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Entropy generation analysis of two-dimensional high-temperature confined jet

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Abstract

In high-temperature systems, thermal radiation becomes the dominant mode of heat transfer. The analysis of entropy generation mechanism is very important to optimize the second-law performance of these energy conversion devices. In this paper, the entropy generation in a two-dimensional high-temperature confined jet flow is analyzed. The computation of combined radiation and convection heat transfer is carried out with the help of a CFD code, and the 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. Numerical results show the entropy generation due to radiative transfer cannot be omitted in high-temperature systems such as boilers and furnaces, in which thermal radiation is one of the main modes of heat transfer. In the case that the temperatures of the inlet gas and the top and bottom are not changed, the total entropy generation number decreases with the increase of jet Reynolds number and Boltzmann number, respectively. For enhancing heat transfer and advancing energy conversion efficiency, large jet Reynolds number and Boltzmann number should be selected.

Keywords: Entropy generation; Radiative heat transfer; High-temperature system; Jet flow

1. Introduction

The second law of thermodynamics has extensive application in problems involving heat transfer and fluid flow. Entropy generation is associated with thermodynamic irreversibility, which is present in all heat transfer and fluid flow processes. Bejan [1–3] developed the concept and the methodology of entropy generation minimization. The minimization of entropy generation in heat transfer and fluid flow equipments provides considerable improvement in efficient operation.

Recently, considerable research work has been carried out to understand the mechanism of entropy generation in heat transfer and fluid flow processes. Balaji et al. [4] examined the role of buoyancy in the total entropy generation rate in turbulent mixed convection flows. Ko and Ting [5] analyzed the entropy generation induced by forced convection in a curved rectangular duct with external heating. Ko and Cheng [6] investigated the entropy generation in the developing laminar forced convection within a wavy channel, and analyzed the effects of Reynolds number on entropy generation. Based on the Reynolds-average transport equation, Kock and Herwig [7] studied the local entropy production in turbulent shear flows. Hooman et al. [8] analyzed heat transfer and entropy generation optimization of forced convection in porous-saturated ducts of rectangular cross-section. Due to the low temperature level within the heat transfer devices considered in these studies, in which heat convection is the dominant mode of heat transfer, the effect of thermal radiation was often omitted.

In many high-temperature systems such as solar collectors, boilers and furnaces, thermal radiation becomes the dominant mode of heat transfer. The analysis of entropy generation mechanism is very important to optimize the second-law performance of these energy conversion devices. The second law analysis in combustion processes was carried out by many researchers, for example, Raghavan et al. [9], Nishida et al. [10], Arpaci and Selamet [11], Datta [12], Datta and Som [13], Yapıcı et al. [14]. Theoretically, the effect of thermal radiation needs to be considered in the analysis of entropy generation

