Volumetric and wall non grey gas entropy creation in a cylindrical enclosure

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Abstract: - We analyse a numerical computation of entropy generation by radiative heat transfer through an emitting-absorbing non-grey gas, confined in a cylindrical enclosure. The "statistical narrow band correlated-k" model is associated to the "Ray Tracing" method to deduce the radiative properties of the gas and to solve the radiative transfer equation. We present the impact of boundary conditions and cylinder dimensions on the entropy generation.

Key-Words: - Entropy, Emission, Absorption, Non-grey gas, Ray tracing, SNBCK model

1 Introduction

The assessment of energy systems is related to the use of energy, which is based on the first law of thermodynamics, reflecting the principle of energy conservation. But energy analysis has many weaknesses that can be overcome with an alternative thermodynamic analysis method. Exergy analysis, based on the second law, is a well-known tool for the evaluation and optimization of energy systems, and is used as a benchmark for energy efficiency and rational use of natural resources. Exergy analysis continues to receive considerable attention because of its importance in many practical applications like electrical generation, cogeneration, transportation, heating and cooling, and chemical and metallurgical processing. Rosen [1] affirmed that exergy analysis provides useful information, which can have direct implications on process designs and improvements. He declared also that exergy methods help in understanding and improving not only efficiency, but also environmental and economic performance as well as sustainability. Rosen [2] detailed in his study the advantages of exergy analysis over energy analysis from a combined thermodynamic and economic perspective. He [3] presented an illustration to demonstrate the importance of size considerations in applications of exergy. He concluded that an understanding of these size considerations can help guide users of exergy analysis to the most suitable manner of application for a given system.

The objective of this paper is to analyze the effect of thermal radiation on entropy generation minimization for high-temperature systems, since radiation represents the dominant form of heat transfer in many applications such as solar collectors, boilers, furnaces and other combustion systems and represents an important source of entropy creation, contributing significantly to inefficiency [4]. Planck [5] was the first investigator who implicated radiative entropy production in his researches, which deal with irreversibility provided by interaction of light and matter. The first formulation of the transfer equation for the radiative entropy was developed by Wildt [6] in his study of thermodynamic aspects of radiative transfer processes. The irreversibility of the interaction of radiation with matter was studied by Oxenius [7] by considering a stationary isothermal gas that emits the resonance line of atoms with only two discrete energy levels. The analysis of the general form of the entropy production was developed by Kroll [8], starting from basic statistical relations. In this study, entropy production due to emission, absorption and scattering of radiation is showed to be a form bilinear in generalized thermodynamic fluxes and forces. Wright et al [9] determined the significant error that is introduced in second law analysis when the heat conduction relation is used for thermal radiation transfer. In fact, the correct evaluation of thermal radiation entropy is important when determining second-law performance of energy conversion devices. They obtained simple approximate expressions for calculating the entropy of grey radiation emission, as the exclusive use of numerical integration is laborious. Caldas and Semiao [4] approached an issue of entropy generation by radiative transfer in participating media from the view-points of a numerical simulation using standard radiative heat transfer techniques, to deduce the radiant entropy transfer equation. The only source of irreversible entropy generation is assumed to be that due to interaction between radiation and matter, entropy fluxes at the walls are not analyzed. They verified that the entropy change in the radiation side is much larger than that on the matter side. They also concluded that entropy generating through emission and absorption is much larger than that produced through scattering.

