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# Numerical Simulation of Radiating Flows Inside an Inclined Concentric Annulus

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***Abstract*— A numerical simulation of radiating laminar flows of emitting and absorbing gases inside an inclined concentric annulus is presented. The interaction of thermal radiation with the other modes, the non-gray radiative behavior of gases and the multidimensional nature of radiative transfer are considered in this simulation. The proposed numerical method transforms the elliptic radiative problem to a series of parabolic ones where the marching solution can be used. The opportunity to use this procedure offers a reasonable compromise between time computing and storage capacity for treating the non-gray two-dimensional radiative problem simultaneously with the parabolic boundary-layer flow equations. The infrared radiative properties of the flowing $H_2O$-$CO_2$ gas mixtures are modeled by using the global Absorption Distribution Function model. The results are presented in terms of axial and radial velocities and temperature fields.text.**

***Keywords*— Gas radiation- Convection- Coupled heat transfer- Concentric annulus.**

## I. INTRODUCTION

At high temperature, accurate prediction of thermal radiation is the key in most industrial systems. In fact, radiative energy transfer is an important issue and well recognized especially for applications considering real gaseous treatment such as regenerating high-temperature heat exchangers, cooling processes in nuclear reactors, industrial furnaces, combustion chambers, reentry applications, etc

In most situations of interest, the radiant energy transfer of radiative species is coupled in a nonlinear way with conduction and convection. Therefore, the need for computationally efficient and accurate solution methods to combined thermal radiation and convection with minimized simplifying assumptions exists. Finding such a solution still a difficult task and the investigations for obtaining yet efficient solutions have been conducted for a long period time.

An extensive overview of interaction of thermal radiation and convection for radiative participating flows in circular and non circular ducts, when considering a radiation field is given in Refs.[1-5]. Other references may be found in classical textbooks or reviews papers in Refs.[6-7].

In the available literature, no studies related to simultaneous effects of real gas radiation and laminar mixed convection in the entrance region of inclined concentric annulus have been conducted.

The present study focus on the interaction between thermal radiation and mixed convection through an absorbing-emitting gas mixtures flowing inside an inclined concentric annulus with heated walls by an uniform wall temperatures.

In this paper special attention is devoted to the treatment of the spectral nature of radiation in real $H_2O$-$CO_2$ gas mixtures at high temperature. The lack of information in this topic motivated this work.

To solve the mass, momentum and energy parabolic equations, an implicit finite difference technique is used. The major advantage of parabolizing equations is the opportunity to use a marching technique, which saves computing time and storage capacity. This assumption offers a reasonable compromise for treating the non-gray two-dimensional radiative problem with an acceptable accuracy by using the numerical procedure presented in [2,3] which transforms the elliptic radiative transfer problem to a series of parabolic ones.

The flow equations and energy balance equation are solved simultaneously with temperature-dependent fluid properties. However, as pointed out by Soufiani et al. [1] and Sediki et al.[2-4], dimensionless treatment of these equations have a very limited utility in the case of realistic gas mixtures band radiation and when thermophysical properties are temperature dependent. So, the resolution of the problem is undertaken in dimensional form.

The radiative properties of the flowing gases are modeled by using the Absorption Distribution Function (ADF) infrared radiative property model [8-9]. The spectral correlation phenomenon is taken into account through the ADF global model.

The Discrete Transfer Method (DTM) is applied to solve the geometrical part of radiative transfer. Numerical calculations are performed to simulate the radiation effects on developing laminar flow and heat transfer for real $H_2O$-$CO_2$ gas mixtures in symmetrically and asymmetrically heated or cooled flows with taking into account the spectral nature of the gas mixture thermal radiation and its axial propagation.

The goal of this paper is to develop a tool that is capable to simulate the axial and radial radiative flux and the spectral correlation phenomena between elementary volume elements. with a reasonable compromise between accuracy and CPU time consuming. Effects of thermal radiation in conjunction with the other modes on velocity and temperature distributions for non-isothermal $H_2O$-$CO_2$ mixture gas flowing inside concentric annulus are investigated. Therefore we introduce, first in section 2, the principles of the radiative transfer problem modeling and second we recall briefly and we validate results of the Discrete Transfer Method (DTM) for different convective and radiative grids.

In section 3, we present the basic formulation for combined radiative and convective problem and the numerical methods used to solve the coupled transport equations.

