$$

One has

$$\frac{\partial \boldsymbol{J}_{i,j}}{\partial s} = -\kappa_j \boldsymbol{J}_{i,j} + \kappa_j f_{wi,j} \int_{\eta_{i-1}}^{\eta_i} \boldsymbol{I}_{b\eta}(T(s),\eta)d\eta \tag{17}$$

Examining the last equation, one notices that the last term in right side work as one source term for $J_{i,j}$ where the factor $f_{wi,j}$ is a weight factor which depends on wavenumber interval Δ_i .

Also, for homogeneous media (Solovjov and Webb, 2002), $u_{i,j}(s)$ =1, one can to write

$$\boldsymbol{I}(s) = \sum_{i,j} J_{i,j}(s) = \sum_{j}\left(\sum_{i} J_i(s)\right)_j = \sum_{j} J_j(s) \tag{18}$$

The radiation Planck function in Eq. (17) is evaluated at the local temperature. The sum of the $\boldsymbol{J}_{bi,j}\ (s)$ for all the fractional gray gases is equal to

$$\boldsymbol{I}_b = \sum_{i,j} \boldsymbol{J}_{bi,j} = \frac{\sigma T^4}{\pi} \tag{19}$$

One can rewrite the Eq. (19) as

$$\boldsymbol{I}_b = \sum_j \left(\sum_i \boldsymbol{J}_{b_i} \right)_j = \sum_j \boldsymbol{J}_{bj} = \frac{\sigma T^4}{\pi}$$

and

$$\boldsymbol{J}_{bj} = \sum_i \boldsymbol{J}_{b_i} = \sum_i f_{wi} \int_{\eta_{i-1}}^{\eta_i} \boldsymbol{I}_{b\eta}(T(s),\eta) d\eta \tag{20}$$

By analogy with Eq. (10.c), one can calculate J_j by

$$\frac{\partial \boldsymbol{J}_j}{\partial s} = -\kappa_j \boldsymbol{J}_j + \kappa_j \left(\sum_i f_{wi} \int_{\eta_{i-1}}^{\eta_i} \boldsymbol{I}_{b\eta}(T(s),\eta) d\eta \right)_j \tag{21}$$

This should be solved with the appropriate boundary condition in analogy with Eq. (11.c).
The boundary condition for non-gray walls, diffusively emitting can be written as (Siegel and Howell, 1992)
.

$$\boldsymbol{I}_\eta (s_w, \hat{\boldsymbol{\Omega}}) = \varepsilon_{\eta \boldsymbol{w}} \boldsymbol{I}_{b\eta}(T_w) \tag{22}$$

where Ω is the direction vector along s, S_w define the point on the frontier surface and the subscript w refers to the quantity evaluated at the frontiers. $\varepsilon_{\eta w}$ is the spectral emissivity of the frontier. Integration of Eq. (22) yields

$$\boldsymbol{J}_{i,j} (s_w, \hat{\boldsymbol{\Omega}}) = \varepsilon_{iw} \boldsymbol{J}_{bi,j}(T_w)$$

and

$$\boldsymbol{J}_j (s_w, \hat{\boldsymbol{\Omega}}) = \left(\sum_i \varepsilon_{iw} \boldsymbol{J}_{bi}(T_w) \right)_j \tag{23}$$

Discretization of the spectral radiative transport equation in the CW model in every gray gas (j) in discrete ordinates is made as in Ismail and Salinas (2005). When the equation of radiative transport, Eq. (21) together with the boundary condition Eq. (22) are solved for all the gray gases $\boldsymbol{J}_j$, the total radiation intensity can be calculated in Eq. (18). The radiative source term for the gray gas j is determined in the discrete ordinates method from equation

$$\nabla . q_{r,j} = 4\pi \kappa_j \sum_i \boldsymbol{J}_{bi,j} - \sum_{m=1}^{M} \boldsymbol{w}_m \kappa_j \boldsymbol{I}_j^m \tag{24}$$