Liu and Chu [10] showed that the traditional formulas of entropy generation rate for heat transfer generally cannot be used to calculate the local entropy generation rate of radiation heat transfer. They considered three counterexamples to conclude , that only in optically extremely thick situations, the traditional formula of entropy generation rate for heat transfer can be approximately used to estimate the local radiative entropy generation rate. Liu and Chu [11] extended the numerical simulation method of radiative entropy generation in participating media presented by Caldas and Semiao [4] to analyze the radiative entropy generation in the enclosures filled with semi-transparent media. They showed that this numerical simulation which can be used in the entropy generation analysis of high-temperature systems must be implemented on the base of spectral integration. Ben Nejma et al [12] developed a numerical computation to establish entropy generation profiles of combined non-grey gas radiation and forced convection through two parallel plates. Their model was applied by Mazgar et al [13] to analyze the entropy generation at the entrance region of a circular duct for a non-grey media. They presented both of local entropy generation distributions and global entropy production in the whole flow fields of the duct. Using the same modeling principles for determining the radiative properties of non-grey gas, Mazgar et al [14] analyzed the entropy generation for coupling thermal radiation and natural convection in a cylindrical and vertical disposition. They concluded that the radiative contribution enhances heat transfer in the central region of the flow, permits to accelerate the flow establishment and increases the evacuated mass flow rate. Based on the radiative entropy generation formula given in [4,11], Chu and Liu [15] studied the entropy generation of two-dimensional high-temperature confined jet flow. They carried out the computation of combined radiation and convection heat transfer, and the local entropy generation due to heat transfer and fluid friction is calculated as post-processed quantities with the computed data of velocity, temperature and radiative intensity. Makinde [16] has examined the effect of thermal radiation on the inherent irreversibility in a flow between two isothermal plates with optically thick medium whose viscosity varies. He showed that the decrease in fluid viscosity promotes both entropy generation rate and the dominant effect of heat transfer irreversibility in vicinities of the walls. He concluded also that, increasing the thermal radiation parameter inhibits the rate of entropy generation and the dominant effect of heat transfer irreversibility at the walls, while the dominant effect of irreversibility due to heat transfer in the centerline region of the flow is enhanced. Meanwhile, Chu and Liu [17] were based on the radiative exergy definition of Caudau to analyze the exergy of solar radiation. Recently, Agudelo and Cortés [18] presented the fundamental concepts about second law analysis of thermal radiation. He concluded that this theoretical basis is well established but its complex nature hinders the application to practical engineering systems. The objective of Makhanlall and Liu [19] in their study of entropy production analysis of swirling diffusion combustion processes is to map thermodynamic irreversibility in terms of entropy production for methane combustion. They showed that radiative heat transfer which is an important source of entropy production cannot be omitted for combustion systems. Makhanlall and Liu [20] analyzed entropy generation in a two-dimensional coupled natural convection and radiation heat transfer process. They concluded that evolvement of total entropy generation of the system with time from unsteady-state to steady-state is consistent with classical thermodynamic law. They performed also an exergy analysis for the coupled conduction radiation transfer with phase change in a semi-transparent, absorbing, emitting, anisotropic scattering, medium with constant thermodynamic properties [21]. They found that radiation exergy loss is significant in the high-temperature phase change process. Their results show that the total exergy loss increases with Biot number, single scattering albedo and wall emissivity. Recently, Makhanlall et al [22] presented a thermodynamic analysis of a high-temperature confined turbulent gas-jet. Their results showed that the exergy loss through the radiative entropy production is higher than that due to heat transfer by conduction and convection when the inlet gas temperature is high. They also found that in contrast to the conventional head loss coefficient, the exergy loss coefficient increases with inlet gas temperature, optical thickness and Plank number. Lately, Mokheimer [23] presented results of a parametric analysis of the entropy generation due to mixed convection in the entry-developing region between two differentially heated isothermal vertical plates. He introduced the entropy generation minimization via controlling the operating parameters and clearly identified the optimum buoyancy parameter at which entropy generation assumes its minimum under different operating conditions. Makhanlall et al [24] extended recently the second law analysis of steady-state radiative transfer in participating media carried out by Liu and Chu [25] to analyse the transient radiative transfer in semi-transparent absorbing, emitting and scattering media with uniform refractive index. This analysis can be used to study the performance of high temperature systems in which the transient radiative transfer is an important mode of heat transfer.

The radiative entropy creation through semi-transparent and non-grey media has not been adequately studied even less for a cylindrical geometry. In the present paper we study the entropy production for non-grey gas radiation in a cylindrical enclosure. The entropy production profiles are illustrated with a variety of boundary conditions. The radiative properties of water vapor and its spectral nature are modeled using the 'Ray Tracing' method through S6 directions, associated with the "Statistical Narrow Band Correlated-k" SNBCK model. The implementation of the SNBCK model for radiation computation described and employed by Liu et al. [26] and recently used by Ben Nejma et al [12] and Mazgar et al [13,14], represents an effective approach to avoid the expensive on-line inversion of the cumulative distribution function.

2 Problem Formulation

Consider over heated water vapor, an absorbing-emitting non-grey gas confined in a cylindrical enclosure with isothermal boundaries as shown in Fig.1.

To solve the radiative transfer equation, we have applied the SNBCK method using the 4-point gauss quadrature, known as the SNBCK4 model.

$$\frac{dI_\nu^i(r,\vec{\Omega})}{dx} = -\kappa_\nu^i . I_\nu^i(r,\vec{\Omega}) + \kappa_\nu^i . I_\nu^b(T) \qquad (1)$$

$$I_k = exp\left[-\kappa_\nu^i . l_{j_{k+1\to k}}(\vec{\Omega})\right] I_{k+1}(r,\vec{\Omega}) + \left[1 - exp\left[-\kappa_\nu^i . l_{j_{k+1\to k}}(\vec{\Omega})\right]\right] I_\nu^b(T) \qquad (2)$$

Where $l_{j_{k+1\to k}}(\vec{\Omega})$ is the optical path (Fig.2), calculated with:

$$l_{j_{k\to k+1}}(\vec{\Omega}) = \left| \frac{\sqrt{(1-\eta^2) r_{k+1}^2 - r_j^2 . \mu^2} - \sqrt{(1-\eta^2) r_k^2 - r_j^2 . \mu^2}}{1-\eta^2} \right| \qquad (3)$$