Discussion of the numerical simulation results and its effects on thermal and hydrodynamic flow developing are provided in section 4.

## II. RADIATIVE TRANSFER MODELING

In the current study, Absorption Distribution Function model is coupled with the discrete-direction method for radiative transfer equation solution, to calculate more accurately the volumetric radiative power in participating media for use in solving the energy transport equation.

The presence of radiating species in gas flows affects the total (convective + radiative) heat flux in two ways: directly and indirectly. Directly, the temperature distribution in the fluid determines the local radiative flux through ″the action at distance″. Indirectly, the interaction of convection and radiation alters the temperature distribution in the duct and modify the convective flux, besides its effect on hydrodynamic fields through the temperature-dependent thermophysical properties.

Solution of combined heat transfer problems in high-temperature mixture gas flows requires both the knowledge of the spectral radiative properties and efficient methods for solving the radiative transfer equation (RTE), to determine the spectral radiation fields, the radiation flux vector ( $\vec{q}_r$ ) and its divergence ( $\nabla\vec{q}_r$ ), which needed to solve the thermal energy equation. However the numerical models for solving the RTE must be compatible with the numerical method used to solve the transport equations.

The high-resolution structure of emission and absorption spectra of gases generates spectral correlation effects between emission, transmission and absorption by consecutive elementary columns. These effects strongly modify the local intensity field and consequently the radiative fluxes and the radiative source term at each point of the medium.

In global models, the entire spectrum is considered as a whole. So, the use of this method leads to small computational times [8-9]. Comparisons between the results from the ADF model and from the more elaborated correlated-k band model have shown a reasonable accuracy of the ADF model, besides saving CPU times and storage computational volumes [2]. For this reason, the ADF model is implemented for radiative transfer combined with laminar mixed convection.

Parameters of ADF models are deduced from line by line calculations founded on the same high temperature spectroscopic data bases [10,11].

In the following, we provide details related to the model parameters and the practical way to use them in radiative transfer calculations. Indeed, model accuracies and required CPU times strongly depend on model parameterizations.

The absorption coefficient values are discretized into N ranges $[k_j^-, k_j^+]$ for a reference thermophysical condition $(X_{ref}, p_{ref}, T_{ref})$ where X is the molar fraction of the absorbing species, p the local pressure and T the temperature. The values of $k_j$ in any other thermo physical condition X, p, T are given by an implicit relation which constitutes the correlation approximation. This approximation is rigorous in the case of scaling spectra. The values of $k_j/(X.p)$ and the weights aj, satisfying: $\Sigma aj = 1$, are the parameters of the ADF model. Different implementations of the ADF model in the case of absorbing gas mixtures are discussed by Pierrot and al. [8].

In the present investigation, the ADF model is implemented for $H_2O$-$CO_2$ gas mixtures. In instance, the molar fractions are imposed to $X_{H2O}=0.45$ and $X_{CO2}=0.55$, which roughly corresponds to combustion of heavy fuels with pure oxygen and the mixture is treated as single gas with the spectral absorption coefficient:

$$\kappa_\nu = \kappa_{\nu,H2O} + \kappa_{\nu,CO2} \qquad (1)$$

The chosen reference conditions were $T_{ref}=1100K$ and $X_{H2O}$ or $X_{CO2}$ equal to 0.1.

To solve the radiative transfer problem, we use in this study the discrete-direction method, developed initially for radiative transfer in axisymmetric systems using statistical narrow-band models [12,13]. This method is adapted here to ADF model, which do not require the recourse to any further approximations. The discrete-direction method is close to the discrete ordinates method. In one hand the directional integration quadrature is used for a regular integration with prescribed angular increments and solid angles, and in the other hand intensity interpolations are used instead of integrations over control volumes.

In order to compute the radiative flux and radiative powers, the method uses two discretizations as shown in Fig.1:

- a spatial discretization which consists in defining the radial and axial grid points where radiative intensities are calculated,
- a directional discretization of two angles θ and φ. The calculations are carried out in the planes parallel to the system axis and tangential to the coaxial cylinders, defined by the radial discretization ($r_k$).