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Nomenclature

A	surface area of boundary	m^2
Bo	Boltzmann number	
c_0	speed of light in vacuum	m/s
c_P	specific heat at constant pressure	$J\,kg^{-1}\,K^{-1}$
d	height of the spout	m
h	Planck's constant	J s
H	height of the duct	m
I_λ	spectral radiative intensity	$W\,m^{-3}\,sr^{-1}$
$I_{b,\lambda}$	spectral radiative intensity of blackbody	$W\,m^{-3}\,sr^{-1}$
k	turbulent kinetic energy	$m^2\,s^{-2}$
k_b	Boltzmann's constant	$J\,K^{-1}$
k_m	thermal conductivity of gas	$W\,m^{-1}\,K^{-1}$
k_{eff}	effective thermal conductivity	$W\,m^{-1}\,K^{-1}$
L	length of the duct	m
L_λ	spectral radiative entropy intensity	$W\,m^{-3}\,sr^{-1}\,K^{-1}$
$L_{b,\lambda}$	spectral radiative entropy intensity of blackbody	$W\,m^{-3}\,sr^{-1}\,K^{-1}$
$\mathbf{n}_w$	unit outward normal vector of boundary wall	
Ns	total entropy generation number	
Ns_c	entropy generation number due to heat conduction and convection	
Ns_f	entropy generation number due to viscous dissipation	
Ns_r	entropy generation number due to radiative heat transfer in gas	
Ns_A	entropy generation number due to wall radiation	
$\mathbf{q}$	heat flux vector	$W\,m^{-2}$
Q	total heat transfer rate of the system	W
$\mathbf{r}$	position vector	m
Re_d	jet Reynolds number	
$\mathbf{s}$	direction vector	
$\dot{S}'''_{\text{gen},c}$	volumetric entropy generation rate due to heat conduction and convection	$W\,m^{-3}\,K^{-1}$
$\dot{S}'''_{\text{gen},f}$	volumetric entropy generation rate due to viscous dissipation	$W\,m^{-3}\,K^{-1}$
$\dot{S}'''_{\text{gen},r}$	volumetric entropy generation rate due to radiative transfer in gas	$W\,m^{-3}\,K^{-1}$
$\dot{S}''^{A}_{\text{gen},r}$	entropy generation rate per unit area due to radiative transfer at wall	$W\,m^{-2}\,K^{-1}$
S_G^c	total entropy generation due to heat conduction and convection	$W\,K^{-1}$
S_G^f	total entropy generation due to viscous dissipation	$W\,K^{-1}$
S_G^r	total entropy generation due to radiative heat transfer in gas	$W\,K^{-1}$
S_G^A	total entropy generation due to wall radiation	$W\,K^{-1}$
S_G	total entropy generation	$W\,K^{-1}$
T	matter temperature	K
T_0	environment temperature	K
T_{ref}	reference temperature	K
T_λ	spectral radiation temperature	K
u	velocity component in x-direction	$m\,s^{-1}$
u_{in}	axial inlet velocity of jet	$m\,s^{-1}$
v	velocity component in y-direction	$m\,s^{-1}$
V	volume	m^3
x, y	Cartesian coordinates	m
y_P	distance between the solid wall and the closest node	
ε	emissivity	
$\kappa_{a,\lambda}$	spectral absorption coefficient	m^{-1}
$\kappa_{s,\lambda}$	spectral scattering coefficient	m^{-1}
λ	wavelength	μm
μ_m	dynamic viscosity of gas	$kg\,m^{-1}\,s^{-1}$
μ_{eff}	effective dynamic viscosity	$kg\,m^{-1}\,s^{-1}$
μ_t	turbulent viscosity	$kg\,m^{-1}\,s^{-1}$
ρ	density	$kg\,m^{-3}$
Φ	single scattering phase function	
Ω	solid angle	sr

in high-temperature systems. Unfortunately, even for the high-temperature reacting flows in combustion devices, up to now the thermal radiation is still not taken into account in the analysis of entropy generation.

Traditionally, the local entropy generation rate for radiative heat transfer is often written as [15–19]

$$\dot{S}'''_{\text{gen},r}(\mathbf{r}) = -\mathbf{q}^r(\mathbf{r}) \cdot \frac{\nabla T(\mathbf{r})}{T^2(\mathbf{r})} \tag{1}$$

where T is temperature, $\mathbf{q}^r$ is the radiative heat flux vector. Liu and Chu [20] checked the formula of entropy generation used in the community of heat transfer, and found that traditional conduction-type formula of entropy generation rate cannot be used to calculate the local entropy generation rate of radiative heat transfer. Based on Planck's definition of radiative entropy [21], Caldas and Semiao [22] deduced the transfer equation of radiative entropy and presented a numerical simulation method of radiative entropy generation in the participating medium. Liu and Chu [23] extended this method to analyze the radiative entropy generation in the enclosures filled with semi-transparent media.

In this paper, based on the radiative entropy generation formula given in Refs. [22,23], we study the entropy generation in a two-dimensional high-temperature confined jet flow. The computation of combined radiation and convection heat transfer is carried out with the help of CFD code Fluent 6.1.22, 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. The distributions of entropy generation due to heat conduction and convection, thermal radiation transfer in gas and viscous fluid friction are analyzed, and the effect of jet Reynolds number, Boltzmann

number and wall emissivity on entropy generation in the high-temperature confined jet flow are studied, respectively.