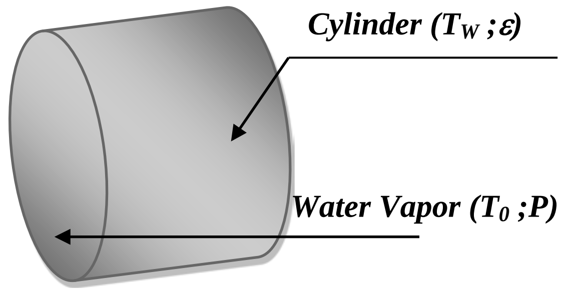


Fig.1 Geometry and boundary conditions

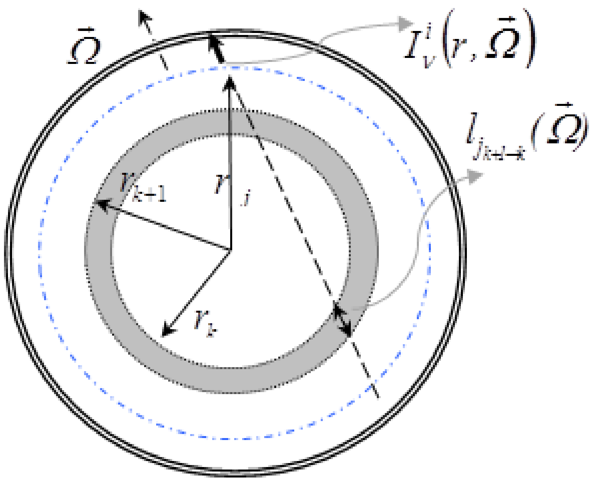


Fig.2 Optical path

The boundary condition of radiative transfer is given as:

$$I_\nu^i(r=R,\vec{\Omega}) = \frac{1-\varepsilon}{\pi} \int_{\vec{\Omega}' / \vec{\Omega}'.\vec{n}<0} I_\nu^i(r=R,\vec{\Omega}') \mu(\vec{\Omega}') d\Omega' + \varepsilon . I_\nu^b(T_W) \qquad (4)$$

3 Radiative Entropy Production

Numerical results show that radiative entropy generation cannot be omitted in high-temperature systems, in which radiation is the dominant mode of heat transfer. This work presents a numerical computation of radiative entropy generation through an absorbing-emitting non gray-gas radiation, confined into a cylindrical enclosure. In addition to the volumetric entropy production due to absorption and emission, the wall entropy creation of thermal radiation is taken into account.

3.1 The Volumetric Entropy Generation

Caldas and Semiao [4] and Liu and Chu [11] used (5) to calculate spectral, directional, local and volumetric entropy production of thermal radiation,

$$s_{V\nu}(\vec{\Omega}) = -\kappa_\nu\left[I_\nu{}^b(T) - I_\nu(\vec{\Omega})\right]\left[\frac{1}{T} - \frac{1}{T_\nu(\vec{\Omega})}\right] \quad (5)$$

$$T_\nu(\vec{\Omega}) = \frac{h.\nu}{K.Ln\left[\dfrac{2.h.\nu^3}{c^2.I_\nu(\vec{\Omega})} + 1\right]} \quad (6)$$

As shown by Ben Nejma et al [12] and Mazgar et al [13,14], and as in the case of the CK model, the use of the SNBCK4 method gives the local volumetric radiative entropy production for non-grey gases. In fact, the expression of the spectral and directional radiative intensity corresponding to a spectral band $\Delta\nu$ will be expressed as:

$$\bar{I}^{\Delta\nu}(\vec{\Omega}) = \sum_{i=1}^{n} w^i.I_\nu^i(\vec{\Omega}) \quad (7)$$

This equation will give the expression of the radiative source term:

$$\overline{div(\vec{q}_\nu(\vec{\Omega}))}^{\Delta\upsilon} = \sum_{i=1}^{n} w^i.\kappa_\nu^i\left[I_\nu^0 - I_\nu^i(\vec{\Omega})\right] \quad (8)$$

$$div(\vec{q}) = \sum_{bands}\int_{4\pi}\sum_{i=1}^{4} w^i.\kappa_\nu^i\left(I_\nu{}^b - I_\nu^i(\vec{\Omega})\right)d\Omega\Delta\nu \quad (9)$$

The expression of the local, spectral and directional volumetric radiative entropy production to non-gray gases will be then:

$$s_{V\nu}(r,\vec{\Omega}) = -\sum_{i=1}^{4} w^i.\kappa_\nu^i.\left[I_\nu^b(T) - I_\nu^i(r,\vec{\Omega})\right]\left[\frac{1}{T} - \frac{1}{T_\nu^i(r,\vec{\Omega})}\right] \quad (10)$$

The total volumetric radiative entropy production becomes:

$$s_V(r) = -\sum_{bands}\int_{\Omega}\sum_{i=1}^{4} w^i.\kappa_\nu^i.\left[I_\nu^b(T) - I_\nu^i(r,\vec{\Omega})\right]\left[\frac{1}{T} - \frac{1}{T_\nu^i(r,\vec{\Omega})}\right]d\Omega\Delta\nu \quad (11)$$

And the global volumetric radiative entropy production is given by:

$$S_V = 2\pi\int_{r=0}^{r=R} s_V(r).r.dr \quad (12)$$

3.2 The wall Entropy Generation

The spectral and directional wall entropy production of thermal radiation can be calculated according to Liu and Chu [11] and Chu and Liu [15], and as shown by Mazgar et al [14]:

$$s_{W\nu} = \int_{4.\pi}\sum_{i=1}^{4} w^i\left[\frac{I_\nu^i(r=R,\vec{\Omega})}{T_W} - L_\nu(I_\nu^i(r=R,\vec{\Omega}))\right]\mu(\vec{\Omega})d\Omega \quad (13)$$