For each plane and each transfer direction θ, the radiative intensity at a point M is step by step calculated by using interpolations between upstream grid points (B,C) where the intensities are known. The use of the radiative intensity equation and the radiative boundary condition for each direction inside each plane leads to a system of linear equations where the unknowns are the intensities leaving the wall points. After the inversion of this system, the intensities inside the volume are computed and the radiative source term ( $\nabla\vec{q}_r$ ) is then calculated directly from the intensity field.

Fig. 1 illustrates the investigated situation corresponding to a laminar steady flow of non-scattering gas mixtures inside a concentric annulus. The geometrical configuration and physical conditions are summarized in this figure. At the inlet section (x=0), the flow is fully developed and the rate is assumed to be fixed by a metering device. An isothermal length ($x=L_0$) allows to account for realistic radiative inlet conditions with the possibility of preheating or precooling of the gas mixtures before this section. For the radiative intensity, the walls are assumed to emit and reflect thermal radiation isotropically. The walls are also assumed to be gray with a constant emissivity.

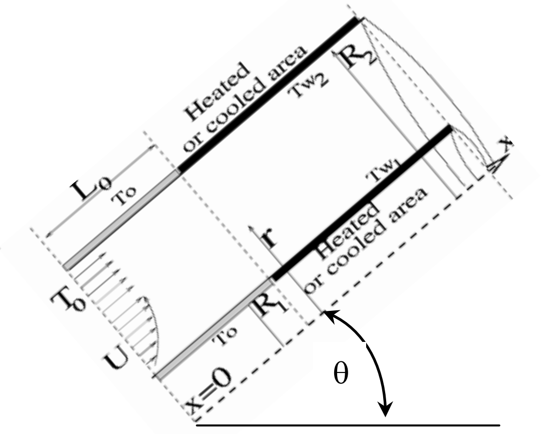


Fig. 1 Geometry and boundary conditions.

A constant mesh size is used for the radial direction and a variable one in the axial direction. This mesh size increases far from the entrance, which allows a higher accuracy for the temperature and velocity fields in the thermal entrance region where steep axial gradients occur. This mesh size increases far from the entrance, which allows a higher accuracy for the temperature and velocity fields in the thermal entrance region where steep axial gradients occur. Numerical linear interpolations and extrapolations are used to convert the results from the convective grid mesh to the radiative one and vice versa. Global iterations between these sequences are performed until convergence. This iterative procedure starts with the 1-D radiation temperature field for the 2-D calculation of the radiative field.

The numerical solution method starts first with the prediction of the temperature and velocity fields using local 1-D radiative transfer calculations and a marching procedure along the axial direction. The radiative source term ( $\nabla \vec{q}_r$ ) or the volumetric radiative power dissipated in the medium for a given section i is calculated from a one-dimensional temperature field. In practice, for 1-D radiative transfer calculations the same numerical procedure is used with a few discretized axial sections of number $N_x1D$ and a very large spacing between these sections in comparison with the tube diameter, as indicated in Fig.2. In a second step, an iterative procedure is undertaken. Two-dimensional radiative powers and fluxes are calculated from the 2-D temperature field and then the flow and energy equations are solved using the marching procedure and the computed radiative powers as source terms. The required number of global iterations depends on the optical thickness of the medium.

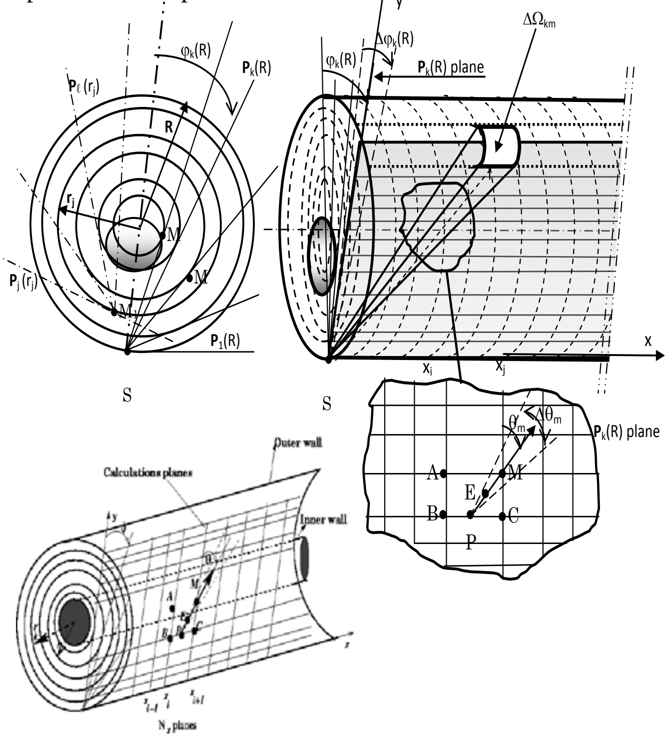


Fig. 2 Spatial and directional discretizations.

