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Radiative entropy generation in a gray absorbing, emitting, and scattering planar medium at radiative equilibrium

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ABSTRACT

Radiative entropy generation through a gray absorbing, emitting, and scattering planar medium at radiative equilibrium with diffuse-gray walls is investigated. The radiative transfer equation and radiative entropy generation equations are solved using discrete ordinates method. Components of the radiative entropy generation are considered for two different boundary conditions: two walls are at a prescribed temperature and mixed boundary conditions, which one wall is at a prescribed temperature and the other is at a prescribed heat flux. The effect of wall emissivities, optical thickness, single scattering albedo, and anisotropic-scattering factor on the entropy generation is attentively investigated. The results reveal that entropy generation in the system mainly arises from irreversible radiative transfer at wall with lower temperature. Total entropy generation rate for the system with prescribed temperature at walls remarkably increases as wall emissivity increases; conversely, for system with mixed boundary conditions, total entropy generation rate slightly decreases. Furthermore, as the optical thickness increases, total entropy generation rate remarkably decreases for the system with prescribed temperature at walls; nevertheless, for the system with mixed boundary conditions, total entropy generation rate increases. The variation of single scattering albedo does not considerably affect total entropy generation rate. This parametric analysis demonstrates that the optical thickness and wall emissivities have a significant effect on the entropy generation in the system at radiative equilibrium. Considering the parameters affecting radiative entropy generation significantly, provides an opportunity to optimally design or increase overall performance and efficiency by applying entropy minimization techniques for the systems at radiative equilibrium.

1. Introduction

Entropy generation is common in all kinds of heat transfer processes and causes loss of the available work. Hence, consideration of the entropy generation or the second law of thermodynamics analysis results in improving overall performance and efficiency of the thermal equipment and systems. It is readily comprehensible that an apparatus with less entropy generation destructs less available work. Bejan [1-3] investigated entropy generation and presented optimization method of the entropy generation minimization.

Thermal radiation is the dominant mode of heat transfer in the majority of high-temperature systems such as furnaces, boilers and heat exchangers; therefore, dealing with entropy generation through radiative transfer process is significant to evaluate second-law performance of these systems correctly. Max Planck [4] was the first to investigate the interaction of light and matter with respect to its irreversibility. Arpaci [5,6] and Arpaci and Esmaeeli [7] evaluated entropy generation through radiative heat transfer by the formula of the entropy generation rate for conductive heat transfer, which is compatible with an optically extremely thick medium. Wright et al. [8] dealt with radiative entropy transfer and generation in engineering systems. Their analysis was only accounting for entropy generation in solid boundaries. Moreover, Wright et al. [9,10] studied radiative exergy flux between surfaces. Caldas and Semiao [11], for the first time, derived the formulation of radiative entropy generation through participating media by developing the radiative entropy intensity introduced by Planck [4]. They presented a numerical simulation method, which is compatible with standard radiative transfer calculations such as DOM (discrete ordinates method). Liu and Chu [12] extended this method to analyze radiative entropy generation in enclosures filled with semitransparent media. In addition, they obtained radiative entropy generation rate on the surfaces. Liu and Chu [13] analyzed entropy generation through one-dimensional absorbing, emitting, and isotropic scattering gray medium with specified temperature field bounded by two isothermal blackbody plates.

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Nomenclature

A_1	Linear-anisotropic scattering factor
c	Speed of light [ms^{-1}]
D	Distance between plates [m]
h	Planck's constant (h = 6.626 × 10^{-34} [Js])
$I_{b,\lambda}$	Spectral radiative intensity of the blackbody [$\text{Wm}^{-2}\text{Sr}^{-1}\mu\text{m}^{-1}$]
I_λ	Spectral radiative intensity [$\text{Wm}^{-2}\text{Sr}^{-1}\mu\text{m}^{-1}$]
k	Boltzmann's constant (k = 1.38 × 10^{-23} [JK^{-1}])
L_λ	Spectral radiative entropy intensity [$\text{Wm}^{-2}\text{Sr}^{-1}\mu\text{m}^{-1}\text{K}^{-1}$]
$\hat{n}_w$	Unit outward normal vector of boundary wall
q_R	Radiative heat flux [Wm^{-2}]
q_w	Radiative heat flux at wall [Wm^{-2}]
$\vec{r}$	Spatial position vector
$\hat{s}, \hat{s}'$	Direction vector
$\dot{S}'''_{ae}$	Local radiative entropy generation rate due to medium absorption and emission processes [$\text{WK}^{-1}\text{m}^{-3}$]
$\dot{S}'''_{s}$	Local radiative entropy generation rate due to scattering processes [$\text{WK}^{-1}\text{m}^{-3}$]
$\dot{S}''_{ae}$	Radiative entropy generation rate of the planar medium due to medium absorption and emission processes [$\text{WK}^{-1}\text{m}^{-2}$]
$\dot{S}''_{s}$	Radiative entropy generation rate of the planar medium due to scattering processes [$\text{WK}^{-1}\text{m}^{-2}$]
$\dot{S}''_{w1}$	Radiative entropy generation rate due to radiation processes at opaque solid wall 1 [$\text{WK}^{-1}\text{m}^{-2}$]
$\dot{S}''_{w2}$	Radiative entropy generation rate due to radiation processes at opaque solid wall 2 [$\text{WK}^{-1}\text{m}^{-2}$]
T	Temperature in the medium [K]
T_{w1}	Temperature of wall 1 [K]
T_{w2}	Temperature of wall 2 [K]