where $\mathbf{w}_m$ is the weight of the angular quadrature and

$$\boldsymbol{I}_j^m = \sum_i \boldsymbol{J}_{i,j}^m \tag{25}$$

And the total source term is

$$\nabla . q_r = \sum_j \nabla . q_{r,j} \tag{26}$$

3.4 Spectral approximation

To solve numerically the RTE in the CW model it is necessary to chose Δ_i in the wavenumber range, and by using the cumulative wavenumber functions the parameters $f_{w\,ij}$ and $u_{i,j}$ should be calculated. Actually, when one calculates the cumulative wavenumber functions by application of the definition in Eq. (1), one obtains a set of discrete characteristic points and it is necessary to use step wise interpolating functions along the set of points. As can be seen in Fig. (2), within one subinterval Δ_i there are a set of fractional gray gases subintervals D_{ij} . As Δ_i increases, the interpolating function is less accurate with the cumulative wavenumber function and the values of $f_{w\,ij}$ and $u_{i,j}$ will be less accurate and one loose precision in the calculations. Previously, the use of large Δ_i as for example 100 cm^{-1} (Solovjov and Webb, 2002; Ismail and Salinas, 2005) was justified because of the large computational time of original procedure necessary to solve the set of transformed spectral RTE in CW model. For example, if one has n=20 gray gases C_j and p =100 subintervals Δ_i one needs to solve 2000 simultaneous transformed spectral RTEs, and if p = 400 (for Δ_i = 25 cm^{-1}) it will be necessary to solve 8000 simultaneous RTEs in every iteration, and so on. But using the additive property in the radiative intensity field in this case, one can select the smallest subinterval Δ_i and use more accurate interpolating functions to obtain more representative values of $f_{w\,ij}$ and $u_{i,j}$ for the CW model without an increase of the computational time. Figure (2) shows the calculated cumulative wavenumber function $C_j = C_{14}$, calculated for H_20 at 2000 K for absorption cross-section coefficients in the range $10^{-25} < C < 10^{-17}$ cm^2/molecule, between the subinterval Δ_i = [4300 to 4400 cm^{-1}]. The upper curve corresponds to $C_1 = 10^{-17}$ cm^2/molecule while the bottom curve corresponds to $C_{20} = 10^{-25}$ cm^2/molecule in logarithm half decade increments.