2. Mathematical formulae and method of simulation

As shown in Fig. 1, the problem under consideration is a two-dimensional symmetric confined plane jet flow. The heights of the duct and the spout are $H = 0.4$ m and $d = 0.06$ m, respectively, and the length of the duct simulated in the following is $L = 1.0$ m. A carbon dioxides jet with temperature $T_{\text{in}} = 1000$ K is sprayed into the duct. The top and the bottom boundaries of the duct are opaque walls with temperature $T_w = 500$ K, respectively, but the left boundary of the duct is an adiabatic wall. The environment temperature is $T_0 = 500$ K.

The thermal conductivity, molecular viscosity, density and specific heat of carbon dioxide in FLUENT 6.1.22 are given by $k_m = 0.0145$ W/m K, $\mu_m = 1.37 \times 10^{-5}$ kg/m s, $\rho = 1.7878$ kg/m^3 and $c_p = 840.37$ J/kg K, respectively. The kinematic coefficient of viscosity is $\nu = \mu/\rho$. When inlet velocity of gas is $u_{\text{in}} = 1$ m/s, the Reynolds number at the nozzle of spout is $Re_d = u_{\text{in}} d/\nu = 7830$. In the following analysis, $u_{\text{in}} \geqslant 1$ m/s, thus the jet flow is turbulent. The turbulence intensity at the inlet can be specified by

$$I = 0.16(Re_d)^{-1/8} \tag{2}$$

2.1. Calculation tools

The FLUENT 6.1.22 program was chosen as the CFD computer code for this work. The FLUENT computer code uses a finite volume procedure to solve the Navier–Stokes equations of fluid flow in primitive variables such as velocity and pressure. This computer code also can model the radiative heat transfer of semitransparent medium by solving radiative transfer equation [24–27].

The standard k–ε model has been usually used to simulate the turbulent flow with no swirl for its efficiency [27–29]. Because the flow considered here has no swirl and the standard k–ε model required short computing time compared with the others, we use the standard k–ε model to simulate the turbulent jet flow in this paper. For the region of flow parameter considered in this paper, the distance between the solid wall and the closest node, y_P, meets the following condition

$$11.5 \leqslant \frac{y_P C_\mu^{1/4} k^{1/2}}{\nu} \leqslant 200 \tag{3}$$

Hence, we adopt the standard wall function for handling the wall-bounded turbulent flow problems considered here.

The P-1 radiation model was adopted in Refs. [24–26] to model radiative heat transfer for its low computational requirements and simplicity. However, the accuracy of P-1 radiation model is only appropriate to optical thickness medium [30]. The discrete ordinates method (DOM) is widely used to model radiative heat transfer for its better accuracy [31–34]. So we select the DOM for the computation model of radiative heat transfer in FLUENT software.

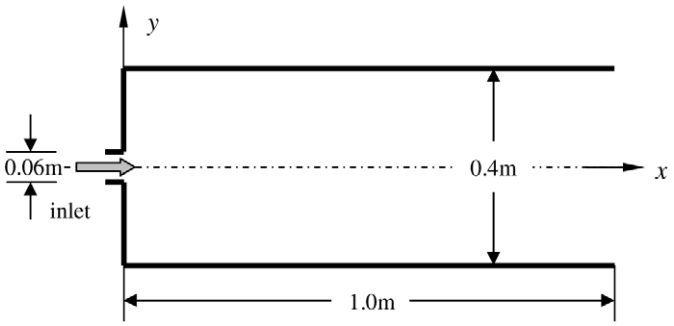

Fig. 1. Geometry of turbulent confined jet.

After the velocity and temperature distributions are solved using the FLUENT computer code. The local entropy generation due to heat conduction, heat convection and fluid friction is calculated as post-processed quantities with the computed data of velocity and temperature. The radiative intensity and then the local entropy generation due to radiative transfer are solved using the DOM (S_8) with the temperature data.

The assumptions made in the following analysis are as follows:

(1) The confined jet flow is steady, two-dimensional symmetric, turbulent and incompressible;
(2) The carbon dioxides is assumed to behave as an ideal gas with absorption coefficient $\kappa_a = 0.43$;
(3) No-slip condition is assumed at the solid walls;
(4) The gradients of velocity, temperature, turbulent kinetic energy and turbulent energy dissipation rate are zero at the outlet of duct;
(5) The inlet and the outlet boundaries are assumed as blackbody with the same temperature as local fluid medium for the solution of radiative transfer equation [35,36].