The use of the radiative intensity equation and the radiative boundary condition for each direction inside each plane leads to a system of linear equations where the unknowns are the intensities leaving the wall points. After the inversion of this system, the intensities inside the volume are computed and the radiative source term ( $\nabla \vec{q}_r$ ) is then calculated directly from the intensity field.

The total radiative intensity $I(\vec{u},s)$ at curvilinear abscissa s and for the direction $\vec{u}$ is written as the sum of the partial intensities:

$$I(\vec{u},s)=\sum_{j=1}^{N} I_j(\vec{u},s) \tag{2}$$

Each partial intensity $I_j(\vec{u},s)$ satisfies the radiative transfer equation:

$$\frac{\partial I_j(\vec{u},s)}{\partial s}=\sum_{j=1}^{N} k_j(s)\,X_{H_2O}\,p(s)\,[a_j(s)\frac{\sigma T^4}{\pi}-I_j(\vec{u},s)] \tag{3}$$

The divergence of the radiative flux or the radiative source term, appearing in the energy equation, is given by:

$$\overrightarrow{\nabla q_r}=\sum_{j=1}^{N} k_j(s)\,X_{H_2O}\,p(s)\int_{4\pi}[a_j(s)\frac{\sigma T^4}{\pi}-I_j(\vec{u},s)]\,d\Omega \tag{4}$$

The discrete-direction method is adapted to ADF model, to solve the radiative transfer problem without any further approximations. In one hand the directional integration quadrature is used for a regular integration with prescribed angular increments and solid angles, and in the other hand intensity interpolations are used instead of integrations over control volumes.

To compute the radiative flux and radiative powers in the medium, the method uses both spatial and directional discretizations. The approach is based on the determination at any grid point $M_i(r_i,x_i)$ of the spectral intensity for a set of chosen discretized directions. The spatial discretization consists in defining the radial ($0< r_j<R$) and the axial grid points ($0<x_i<L$) where radiative intensities are calculated. The directional discretization $\Delta(\vec{u})$ is done for two angles θ and φ. We consider a number of directional discretizations where the mean intensity in each solid angle $\Delta\Omega(\theta,\varphi) = \int_{\Delta\theta}\left(\int_{\Delta\varphi}\cos\theta\, d\varphi\right) d\theta$ is equal to the intensity in the direction $\Delta(\vec{u}(\theta,\varphi))$.

The calculations are carried out in the planes parallel to the system axis and tangential to the coaxial cylinders, defined by the radial discretization ($r_j$). For each plane and each transfer direction $\vec{u}$, the radiative intensity at a point M is step by step calculated by using interpolations between upstream grid points (B,C) where the intensities are known. When the solution of the RTE, is obtained, the radiative heat flux vector inside the participating medium is expressed as:

$$\vec{q}_r(M) = \int_{2\pi} I_j(M,\vec{u})\,\vec{u}\,d\Omega \qquad (5)$$

When we assume that the mean intensity in the elementary solid angle is equal to the intensity in the direction defined by $\Delta(\vec{u}(\theta,\varphi))$, the radiative heat flux vector became:

$$q_{r,\nu}(M) = \sum_{k=1}^{N_\varphi}\sum_{m=1}^{N_\theta} I_\nu(\theta_m,\varphi_k)\left|\vec{\Omega}_{km}.\vec{n}\right|\sin\theta_m\,\sin(\Delta\theta)\,\Delta\varphi \qquad (6)$$

The partial intensities $I_j(\vec{u},s)$ at a point M of the medium is computed by using:

$$I_j(\vec{u},M) = I_j(\vec{u},P)\exp(-kj(E)Xp\ell + [1-\exp(-k_j(E)Xp\ell)]$$

$$a_j(E)\frac{\sigma T^4(E)}{\pi} \qquad (7)$$

Where the partial intensity at point P is deduced by interpolation between B and C:

$$I_j(\vec{u},P) = \tan\theta\frac{\Delta x}{\Delta y}\,I_j(\vec{u},B) + \left(1-\tan\theta\frac{\Delta x}{\Delta y}\right)\,I_j(\vec{u},C) \qquad (8)$$

## III. CONVECTIVE HEAT TRANSFER MODELING

We consider a laminar steady flow of non-scattering ($H_2O$-$CO_2$) gas mixtures, different inclination angles are considered. The buoyancy-opposed flow corresponds to the cooled ascending flow (negative Grashof Number). In the formulation of heat transfer and fluid flow without radiation, the usual boundary layer approximations are made.