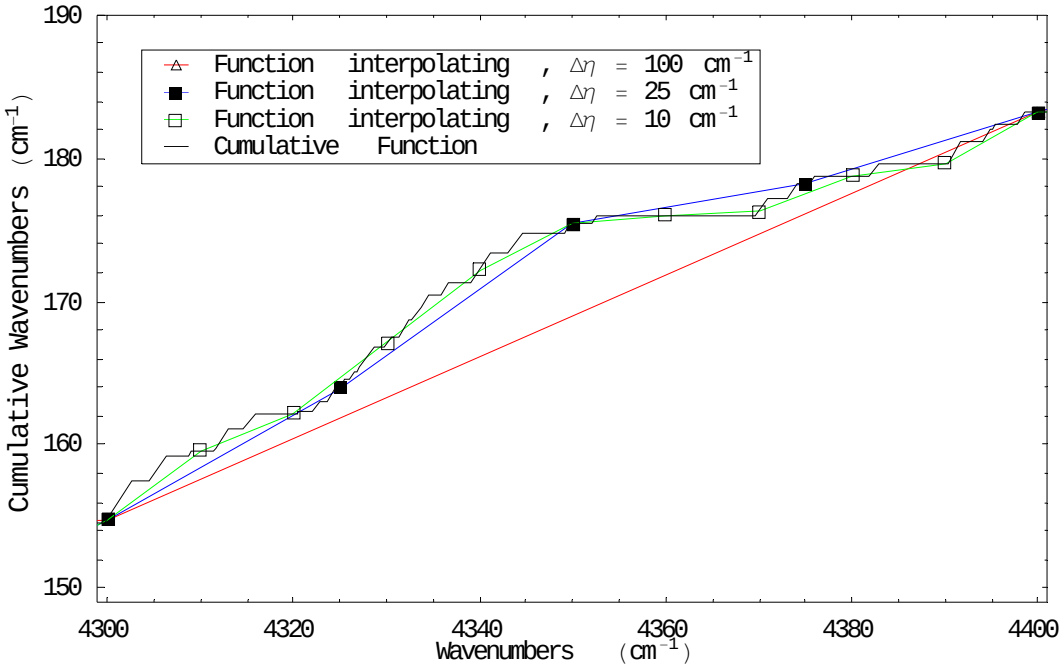

Figure 2. Comparison of Interpolating functions of CW functions distribution gray gas $C_j = C_{14}$, H_2O at 2000 K.

4. Results and discussion

4.1 Validation 1D

Two problems presented in Solovjov and Webb (2000) are solved to test the new fast approach for the CW model.

Problem 1. Consider the radiative heat exchange of a mixture of three combustion gases, H_2O, CO_2 and CO. The mixture is homogeneous and isothermal at 1000 K and 1 atm of total pressure occupying 1 m. wide space between two parallel plates. The molar fractions of H_2O, CO_2 and CO in the mixture are 0.2, 0.1 and 0.03 respectively. The frontiers are black and non-emitting. The distribution function of the black body absorption lines for H_2O, CO_2 and CO and its mixture are calculated by using the spectral database HITEMP (Hitran, 2005) at 1000 K. The solution of the radiative transport equation for the local spectral correlation is obtained by using the method of discrete ordinates with 20 gray gases, three different uniform spectral intervals: Δ_i = 10 cm^{-1}, Δ_i = 25 cm^{-1}, Δ_i = 100 cm^{-1}, over a 0-10,000 cm^{-1} range of wavenumber, angular quadrature T_n 6, spatial grid of 250 volumes and the CLAM scheme for interpolating the intensity of radiation over the faces. Using the calculated intensities of the gray gases, one can determine the radiative source term for the mixture of real gases. Figure (3) shows the calculated radiative source term against distance for different Δ_i compared with the obtained by the Line-by-Line method (Solovjov and Webb, 2000). One observes that as Δ_i decreases,

the solution is more accurate compared to the Line-by-Line solution; and for $\Delta_i = 10$ cm^{-1} the numerical solution of CW model and the Line-by-Line shows good agreement.

Problem 2. Consider the same case as above but where the distance between plates is 5 m. Figure (4) shows the calculated radiative source term against distance for 20 gray gases, spectral intervals: $\Delta_i = 10$ cm^{-1}, $\Delta_i = 25$ cm^{-1}, $\Delta_i = 100$ cm^{-1}; angular quadrature T_n 6, spatial grid of 1250 volumes and the CLAM scheme for interpolating the radiation intensities. The results for different Δ_i are compared with the results of Solovjov and Webb (2000) and again one can observe that for smallest Δ_i the numerical solution of the CW model is accurate as the Line-by-Line solution.