2.2. Local entropy generation rate

In the high-temperature non-reacting jet, irreversibility arises due to the heat transfer and the viscous effects of the fluid. The local volumetric entropy generation rate can be expressed as the sum of contributions due to thermal effects and viscous effects. The viscous effects depend on the local velocity gradient of fluid, and the local entropy generation of heat conduction and convection is dependent on the local temperature gradient of the fluid. However, because thermal radiation is a long-range phenomenon, the local radiative heat transfer and the entropy generation rate are dependent on the temperature distribution of the entire enclosure under consideration and are not determined by the local temperature gradient.

Similar to the method adopted in Ref. [14], in this paper the local entropy generation of viscous dissipation and that of heat conduction and convection are determined by effective dynamic viscosity and effective thermal conductivity, respectively, in which the effective dynamic viscosity and the effective thermal conductivity are defined respectively as

$$\mu_{\text{eff}} = \mu_m + \mu_t \tag{4}$$

$$k_{\text{eff}} = k_m + \frac{c_p \mu_t}{Pr_t} \tag{5}$$

where Pr_t is turbulent Prandtl number, and μ_t is turbulent dynamic viscosity given by

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{6}$$

Here, C_μ is 0.09, and k is turbulent kinetic energy.

In the two-dimensional high-temperature and non-reacting flow system, the volumetric entropy generation rate per unit volume can be written as:

$$\dot{S}'''_{\text{gen}} = \dot{S}'''_{\text{gen},c} + \dot{S}'''_{\text{gen},f} + \dot{S}'''_{\text{gen},r} \tag{7}$$

where $\dot{S}'''_{\text{gen},c}$, $\dot{S}'''_{\text{gen},f}$ and $\dot{S}'''_{\text{gen},r}$ denote the volumetric entropy generation rates due to the heat conduction and convection, the viscous fluid friction and the thermal radiative transfer in carbon dioxide gas flow, respectively, and they are given as

$$\dot{S}'''_{\text{gen},c} = \frac{k_{\text{eff}}}{T^2}(\nabla T)^2 \tag{8}$$

$$\dot{S}'''_{\text{gen},f} = \frac{\mu_{\text{eff}}}{T}\left\{2\left[\left(\frac{\partial u_x}{\partial x}\right)^2 + \left(\frac{\partial u_y}{\partial y}\right)^2\right] + \left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}\right)^2\right\} \tag{9}$$

$$\begin{aligned}\dot{S}'''_{\text{gen},r} = {} & \int_0^\infty \int_{4\pi} \left[-(\kappa_{a,\lambda} + \kappa_{s,\lambda})\frac{I_\lambda(\mathbf{r},\mathbf{s})}{T_\lambda(\mathbf{r},\mathbf{s})} + \kappa_{a,\lambda}\frac{I_{b,\lambda}(\mathbf{r})}{T_\lambda(\mathbf{r},\mathbf{s})}\right. \\ & \left. + \frac{\kappa_{s,\lambda}}{4\pi}\int_{4\pi}\frac{I_\lambda(\mathbf{r},\mathbf{s}')}{T_\lambda(\mathbf{r},\mathbf{s})}\Phi(\mathbf{s}',\mathbf{s})\,\mathrm{d}\Omega'\right]\mathrm{d}\Omega\,\mathrm{d}\lambda \\ & + \int_0^\infty \int_{4\pi} \frac{\kappa_{a,\lambda}}{T(\mathbf{r})}\left[I_\lambda(\mathbf{r},\mathbf{s}) - I_{b,\lambda}(\mathbf{r})\right]\mathrm{d}\Omega\,\mathrm{d}\lambda\end{aligned} \tag{10}$$

Here the spectral radiation temperature corresponding to spectral radiative intensity $I_\lambda(\mathbf{r},\mathbf{s})$ is defined as

$$T_\lambda(\mathbf{r},\mathbf{s}) = \frac{hc_0}{\lambda k_b}\frac{1}{\ln[2hc_0^2\lambda^{-5}/I_\lambda(\mathbf{r},\mathbf{s}) + 1]} \tag{11}$$

where, $\mathbf{r}$ is spatial position vector, and $\mathbf{s}$ is direction vector, Ω is solid angle, λ is wavelength, c_0 is the speed of light in vacuum, h is Planck's constant, k_b is Boltzmann's constant, $\kappa_{a,\lambda}$ and $\kappa_{s,\lambda}$ are spectral absorption and scattering coefficients, respectively.

