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Radiative Exergy Transfer Equation

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Nomenclature

A = surface area of the opaque solid boundary
a_λ^A = spectral radiation exergy loss per unit surface
a_λ^V = spectral radiation exergy loss per unit volume
c = speed of light
$e_{M,\lambda}^A$ = local net exergy increment in the wall medium due to absorbing spectral radiation heat
$e_{R,\lambda}^A$ = local net increment of spectral radiation exergy in the radiative field at the opaque wall
$e_{M,\lambda}^V$ = local net exergy increment of the semitransparent medium due to absorbing spectral radiation heat
$e_{R,\lambda}^V$ = local net increment of spectral radiation exergy in radiative field in the semitransparent medium
h = Planck's constant
$I_{b,\lambda}$ = spectral radiative intensity of the blackbody
I_λ = spectral radiative intensity
$L_{b,\lambda}$ = spectral radiative entropy intensity of the blackbody
L_λ = spectral radiative entropy intensity
$\mathbf{n}_w$ = unit outward normal vector of the boundary wall
Q_λ = net spectral radiation heat absorbed by matter
$\mathbf{r}$ = position vector
$S_{G,\lambda}^A$ = local spectral radiative entropy generation due to radiation processes at the opaque solid wall
$S_{G,\lambda}^{\mathrm{ae}}$ = local spectral radiative entropy generation due to absorption and emission processes in the semitransparent medium
$S_{G,\lambda}^s$ = local spectral radiative entropy generation due to scattering processes in the semitransparent medium
$\mathbf{s}$ = direction vector
T_M = medium temperature
T_λ = spectral radiation temperature
T_0 = temperature of environment
V = volume
$\kappa_{a,\lambda}$ = spectral absorption coefficient
$\kappa_{s,\lambda}$ = spectral scattering coefficient
λ = wavelength
Φ = single scattering phase function
ψ_λ = spectral radiative exergy intensity
Ω = solid angle

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I. Introduction

ENTROPY generation is associated with thermodynamic irreversibility, which results in the loss of exergy. Thermal radiation is an important factor in many high-temperature systems such as solar collectors, boilers, and furnaces. The evaluation of radiative entropy generation and radiative exergy loss is important when determining the second-law performance of these energy-conversion devices.

Planck [1] was the first to investigate the interaction of light and medium with respect to its irreversibility. Because of its importance in the thermodynamic analysis of high-temperature devices such as solar collectors, radiative entropy and exergy analysis has recently evoked much research interest in the academic community. Wright et al. [2] studied the radiative entropy generation of gray walls and presented an approximate expression for the entropy of gray radiation. Liu and Chu [3] checked the formula of entropy generation used in the community of heat transfer and found that the traditional conduction-type formula of entropy generation rate cannot be used to calculate the local entropy generation rate of radiative heat transfer. Caldas and Semiao [4] deduced the transfer equation of radiative entropy and presented a numerical simulation method of radiative entropy generation in a participating medium. Liu and Chu [5] extended this method to analyze the radiative entropy generation in the enclosures filled with semitransparent media and verified it by two different examples. Zhang and Basu [6] discussed the entropy flow and entropy generation in radiative transfer between surfaces and analyzed the hypotheses used to deduce Planck's formula of spectral radiative entropy intensity.

Exergy analysis is a very effective method for thermal process analysis because it provides insight that cannot be obtained from energy analysis. Wright et al. [7,8] studied the radiative exergy flow between opaque surfaces. Petela [9] and Bejan [10] discussed some existing formulas for the calculation of thermal radiation exergy. Based on Planck's formula of spectral radiative entropy intensity, Candau [11] proposed a derivation of the spectral exergy intensity of radiation. Although application of radiative exergy analysis in the semitransparent medium could be very interesting for some technical fields; unfortunately, up to now, the definition of radiative exergy has not been clearly formulated, and the transfer equation of radiative exergy in the semitransparent medium still has not been set up.

In this Note, we consider the radiative exergy transfer in the semitransparent medium under the hypothesis that radiation is incoherent and unpolarized, and the wave interference and diffraction effects are neglected. Based on the definition of spectral radiative exergy intensity proposed by Candau [11], the radiative exergy transfer equation is deduced. To verify this radiative exergy transfer equation, the radiative exergy losses in the semitransparent medium are analyzed to check the consistency between this radiative exergy transfer equation and classical thermodynamic theorem.