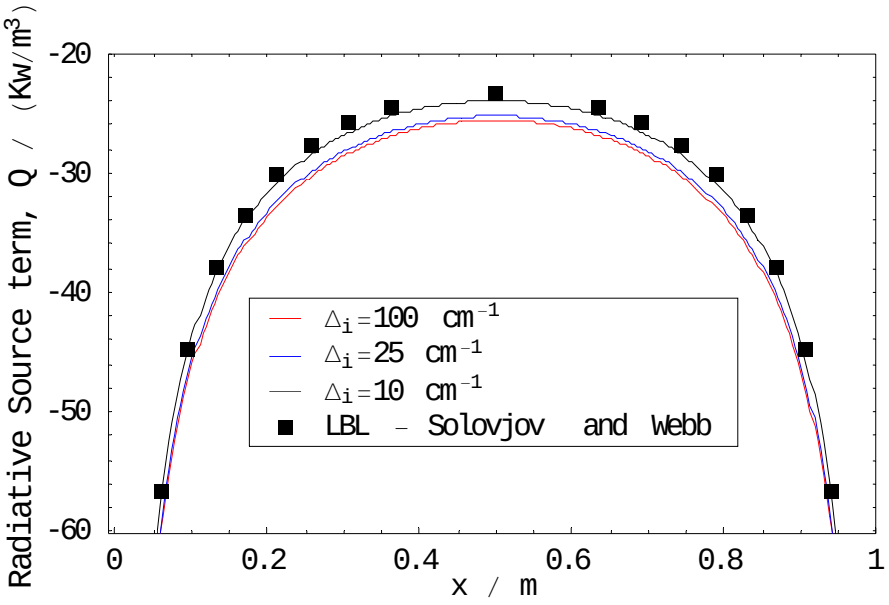

Figure 3. Comparison of the radiative dissipation source in isothermal gas mixture for 1 m separated parallel plates for different Δ_i with Line-by-Line solution (Solovjov and Webb, 2000)

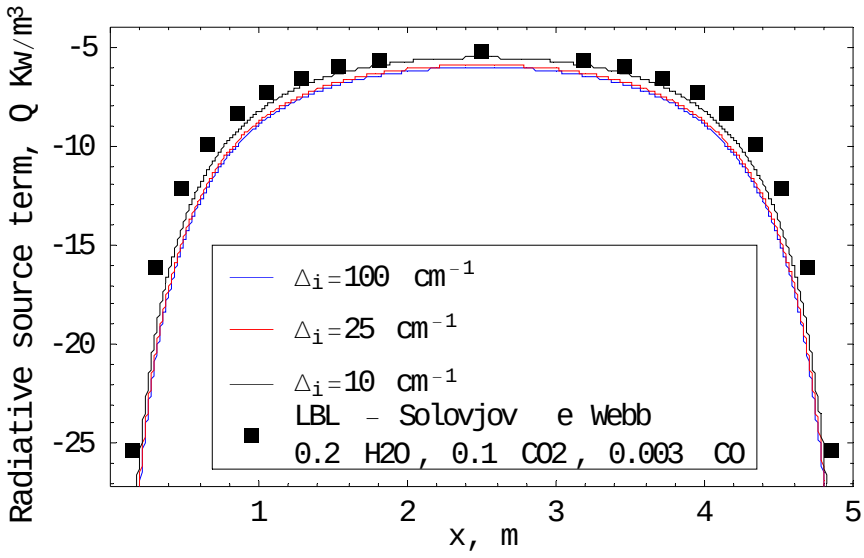

Figure 4. Comparison of the radiative dissipation source in isothermal gas mixture for 5 m separated parallel plates for different Δ_i with Line-by-Line solution (Solovjov and Webb, 2000)

4.2 Application in 2D

Problem 3. This problem involves the radiative heat transport of a mixture of three gases of combustion. The mixture is homogeneous and isothermal at 1000 K and 1 atm total pressure occupying a two-dimensional square cavity of a side equal to 1 m. The molar fractions of H_2O, CO_2 and CO are 0.2, 0.1 and 0.03, respectively. The frontiers are black and non-emitting. The problem is solved using the spectral HITEMP database (Hitran, 2005) at 1000 K. Some numerical simulations were performed to investigate the convergence of the solution and the influence of refining the angular quadrature on the convergence of the solution, which is not shown here. It is found that for T_n 6 and higher or LC11 quadratures the solution does not change. Similarly, the effect of the size of the computational grid was investigated. As a result of the numerical tests, the investigation uses the angular LC11 quadrature with a grid of 20 x 20. The solution of the radiative transport equation for the local spectral correlation is obtained by using the method of discrete ordinates with 20 gray gases. Three different uniform spectral intervals: $\Delta_i = 10$ cm^{-1}, $\Delta_i = 25$ cm^{-1}, $\Delta_i = 100$ cm^{-1}, over a 0-10,000 cm^{-1} range of wavenumber are used.