The mass, momentum and energy balance equations are given respectively by:

$$\nabla.(\rho\vec{V}) = 0$$

$$\nabla.(\rho\vec{V}\vec{V}) = -\nabla p + \rho\vec{g} + \nabla.\nabla(\mu\vec{V}) \qquad (9)$$

$$\nabla.(\rho h\vec{V}) = -\nabla.\vec{q}_{cd} - \nabla.\vec{q}_r$$

Where $\vec{V}(u,v)$ is the velocity vector at a given point M(x, r). h, ρ and μ designate the enthalpy per unit mass, the temperature-dependent density and the viscosity, respectively. $\vec{q}_r$ and $\vec{q}_{cd}$ are respectively the radiative flux vector and the conductive flux vector.

The system of equations formulated above is written in cylindrical coordinates and is assumed parabolic in x direction. Thus no flow boundary conditions are required at the outlet section of the computational domain.

The boundary conditions are summarized in Fig. 1, where u and v are the axial and radial velocity components, respectively h, ρ, μ, λ and Cp designate the enthalpy per unit mass, the temperature-dependent density, viscosity, thermal conductivity and specific heat at constant pressure, respectively, and $\vec{q}_r$ is the radiative vector flux. The system of equations formulated above is written in cylindrical coordinates and is assumed parabolic in x direction. Thus no flow boundary conditions are required at the outlet section of the computational domain.

No flow boundary conditions are required at the outlet section of the computational domain since the problem under consideration is assumed parabolic in x direction.

The significant temperature difference imposed between the walls and the gas requires the use of temperature-dependent fluid properties.

The radiative source term ( $\nabla\vec{q}_r$ ) or the volumetric radiative power dissipated in the medium for a given section i is first calculated from a one-dimensional temperature field. In practice, for 1D radiative transfer calculations the same numerical procedure is used with six discretized axial sections and a very large spacing between these sections in comparison with the tube diameter.

In a second step, an iterative procedure is undertaken. Two-dimensional radiative powers and fluxes are calculated from the 2-D temperature field and then the flow and energy equations are solved using the marching procedure and the computed radiative powers as source terms. The required number of global iterations depends on the optical thickness of the medium. A constant mesh size is used for the radial direction and a variable one in the axial direction. This mesh size increases far from the entrance, which allows a higher accuracy for the temperature and velocity fields in the thermal entrance region where steep axial gradients occur. Typically, we use 160 radial points and 20000 axial ones to compute the flow field. Such refined grid is not required for 2-D radiation calculations; numerical tests show that typically 40x100 nodes are sufficient for the above configuration. Numerical linear interpolations and extrapolations are used to convert the results from the convective grid mesh to the radiative one and vice versa.

## IV. RESULTS AND DISCUSSION

The flow and heat transfer mechanisms are governed by a great number of parameters resulting from the temperature dependent fluid properties and its complex absorption spectra. Consequently, the results cannot be gathered in non-dimensional form. Although, several computations have been conducted for various combinations of these parameters, we limit ourselves, in this presentation, to some examples to illustrate the interaction between thermal radiation and forced convection. The considered gas is $H_2O$-$CO_2$ mixture at atmospheric pressure with uniform molar fraction throughout the medium.

The calculations have been carried out either by including 2-D radiative transfer or for the same flow with the medium considered as transparent. The Reynolds numbers were chosen sufficiently large in order to neglect the effects of axial diffusion. The effects of radiative transfer on temperature, velocity developments, and on bulk temperature are discussed. Several calculations have been carried out for both symmetric and asymmetric heated or cooled gas mixture and for various parameters as wall emissivities, radii $R_1$ and $R_2$ gas inlet temperature, wall temperature values, etc...