II. Radiative Exergy Transfer Equation

In the following analysis, we only consider the incoherent and unpolarized radiation, and the wave interference and diffraction effects are neglected. The spectral radiation temperature corresponding to any spectral radiative intensity $I_\lambda(\mathbf{r},\mathbf{s})$ is given by

$$T_\lambda(\mathbf{r},\mathbf{s}) = \frac{hc}{\lambda k} \frac{1}{\ln[2hc^2\lambda^{-5}/I_\lambda(\mathbf{r},\mathbf{s}) + 1]} \tag{1}$$

where c is the speed of light, h is Planck's constant, k is Boltzmann's constant, $\mathbf{r}$ is the spatial position vector, $\mathbf{s}$ is the radiation direction vector, and λ is the wavelength. A radiation beam carries not only energy but also entropy and exergy. The spectral radiative entropy intensities carried by a radiation beam with spectral radiative intensity $I_\lambda(\mathbf{r},\mathbf{s})$ are defined by Planck [1] as follows:

$$L_\lambda(\mathbf{r},\mathbf{s}) = 2kc\lambda^{-4}\left\{\left(\frac{I_\lambda(\mathbf{r},\mathbf{s})}{2hc^2\lambda^{-5}} + 1\right)\ln\left(\frac{I_\lambda(\mathbf{r},\mathbf{s})}{2hc^2\lambda^{-5}} + 1\right) - \left(\frac{I_\lambda(\mathbf{r},\mathbf{s})}{2hc^2\lambda^{-5}}\right)\ln\left(\frac{I_\lambda(\mathbf{r},\mathbf{s})}{2hc^2\lambda^{-5}}\right)\right\} \tag{2}$$

Based on Planck's definition of radiative entropy intensity, the spectral radiative exergy intensities carried by a radiation beam with spectral radiative intensity $I_\lambda(\mathbf{r},\mathbf{s})$ is defined by Candau [11] as

$$\psi_\lambda = I_\lambda - I_{b,\lambda}(T_0) - T_0\{L_\lambda(I_\lambda) - L_{b,\lambda}[I_{b,\lambda}(T_0)]\} \tag{3}$$

where T_0 is the temperature of the environment, and the subscript b denotes the blackbody.

Under the assumption of local thermodynamic equilibrium, the radiative transfer equation in the semitransparent medium can be written as [12]

$$\frac{\mathrm{d}I_\lambda(\mathbf{r},\mathbf{s})}{\mathrm{d}s} = -(\kappa_{a,\lambda} + \kappa_{s,\lambda})I_\lambda(\mathbf{r},\mathbf{s}) + \kappa_{a,\lambda}I_{b,\lambda}[T_M(\mathbf{r})] + \frac{\kappa_{s,\lambda}}{4\pi}\int_{4\pi} I_\lambda(\mathbf{r},\mathbf{s}')\Phi(\mathbf{s}',\mathbf{s})\mathrm{d}\Omega' \tag{4}$$

where $\kappa_{a,\lambda}$ is the spectral absorption coefficient, $\kappa_{s,\lambda}$ is the spectral scattering coefficient, Φ is the scattering phase function, $T_M(\mathbf{r})$ is the temperature of the semitransparent medium at $\mathbf{r}$, and Ω is the solid angle. Differentiation of Eq. (2) with respect to spectral radiative intensity $I_\lambda(\mathbf{r},\mathbf{s})$ leads to the following relation [4]:

$$\frac{\partial L_\lambda(\mathbf{r},\mathbf{s})}{\partial I_\lambda(\mathbf{r},\mathbf{s})} = \frac{1}{T_\lambda(\mathbf{r},\mathbf{s})} \tag{5}$$

By using Eqs. (4) and (5), the radiative entropy transfer equation can be written as [4,5]

$$\frac{\mathrm{d}L_\lambda(\mathbf{r},\mathbf{s})}{\mathrm{d}s} = -(\kappa_{a,\lambda} + \kappa_{s,\lambda})\frac{I_\lambda(\mathbf{r},\mathbf{s})}{T_\lambda(\mathbf{r},\mathbf{s})} + \kappa_{a,\lambda}\frac{I_{b,\lambda}[T_M(\mathbf{r})]}{T_\lambda(\mathbf{r},\mathbf{s})} + \frac{\kappa_{s,\lambda}}{4\pi}\int_{4\pi}\frac{I_\lambda(\mathbf{r},\mathbf{s}')}{T_\lambda(\mathbf{r},\mathbf{s})}\Phi(\mathbf{s}',\mathbf{s})\mathrm{d}\Omega' \tag{6}$$