The wall entropy production of radiative heat transfer will then be given as:

$$s_W = \sum_{bands}\int_{4.\pi}\sum_{i=1}^{4} w^i\left[\frac{I_\nu^i(r=R,\vec{\Omega})}{T_W} - L_\nu(I_\nu^i(r=R,\vec{\Omega}))\right]\mu(\vec{\Omega})d\Omega\Delta\nu \quad (14)$$

So the total wall radiative entropy production is given by:

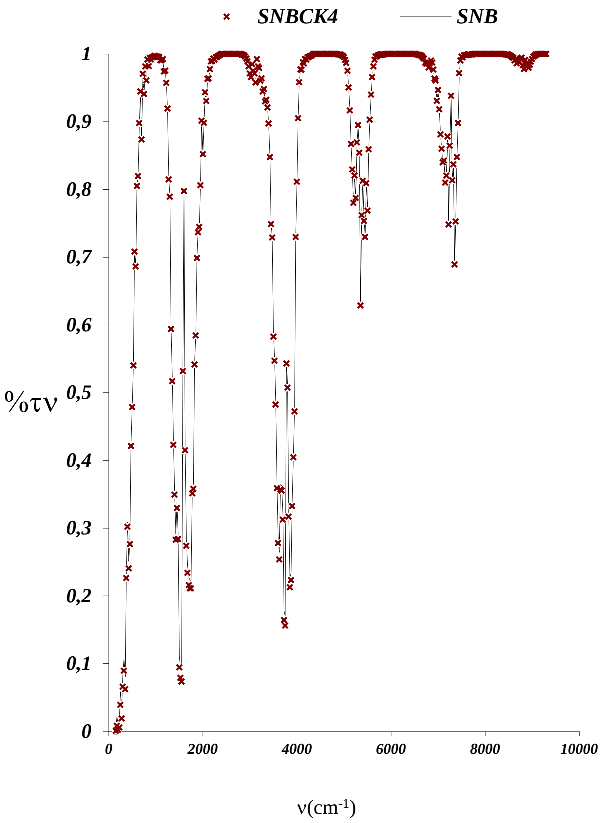
$$S_W = 2\pi R s_W \quad (15)$$

The global radiative entropy generation is then calculated with:

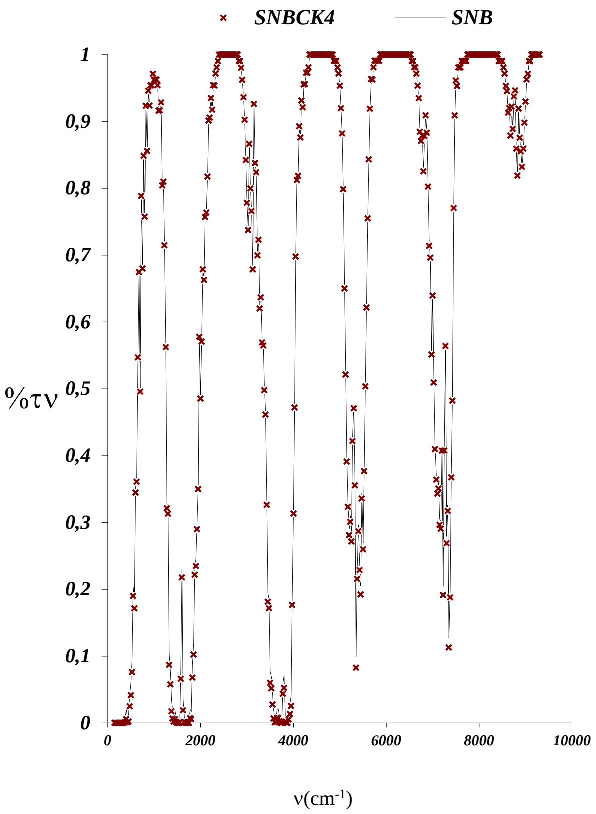
$$S_t = S_V + S_W \quad (16)$$

In order to validate the SNBCK model, the absorption spectra of the water steam using both the SNB and the SNBCK models is plotted. Fig.3 shows that our implementation is well.

Also to validate the radiative model, we consider the case of two concentric spheres. The space that they wrap is filled with a semi-transparent medium with an absorption coefficient equal to unity and we do not consider radiative incidence inside borders. In Fig.4 we plotted the normalized net radiation flux at the outer surface as a function of radius ratio. One can note that the present numerical results are very close to those of Chen et al [27]. The relative error does not exceed 6%.