Figure (5) shows the comparison of the predicted radiative source at the middle cross section for different spectral intervals Δ_i and compares the results with the result obtained by standard method for solving the CW model for $\Delta_i = 100$ cm^{-1}. For the fast approach only 20 transformed spectral RTEs in every iteration are solved; and for the standard method it is necessary to solve 20 x 100 transformed spectral RTEs. It can be observed that, as the spectral interval Δ_i decreases, the solution converges smoothly and the solution for $\Delta_i = 100$ cm^{-1} is still far from converged solution. Also, it is found that the numerical results for the fast approach and for the standard method are closed. Notice that, if one uses the standard method of solution for CW method for $\Delta_i = 10$ cm^{-1} and 20 gray gases one will need to solve 20,000 transformed spectral RTEs instead of 20 for fast approach in every iteration. Using the fast approach for solving the CW model, the computation time in this case is reduced approximately 1000 times.

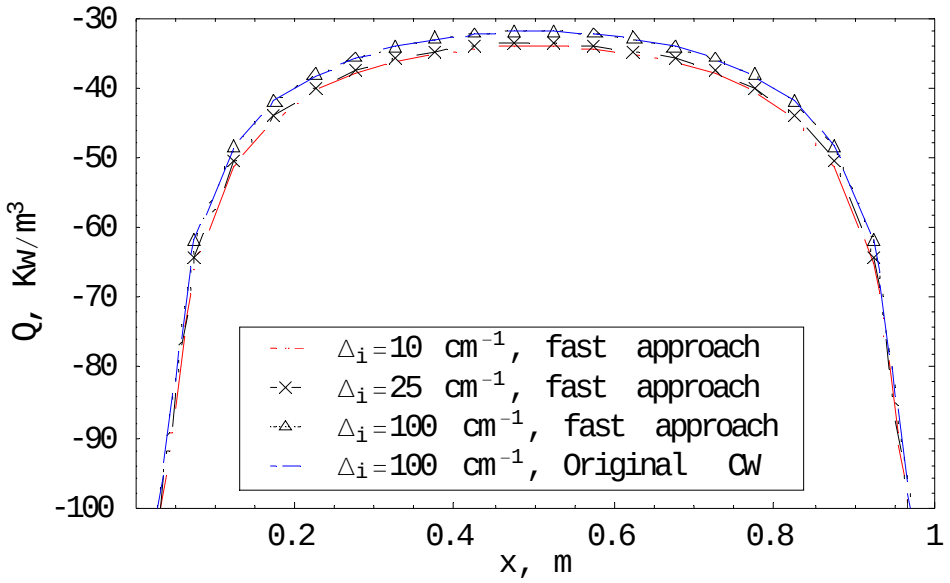

Figure 5. Radiative source term surface in two-dimensional cavity with an isothermal gas mixture at 1000 K, cold black walls. Comparison for different Δ_i with the original CW method of solution.

5. Conclusions

A fast numerical approach to solve the transformed spectral RTE generated by application of the local spectrum model and the cumulative wavenumber distribution function is applied to a mixture of real gases, first in one-dimensional geometry to validate the numerical procedure; the results agree very well with LBL solutions. Then it is applied to the two-dimensional cavity space with black boundaries in the isothermal case. Use of the fast approach for the CW model presented in this work permits reducing 100, 400 or 1000 times the computational time when used respectively in $\Delta_i = 10$ cm^{-1}, $\Delta_i = 25$ cm^{-1}, $\Delta_i = 100$ cm^{-1} over a 0-10,000 cm^{-1} range of wavenumber in comparison with the standard method of solution for the CW model for the same spectral interval Δ_i. In the fast approach, the selection of small spectral intervals Δ_i permit more accurate results and do not affect computational time. A study to extend this approach for non uniform media is in work.

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