From Eq. (3), we have

$$\frac{\mathrm{d}\psi_\lambda(\mathbf{r},\mathbf{s})}{\mathrm{d}s} = \frac{\mathrm{d}I_\lambda(\mathbf{r},\mathbf{s})}{\mathrm{d}s} - T_0\frac{\mathrm{d}L_\lambda(\mathbf{r},\mathbf{s})}{\mathrm{d}s} \tag{7}$$

Substituting Eqs. (4) and (6) into Eq. (7) leads to the following radiative exergy transfer equation:

$$\frac{\mathrm{d}\psi_\lambda(\mathbf{r},\mathbf{s})}{\mathrm{d}s} = -\kappa_{a,\lambda}\left[1 - \frac{T_0}{T_\lambda(\mathbf{r},\mathbf{s})}\right]\{I_\lambda(\mathbf{r},\mathbf{s}) - I_{b,\lambda}[T_M(\mathbf{r})]\} - \kappa_{s,\lambda}\left[1 - \frac{T_0}{T_\lambda(\mathbf{r},\mathbf{s})}\right]\left[I_\lambda(\mathbf{r},\mathbf{s}) - \frac{1}{4\pi}\int_{4\pi}I_\lambda(\mathbf{r},\mathbf{s}')\Phi(\mathbf{s}',\mathbf{s})\mathrm{d}\Omega'\right] \tag{8}$$

In the right-hand side (RHS) of Eq. (8), the first and second terms denote the increments of radiative exergy intensity due to the absorption-emitting processes and the scattering processes, respectively. This equation can be used to analyze the transfer and variation of radiative exergy in the semitransparent medium.

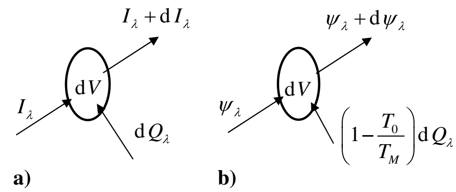

Fig. 1 Radiative energy and exergy transfer in a differential volume of the semitransparent medium: a) radiative energy transfer and b) radiative exergy transfer.

III. Radiative Exergy Loss in Radiative Transfer Processes

A. Radiative Exergy Loss in the Semitransparent Medium

For the radiative transfer processes in the semitransparent medium, exergy variation includes both that in the radiative field and in the medium. As shown in Fig. 1, the transfer of radiative exergy is very similar to that of radiation energy. By using Eq. (8), the local net increment of spectral radiation exergy in radiative field after radiation goes through a differential volume $\mathrm{d}V$ at wavelength λ with wavelength interval $\mathrm{d}\lambda$ can be obtained by integrating Eq. (8) over the entire solid angle, as follows:

$$\begin{aligned}
\mathrm{d}e^V_{R,\lambda}(\mathbf{r}) &= \mathrm{d}V\mathrm{d}\lambda\int_{4\pi}\frac{\mathrm{d}\psi_\lambda}{\mathrm{d}s}\mathrm{d}\Omega \\
&= -\kappa_{a,\lambda}\mathrm{d}V\mathrm{d}\lambda\int_{4\pi}\left[1 - \frac{T_0}{T_\lambda(\mathbf{r},\mathbf{s})}\right]\{I_\lambda(\mathbf{r},\mathbf{s}) - I_{b,\lambda}[T_M(\mathbf{r})]\}\mathrm{d}\Omega \\
&\quad - \kappa_{s,\lambda}\mathrm{d}V\mathrm{d}\lambda\int_{4\pi}\left[1 - \frac{T_0}{T_\lambda(\mathbf{r},\mathbf{s})}\right] \\
&\quad \times\left[I_\lambda(\mathbf{r},\mathbf{s}) - \frac{1}{4\pi}\int_{4\pi}I_\lambda(\mathbf{r},\mathbf{s}')\Phi(\mathbf{s}',\mathbf{s})\mathrm{d}\Omega'\right]\mathrm{d}\Omega \\
&= -\kappa_{a,\lambda}\mathrm{d}V\mathrm{d}\lambda\int_{4\pi}\left[1 - \frac{T_0}{T_\lambda(\mathbf{r},\mathbf{s})}\right]\{I_\lambda(\mathbf{r},\mathbf{s}) - I_{b,\lambda}[T_M(\mathbf{r})]\}\mathrm{d}\Omega \\
&\quad + \kappa_{s,\lambda}\mathrm{d}V\mathrm{d}\lambda\int_{4\pi}\left[\frac{T_0}{T_\lambda(\mathbf{r},\mathbf{s})}\right] \\
&\quad \times\left[I_\lambda(\mathbf{r},\mathbf{s}) - \frac{1}{4\pi}\int_{4\pi}I_\lambda(\mathbf{r},\mathbf{s}')\Phi(\mathbf{s}',\mathbf{s})d\Omega'\right]\mathrm{d}\Omega
\end{aligned} \tag{9}$$