T=500K P=1atm l=0.1m $\Delta\nu$=25cm^{-1}



T=500K P=1atm l=1m $\Delta\nu$=25cm^{-1}

Fig.3 Absorption spectra of vapour

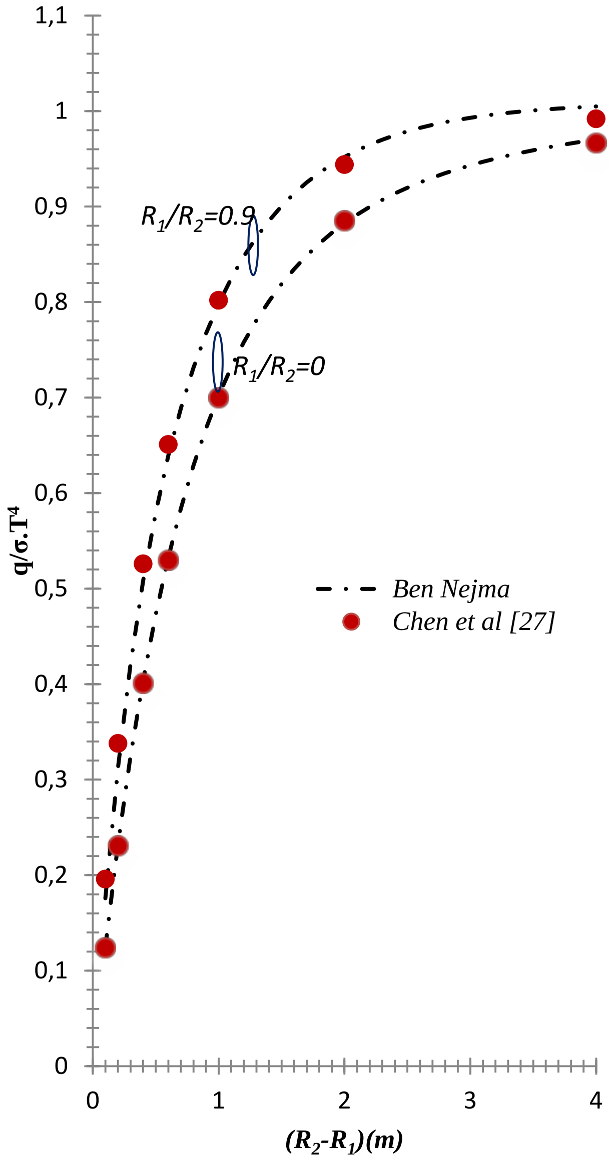


Fig.4 Validation of the radiative model

4 Results and Discussions

A selected set of graphical results is presented in Figs.5-9 to provide an easy understanding of the influence of thermal and geometrical parameters on entropy generation profiles.

In Figs.5-6, we can show the variations of the volumetric radiative entropy production and the radiative source term in heating configuration. We can distinguish uniform profiles inside the enclosure undoubtedly because the medium is optically thick. However, the volumetric radiative entropy production increases remarkably in the vicinity of walls in accordance with the radiative source term profile.

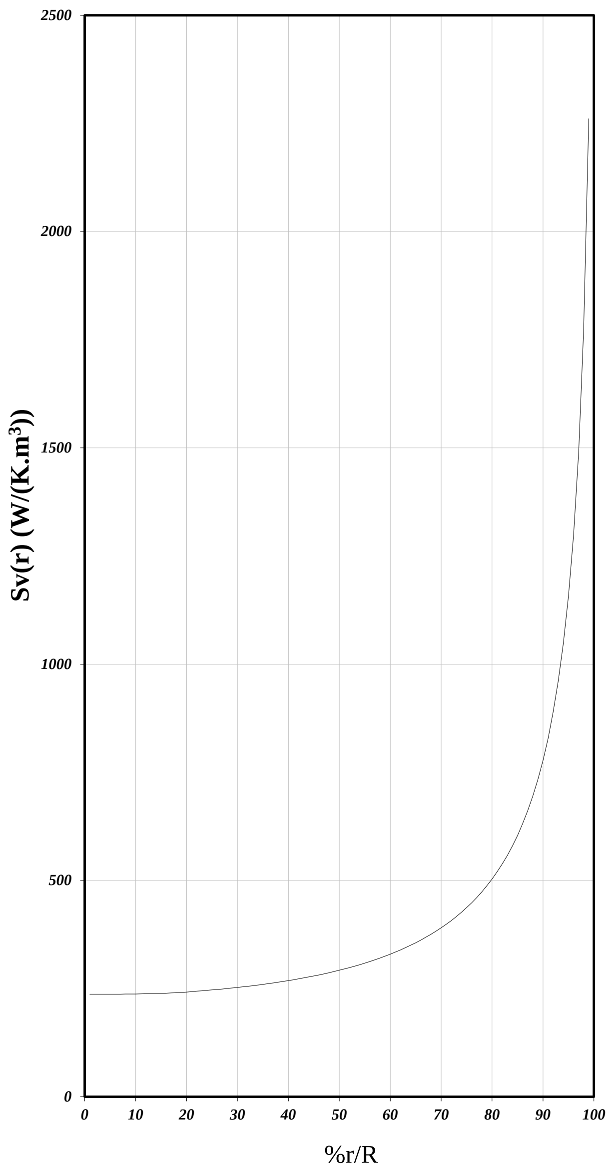


Fig.5 Volumetric radiative entropy generation
P=1atm T_0=300K T_W=1000K R=0.1m $\Delta\nu$=25cm^{-1}
ε=1

The effects of wall and gas temperature on the volumetric radiative entropy production, on the wall entropy generation of thermal radiation and on the global radiative entropy creation, are given in Fig.7. These variations are given in both of heating and cooling configurations. It can be showed that the volumetric and the wall radiative entropy production have comparable values which cannot be neglected. Compared to the volumetric radiative entropy creation in heating configuration, the wall entropy generation of thermal radiation seems to be the smaller while it is more developed in case of cooling. We can signal also that decreasing the temperature difference between gas and boundaries results in a decrease in the difference between the volumetric and the wall radiative entropy production, which is more developed in case of heating.