We consider the $H_2O$-$CO_2$ mixture entering an annular duct defined by $R_1$=0.8m, $R_2$=0.16m, $L_0$=0.3m and a total length L=2.6m. The gas at the inlet section (x=0) is at temperature $T_0$=400K and the wall temperature is $T_w$=1000K. The inlet Reynolds number, based on $2(R_2-R_1)$ is equal to 1000 and the inlet velocity profile is a fully developed one at $T_0$. All the cylindrical walls are assumed to be black.

The performance of the numerical procedure was evaluated by comparison of ours predicted temperature profiles with numerical results of Echigo et al. [14] and Selçuk et al. [15]. For this purpose, the same physicals conditions used by these authors are selected. So, we considered a laminar flow of $CO_2$ in a circular duct with a diameter equal to 20cm. the inlet and wall temperatures are respectively $T_0$=500K and $T_w$=1500K. The optical thickness in radial direction was equal to 2.

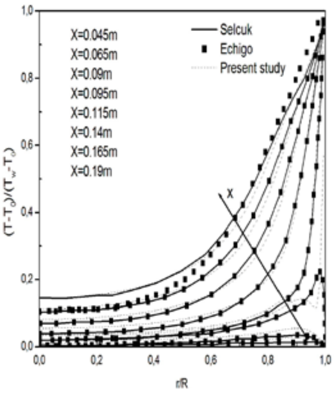
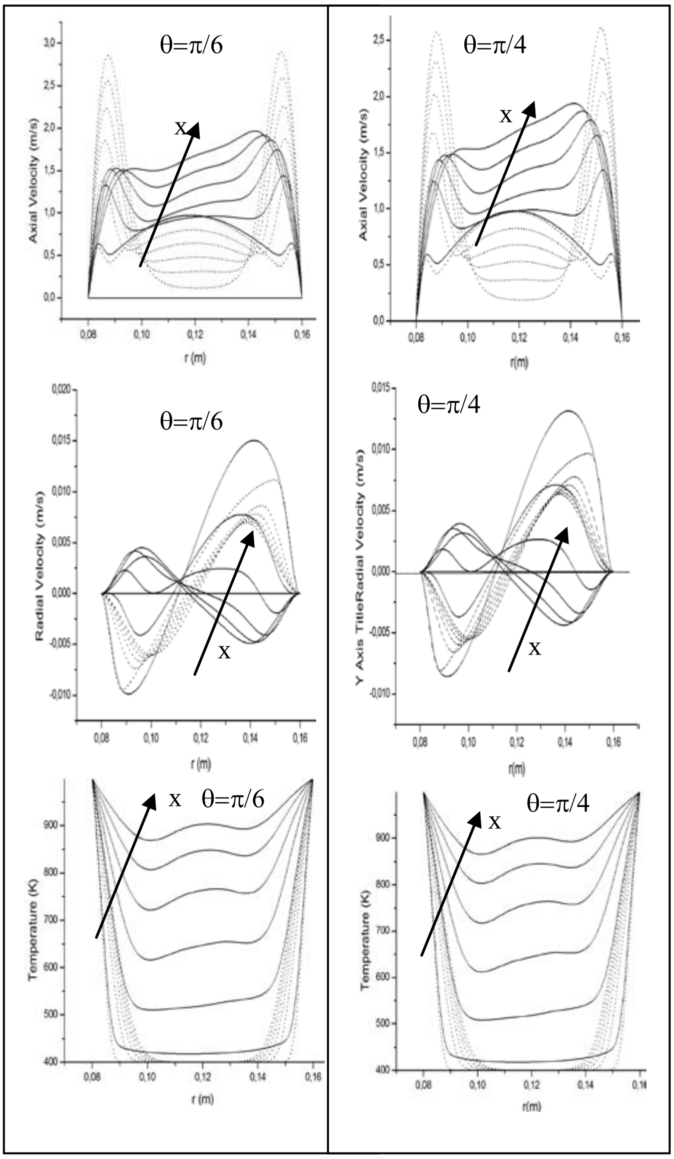


Fig.3 Validation of the coupled code

Fig. 3 shows the variation of the temperature profiles computed under these conditions at some position along the duct. Ours results are agreement with those of Echigo et al. [14] and the results of Selçuk et al. [15].