In Eq. (9), the following relation is used

$$\int_{4\pi}\left[I_\lambda(\mathbf{r},\mathbf{s}) - \frac{1}{4\pi}\int_{4\pi}I_\lambda(\mathbf{r},\mathbf{s}')\Phi(\mathbf{s}',\mathbf{s})\mathrm{d}\Omega'\right]\mathrm{d}\Omega = 0 \tag{10}$$

Because of radiation, the medium within the differential volume $\mathrm{d}V$ will get or release heat by radiation absorption and emission and, hence, get or release exergy. According to the definition of heat exergy, the local net exergy increment of the medium under consideration after absorbing net radiative heat flux $\mathrm{d}Q_\lambda(\mathbf{r})$ can be given by

$$\begin{aligned}
\mathrm{d}e^V_{M,\lambda}(\mathbf{r}) &= \left(1 - \frac{T_0}{T_M(\mathbf{r})}\right)\mathrm{d}Q_\lambda(\mathbf{r}) \\
&= \kappa_{a,\lambda}\mathrm{d}V\mathrm{d}\lambda\left(1 - \frac{T_0}{T_M(\mathbf{r})}\right)\int_{4\pi}\{I_\lambda(\mathbf{r},\mathbf{s}) - I_{b,\lambda}[T_M(\mathbf{r})]\}\mathrm{d}\Omega
\end{aligned} \tag{11}$$

We consider a steady system. By combining Eqs. (9) and (11), the radiative exergy loss after radiation goes through a differential volume $\mathrm{d}V$ at wavelength λ with wavelength interval $\mathrm{d}\lambda$ can be written as

$$\begin{aligned}
\mathrm{d}a^V_\lambda(\mathbf{r}) &= -\mathrm{d}e^V_{R,\lambda}(\mathbf{r}) - \mathrm{d}e^V_{M,\lambda}(\mathbf{r}) \\
&= \kappa_{a,\lambda} T_0 \mathrm{d}V \mathrm{d}\lambda \int_{4\pi}\left[\frac{1}{T_\lambda(\mathbf{r},\mathbf{s})} - \frac{1}{T_M(\mathbf{r})}\right]\{I_{b,\lambda}[T_M(\mathbf{r})] - I_\lambda(\mathbf{r},\mathbf{s})\}\mathrm{d}\Omega \\
&+ \kappa_{s,\lambda} T_0 \mathrm{d}V \mathrm{d}\lambda \int_{4\pi}\frac{1}{T_\lambda(\mathbf{r},\mathbf{s})} \\
&\times \left[\frac{1}{4\pi}\int_{4\pi} I_\lambda(\mathbf{r},\mathbf{s}')\Phi(\mathbf{s}',\mathbf{s})\mathrm{d}\Omega' - I_\lambda(\mathbf{r},\mathbf{s})\right]\mathrm{d}\Omega \qquad (12)
\end{aligned}$$

In the RHS of Eq. (12), the first and second terms denote the radiative exergy loss due to the absorption-emitting processes and the scattering processes, respectively.