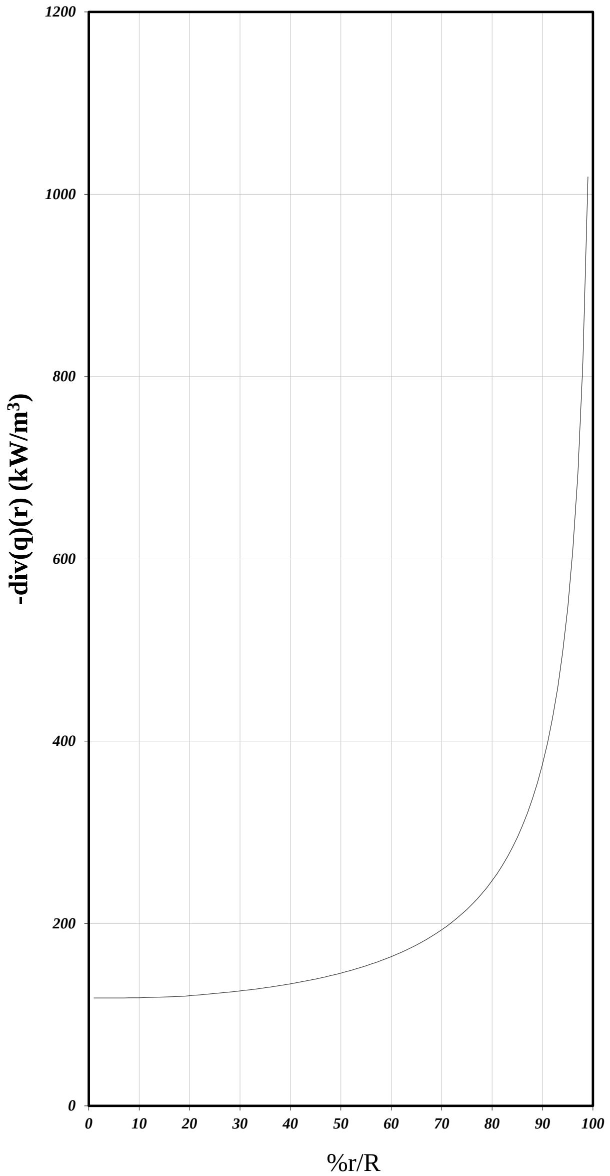
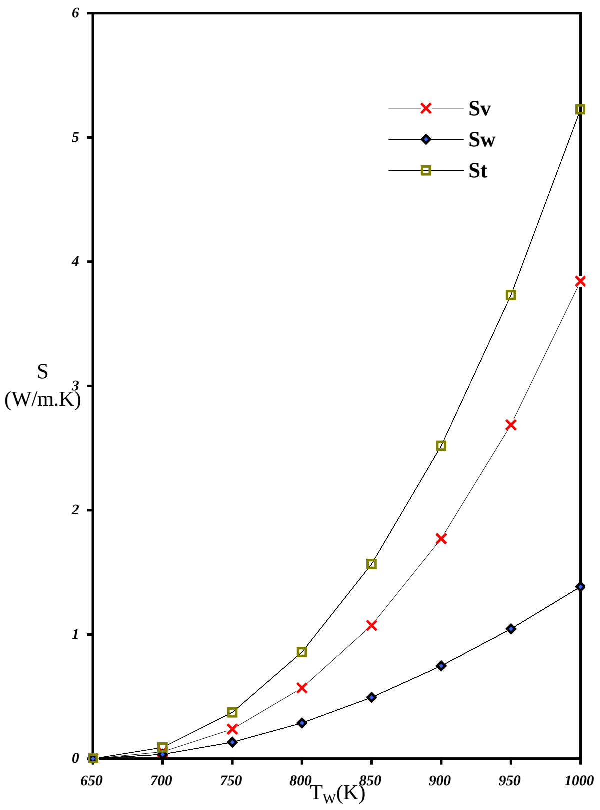
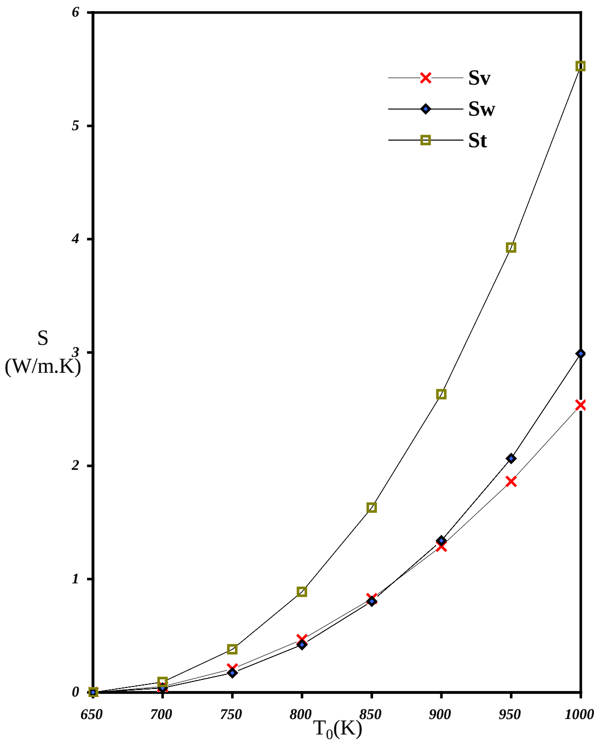