Greek symbols

ε	Wall emissivity
κ	Absorption coefficient [m^{-1}]
σ_s	Scattering coefficient [m^{-1}]
λ	Wavelength [μm]
τ_D	Optical thickness
Π	Dimensionless radiative entropy generation of the system
Π^{ae}	Dimensionless radiative entropy generation rate due to medium absorption and emission processes
Π^{s}	Dimensionless radiative entropy generation rate due to scattering processes
Π^{w1}	Dimensionless radiative entropy generation rate due to radiation processes at opaque solid wall 1
Π^{w2}	Dimensionless radiative entropy generation rate due to radiation processes at opaque solid wall 2
Φ	Scattering phase function
ω	Single scattering albedo
Ω	Solid angle [Sr]

They validated the results by classic thermodynamics' second law and showed that the traditional conductive entropy generation rate formula could not be used to evaluate entropy generation rate of radiative heat transfer. Zhang and Basu [14] paid attention to entropy generation between two diffuse-gray surfaces maintained at constant temperature. Nevertheless, their analysis was limited to radiative entropy transfer and generation between two surfaces without participating medium. Liu and Chu [15] deduced the radiative exergy transfer equation in the semitransparent medium. Wright [16] restated the Clausius inequality to have a general application for heat transfer involving radiative fluxes. Ben Nejma et al. [17] considered entropy generation through combined non-gray gas radiation and convection heat transfer between two isothermal parallel plates. Mazgar et al. [18] determined entropy generation through combined non-gray gas radiation and natural convection in an isothermal and vertical pipe. Makhanlall et al. [19] considered the second-law analysis of the transient radiative transfer processes. They concerned an application of diffuse pulse radiation transfer in an absorbing, non-emitting, and isotropically scattering medium between two isothermal parallel plates. Bright and Zhang [20] paid attention to second law analysis of phonon heat conduction in thin film between two black walls. They evaluated entropy generation from phonon radiative transfer. Agudelo and Cortés [21] reviewed all works associated with second-law analysis of the thermal radiation. Makhanlall [22] derived radiative entropy and exergy transfer equations for the gray gas-particle, two-phase medium. Makhanlall et al. [23] studied entropy generation due to combined convective and radiative heat transfer in solar collectors filled with a radiative participating gas. Aghanajafi et al. [24] studied entropy generation through combined convective and radiative heat transfer in a micro tube maintained at constant heat flux. The medium was considered optically thick; therefore, the entropy generation was evaluated by the conductive formula. Recently, Jarray et al. [25] analyzed entropy generation due to non-gray gas radiation through a concentric cylindrical annulus maintained at a constant temperature.

Having considered all the previous works, it is easily comprehensible that there is a negligence on the second-law analysis of thermal radiation in planar medium at radiative equilibrium, which is a good assumption in applications with extremely high temperatures, such as plasmas and nuclear explosions. In addition, there is a lack of discussion on mixed boundary conditions for two parallel plates, which one plate is at a prescribed temperature and the other is at a prescribed heat flux. The objective of the present study is to analyze the effect of the physical parameters such as wall emissivities, optical thickness, single scattering albedo, and anisotropic-scattering factor on the radiative entropy generation rates at solid walls and in the gray absorbing, emitting, and scattering planar medium at radiative equilibrium. Moreover, the effect of the physical parameters in two different boundary conditions, with a prescribed temperature at walls and mixed boundary conditions is considered. Eventually, it is anticipated that the results provide comprehensive insights into the effect of the participating medium and solid wall properties on the radiative entropy generation rate. Thus, the parametric analysis might make an opportunity to find that one of the parameters has a significant impression on the radiative entropy generation rate of the system at radiative equilibrium, which leads to enhancing devices performance practically.

2. Formulation

We obtain radiative intensity field by solving the radiative transfer equation (RTE), which is given for an absorbing, emitting, and scattering gray medium as follow [26]:

$$\hat{s}.\nabla I_\lambda\left(\vec{r},\hat{s}\right)=\kappa I_{b,\lambda}(\vec{r})-(\kappa+\sigma_s)I_\lambda\left(\vec{r},\hat{s}\right)+\frac{\sigma_s}{4\pi}\int_{4\pi} I_\lambda\left(\vec{r},\hat{s}'\right)\Phi\left(\vec{r},\hat{s}',\hat{s}\right)d\Omega' \tag{1}$$

where I_λ is spectral radiative intensity, κ is absorption coefficient, σ_s is scattering coefficient, Ω is solid angle, $\Phi(\vec{r},\hat{s}',\hat{s})$ is phase function, $\vec{r}$ is special position vector and $\hat{s}$ is directional vector. Eq. (1) is subject to the boundary condition given by the