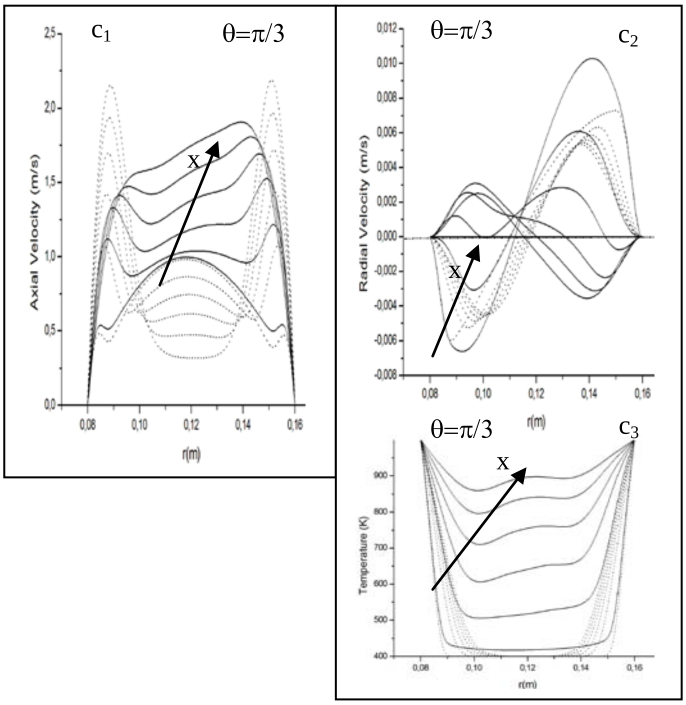


Fig.4 Axial Velocity (a1,b1,c1), radial Velocity (a2,b2,c2) and temperature (c1,b3,c3) profiles.

Fig.4 shows the axial velocity profiles ($a_1$), ($b_1$) and ($c_1$), the radial velocity profiles ($a_2$), ($b_2$) and ($c_2$) and temperature profiles ($a_3$), ($b_3$) and ($c_3$) for different cross sections of the duct (x=0.4; 0.8; 1.2; 1.6; 2 and 2.4m) and for various angular inclinations ($\theta = \pi/6; \pi/4$ and $\pi/3$). Both cases of calculations with and without thermal radiation are illustrated. For comparison purposes, calculations have been done for the same gas considered as transparent (dashed lines) with the presence of buoyancy forces (mixed convection). Coupled modes (solid lines) correspond to calculations for thermal radiation with simultaneous buoyancy and forced convection.

For non-radiating gases, results indicate that the axial velocity profiles are characterized by a strong acceleration close to the walls due to buoyancy effects. The evolution of the axial velocity profiles when accounting for radiative transfer are represented in Fig. 4.a1,b1,c1. When the flow goes downstream, the effect of radiation becomes significant and tends simultaneously to reduce the velocity near the wall and to increase it in the center of the duct. In fact, radiative transfer from the walls acts at distance and leads to a more pronounced heating in the central region of the duct. The flow is then accelerated in this region and slightly decelerated near the wall. This behavior shows that radiation tends to reduce buoyancy effects. Figures 4a2, 4b2 and 4c2 illustrate the evolution of the radial velocity.

Figures 4a1, 4b1 and 4c2 illustrate the evolution of the temperature profiles without and with radiation, respectively. The evolution of the temperature profile towards the walls temperature is obviously faster with radiation than without radiation.

## V. CONCLUSION

Numerical simulation of radiating laminar flows of emitting and absorbing gases inside an inclined concentric annulus is presented. The interaction of thermal radiation with the other modes, the non-gray radiative behavior of gases and the multidimensional nature of radiative transfer are considered in this simulation. The developed numerical method transforms the elliptic radiative problem to a series of parabolic ones.

Interaction between thermal radiation and mixed convection in laminar ascending radiating gas flows in an inclined concentric annulus has been studied and simulated.

For heated gases, it is shown that in one side the radiation tends to reduce the velocity distortion effect of buoyancy and in the other side radiation enhances heat transfer and speeds up the evolution of bulk temperature towards temperatures of the walls.

In the heating case, the propagation of radiation towards the central region of the duct tends to increase the centerline velocity and decreases the friction factor.

A natural extension of this investigation will be the development of a fully coupled elliptic model which will be able to predict more precisely the critical limits of the reverse flow occurrence in presence of radiation.

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