Fig.6 Radiative source term
P=1atm T_0=300K T_W=1000K R=0.1m $\Delta\nu$=25cm^{-1}
ε=1

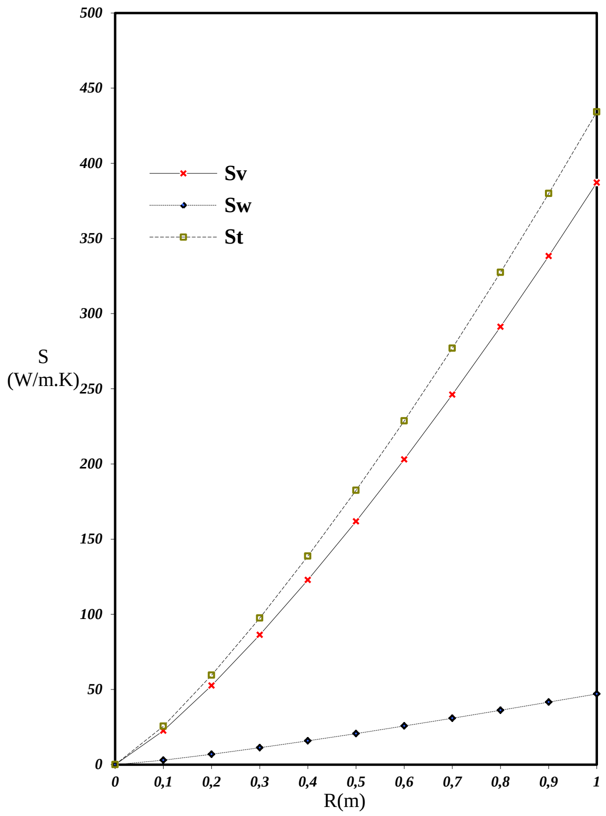


T_0=650K P=2atm R=0.1m $\Delta\nu$=25cm^{-1} ε=1

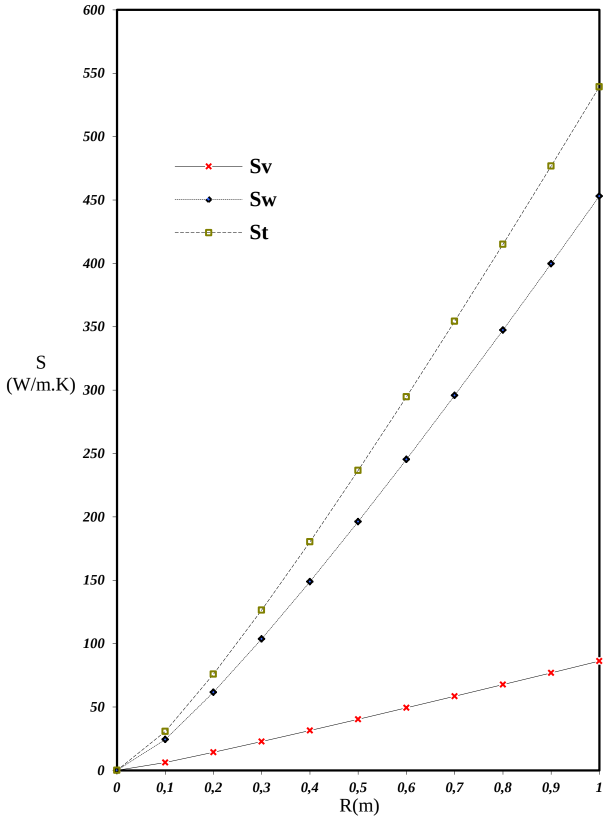


T_W=650K P=2atm R=0.1m $\Delta\nu$=25cm^{-1} ε=1

Fig.7 Effect of wall and gas temperatures on radiative entropy production

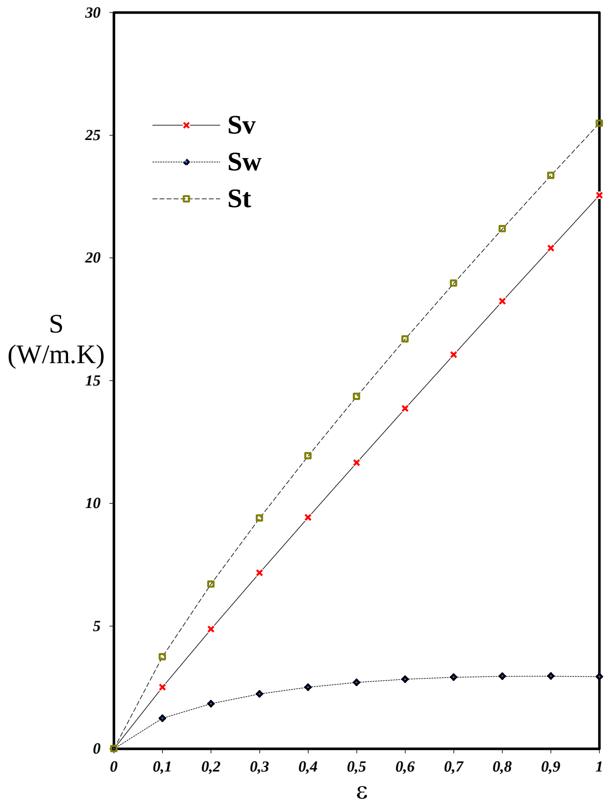


T_0=300K T_W=1000K P=2atm $\Delta\nu$=25cm^{-1} ε=1

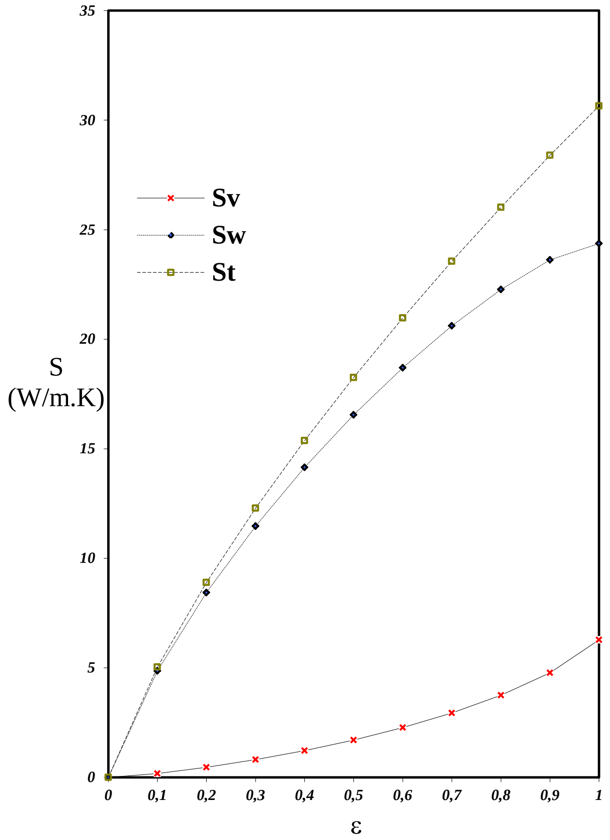


T_0=1000K T_W=300K P=2atm $\Delta\nu$=25cm^{-1} ε=1

Fig.8 Effect of radius on radiative entropy production



T_0=300K T_W=1000K R=0.1m P=2atm Δν=25cm^{-1}



T_0=1000K T_W=300K R=0.1m P=2atm Δν=25cm^{-1}

Fig.9 Effect of emissivity on radiative entropy production

In Fig.8, we can show the effect of radius on the radiative entropy production in heating and cooling conditions. As shown, decreasing the radius reduce the radiative entropy production. This is due, not only to the decrease in wall surface but also to the reduced volume generated by the cylindrical enclosure. Compared to volumetric radiative entropy creation, the wall entropy generation of thermal radiation is less developed in heating configuration and more developed in case of cooling. It can be seen also, that the volumetric radiative entropy production given in heating mode, is nearly confused with the profile of global entropy production.

Computation results using emissivity variation are plotted in Fig.9. It is noted that the volumetric radiative entropy creation shows practically a linear profile in heating mode while the wall entropy generation of thermal radiation is practically constant in the same configuration. Moreover, the wall entropy production of thermal radiation strongly varies in case of cooling, where it is more developed compared to the volumetric radiative entropy creation. In addition, the volumetric radiative entropy generation is practically absent for values of emissivity less than 0.2.