As presented by Caldas and Semiao [4], the local radiative entropy generation after radiation goes through a differential volume $\mathrm{d}V$ at wavelength λ with wavelength interval $\mathrm{d}\lambda$ can be divided into two parts: one due to the absorption and emission processes and the other due to the scattering processes, as follows [4,5]:

$$\begin{aligned}
\mathrm{d}S^{\mathrm{ae}}_{G,\lambda}(\mathbf{r}) &= \kappa_{a,\lambda}\mathrm{d}V\mathrm{d}\lambda \int_{4\pi}\left[\frac{1}{T_\lambda(\mathbf{r},\mathbf{s})} - \frac{1}{T_M(\mathbf{r})}\right] \\
&\times \{I_{b,\lambda}[T_M(\mathbf{r})] - I_\lambda(\mathbf{r},\mathbf{s})\}\mathrm{d}\Omega \qquad (13a)
\end{aligned}$$

$$\begin{aligned}
\mathrm{d}S^{s}_{G,\lambda}(\mathbf{r}) &= \kappa_{s,\lambda}\mathrm{d}V\mathrm{d}\lambda \int_{4\pi}\frac{1}{T_\lambda(\mathbf{r},\mathbf{s})} \\
&\times \left[\frac{1}{4\pi}\int_{4\pi} I_\lambda(\mathbf{r},\mathbf{s}')\Phi(\mathbf{s}',\mathbf{s})d\Omega' - I_\lambda(\mathbf{r},\mathbf{s})\right]\mathrm{d}\Omega \qquad (13b)
\end{aligned}$$

By combining Eqs. (12) and (13), we have the following relation between the radiative exergy loss and the radiative entropy generation:

$$\mathrm{d}\,a^V_\lambda(\mathbf{r}) = T_0[\mathrm{d}S^{\mathrm{ae}}_{G,\lambda}(\mathbf{r}) + \mathrm{d}S^{s}_{G,\lambda}(\mathbf{r})] \qquad (14)$$

This relation is consistent with the Guoy–Stodola theorem in classical thermodynamics.

B. Radiative Exergy Loss at Opaque Solid Surface

As shown in Fig. 2, the transfer of radiative exergy due to absorption and emission at opaque walls is very similar to that of radiation energy. Consider a differential surface $\mathrm{d}A$; after the radiation absorption, emission and reflection processes at the wall the local net increment of exergy flux in radiative field at opaque wall can be written as

$$\begin{aligned}
\mathrm{d}e^A_{R,\lambda}(\mathbf{r}_w) &= -\mathrm{d}A\mathrm{d}\lambda \int_{4\pi}\psi_\lambda(\mathbf{r}_w,\mathbf{s})(\mathbf{n}_w\cdot\mathbf{s})\mathrm{d}\Omega \\
&= -\mathrm{d}A\mathrm{d}\lambda \int_{4\pi}(I_\lambda(\mathbf{r}_w,\mathbf{s}) - I_{b,\lambda}(T_0) \\
&- T_0\{L_\lambda(\mathbf{r}_w,\mathbf{s}) - L_{b,\lambda}[I_{b,\lambda}(T_0)]\})(\mathbf{n}_w\cdot\mathbf{s})\mathrm{d}\Omega \qquad (15)
\end{aligned}$$

where $\mathbf{n}_w$ is the unit outward normal vector of the wall. It is noted that the term $\{I_{b,\lambda}(T_0) - T_0 L_{b,\lambda}[I_{b,\lambda}(T_0)]\}$ in Eq. (16) is independent of the radiation direction $\mathbf{s}$; this leads to the following relation:

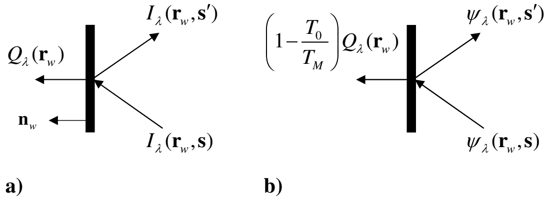

Fig. 2 Radiative energy and exergy transfer in a differential surface of the opaque solid boundary: a) radiative energy transfer and b) radiative exergy transfer.

$$\begin{aligned}
&\int_{4\pi}\{I_{b,\lambda}(T_0) - T_0 L_{b,\lambda}[I_{b,\lambda}(T_0)]\}(\mathbf{n}_w\cdot\mathbf{s})\mathrm{d}\Omega \\
&= \{I_{b,\lambda}(T_0) - T_0 L_{b,\lambda}[I_{b,\lambda}(T_0)]\}\int_{4\pi}(\mathbf{n}_w\cdot\mathbf{s})\mathrm{d}\Omega = 0 \qquad (16)
\end{aligned}$$