5 Conclusion

In this paper, the numerical calculation of radiative entropy generation through a participating media confined in a cylindrical enclosure is investigated. The volumetric and the wall radiative entropy creation are illustrated with a variety of geometrical and thermodynamic parameters. Based on the results we can conclude that the volumetric radiative entropy production is more developed in heating configuration while the wall radiative entropy generation is more developed in case of cooling.

Nomenclature:

c light velocity (m.s^{-1})
h Plank's constant (h=6.626 x 10^{-34} Js)
I radiative intensity (W.m^{-2}.sr^{-1})
K Boltzmann's constant (K=1.38 x 10^{-23} JK^{-1})
L radiative entropy intensity (W.m^{-2}.sr^{-1} K^{-1})
P pressure (atm)
q radiative heat flux (W.m^{-2})
R cylinder radius (m)
r radial position (m)
S total entropy production (W.K^{-1})
s_v local volumetric entropy production (W.K^{-1}m^{-3})

s_W local wall entropy production ($W.K^{-1}m^{-2}$)
T_0 vapour temperature (K)
T_W wall temperature (K)
w weight parameter
l optical path (m)

Greek symbols
κ absorption coefficient (m^{-1})
τ trasmittivity
ε wall emissivity
μ,ξ,η director cosines
$\vec{\Omega}$ ray direction
$d\Omega$ elementary solid angle around $\vec{\Omega}$
$\Delta\nu$ spectral resolution ($\Delta\nu = 25 cm^{-1}$)

Subscript
ν spectral
V volumetric
W wall
t global

Superscript
b black body
i grey gas associated

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