Therefore, Eq. (15) can be rewritten as

$$\mathrm{d}\,e^A_{R,\lambda}(\mathbf{r}_w) = -\mathrm{d}A\mathrm{d}\lambda \int_{4\pi}[I_\lambda(\mathbf{r}_w,\mathbf{s}) - T_0 L_\lambda(\mathbf{r}_w,\mathbf{s})](\mathbf{n}_w\cdot\mathbf{s})\mathrm{d}\Omega \qquad (17)$$

Because of radiation, the wall medium will get or release heat by radiation absorption and emission and, hence, get or release exergy. By definition, the local net increment of exergy in the wall medium under consideration after absorbing net radiative heat flux $\mathrm{d}Q_\lambda(\mathbf{r}_w)$ is given by

$$\begin{aligned}
\mathrm{d}e^A_{M,\lambda}(\mathbf{r}_w) &= \left[1 - \frac{T_0}{T_M(\mathbf{r}_w)}\right]\mathrm{d}Q_\lambda(\mathbf{r}_w) \\
&= \mathrm{d}A\mathrm{d}\lambda\left[1 - \frac{T_0}{T_M(\mathbf{r}_w)}\right]\int_{4\pi} I_\lambda(\mathbf{r}_w,\mathbf{s})(\mathbf{n}_w\cdot\mathbf{s})\mathrm{d}\Omega \qquad (18)
\end{aligned}$$

By combining Eqs. (17) and (18), the radiative exergy loss in wall surface $\mathrm{d}A$ at wavelength λ with wavelength interval $\mathrm{d}\lambda$ can be written as

$$\begin{aligned}
\mathrm{d}a^A_\lambda(\mathbf{r}_w) &= -\mathrm{d}e^A_{R,\lambda}(\mathbf{r}_w) - \mathrm{d}e^A_{M,\lambda}(\mathbf{r}_w) \\
&= T_0\mathrm{d}A\mathrm{d}\lambda\int_{4\pi}\left[\frac{I_\lambda(\mathbf{r}_w,\mathbf{s})}{T_M(\mathbf{r}_w)} - L_\lambda(\mathbf{r}_w,\mathbf{s})\right](\mathbf{n}_w\cdot\mathbf{s})\mathrm{d}\Omega \qquad (19)
\end{aligned}$$

From [5], the radiative entropy generated in wall surface $\mathrm{d}A$ at wavelength λ with wavelength interval $\mathrm{d}\lambda$ can be written as

$$\mathrm{d}\,S^A_{G,\lambda}(\mathbf{r}_w) = \mathrm{d}A\mathrm{d}\lambda\int_{4\pi}\left[\frac{I_\lambda(\mathbf{r}_w,\mathbf{s})}{T_M(\mathbf{r}_w)} - L_\lambda(\mathbf{r}_w,\mathbf{s})\right](\mathbf{n}_w\cdot\mathbf{s})\mathrm{d}\Omega \qquad (20)$$

By combining Eqs. (19) and (20), we have the following relation between the radiative exergy loss and the radiative entropy generation at the opaque wall:

$$\mathrm{d}\,a^A_\lambda(\mathbf{r}_w) = T_0\mathrm{d}S^A_{G,\lambda}(\mathbf{r}_w) \qquad (21)$$

Similar to the radiative exergy loss in the semitransparent medium, the relation between the radiative exergy loss and the radiative entropy generation at the opaque wall is also consistent with the Guoy–Stodola theorem in classical thermodynamics.

IV. Conclusions

The analysis of radiative exergy transfer and the evaluation of radiative exergy loss are important when analyzing the second-law performance of some energy-conversion devices such as solar collectors and boilers. Under the hypothesis that radiation is incoherent and unpolarized, the wave interference and diffraction effects are neglected, and the radiative exergy transfer equation in the semitransparent medium is deduced using Candau's [11] definition of spectral radiative exergy. Within the semitransparent medium, the radiative exergy loss can be divided into two parts: one due to the absorption-emitting processes and the other due to the scattering processes. To verify the radiative exergy transfer equation, the radiative exergy losses in the semitransparent medium are analyzed to check the consistency between this radiative exergy transfer equation and classical thermodynamic theorem. The analytical results of radiative exergy losses show that the relation between exergy loss and entropy generation deduced from Candau's definition of radiative exergy and the radiative exergy transfer equation set up in this Note are consistent with the Guoy–Stodola theorem in classical thermodynamics.

Acknowledgments

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