In addition to the entropy generation due to absorption and scattering in semitransparent medium, the irreversibility of wall absorption and emission processes also lead to entropy generation. The entropy generation rate per unit area due to wall absorption and emission processes can be written as:

$$\dot{S}''^{A}_{\text{gen},r} = \int_0^\infty \int_{4\pi} \left[\frac{I_\lambda(\mathbf{r_w},\mathbf{s})}{T(\mathbf{r_w})} - L_\lambda(\mathbf{r_w},\mathbf{s})\right](\mathbf{n}_W \cdot \mathbf{s})\,\mathrm{d}\Omega\,\mathrm{d}\lambda \tag{12}$$

where L_λ is the spectral radiation entropy intensity corresponding to spectral radiative intensity I_λ and defined as

$$\begin{aligned}L_\lambda(\mathbf{r}_w,\mathbf{s}) = {} & 2k_b c_0 \lambda^{-4}\left\{\left(\frac{I_\lambda(\mathbf{r}_w,\mathbf{s})}{2hc_0^2\lambda^{-5}} + 1\right)\ln\left(\frac{I_\lambda(\mathbf{r}_w,\mathbf{s})}{2hc_0^2\lambda^{-5}} + 1\right)\right. \\ & \left. - \left(\frac{I_\lambda(\mathbf{r}_w,\mathbf{s})}{2hc_0^2\lambda^{-5}}\right)\ln\left(\frac{I_\lambda(\mathbf{r}_w,\mathbf{s})}{2hc_0^2\lambda^{-5}}\right)\right\}\end{aligned} \tag{13}$$

2.3. Total entropy generation and entropy generation number

The total entropy generation due to the heat conduction and convection, the viscous dissipation and the radiative heat transfer in gas can be derived by integrating Eqs. (8), (9) and (10) over volume as follows:

$$S_G^c = \int_V \dot{S}'''_{\text{gen},c}\,\mathrm{d}V \tag{14}$$

$$S_G^f = \int_V \dot{S}'''_{\text{gen},f}\,\mathrm{d}V \tag{15}$$

$$S_G^r = \int_V \dot{S}'''_{\text{gen},r}\,\mathrm{d}V \tag{16}$$

By integrating Eq. (12) over boundary area, the total entropy generation due to wall radiative heat transfer can be written as

$$S_G^A = \int_A \dot{S}''^{A}_{\text{gen},r}\,\mathrm{d}A \tag{17}$$

and the total entropy generation of the jet system consider here is

$$S_G = S_G^c + S_G^f + S_G^r + S_G^A \tag{18}$$

In the second law analysis of heat transfer and flow processes the entropy generation number is often used to evaluate the irreversibility of the process. In the following analysis, the entropy generation number due to heat conduction and convection, viscous dissipation, radiative heat transfer in gas and that due to wall radiation are defined respectively as

$$Ns_c = \frac{S_G^c T_0}{Q} \tag{19}$$

$$Ns_f = \frac{S_G^f T_0}{Q} \tag{20}$$

$$Ns_r = \frac{S_G^r T_0}{Q} \tag{21}$$

$$Ns_A = \frac{S_G^A T_0}{Q} \tag{22}$$

where, Q is the total heat transfer rate of the system. The total entropy generation number of the system can be written as

$$Ns = Ns_c + Ns_f + Ns_r + Ns_A = \frac{S_G T_0}{Q} \tag{23}$$

3. Results and discussion

Grid-refinement studies were also performed for the physical model to ensure that the essential physics are independent of grid size. The axial velocity profiles and the corresponding axial temperature profiles for five different grid numbers, namely, $N_x \times N_y = 101 \times 41$, 141×57, 201×81, 261×105 and 301×121, are shown in Fig. 2. The numerical results show that, when the nodes number is equal to or larger than 261×105, the numerical results are very close to one another. Therefore, we adopt 261×105 nodes for all the following calculations.

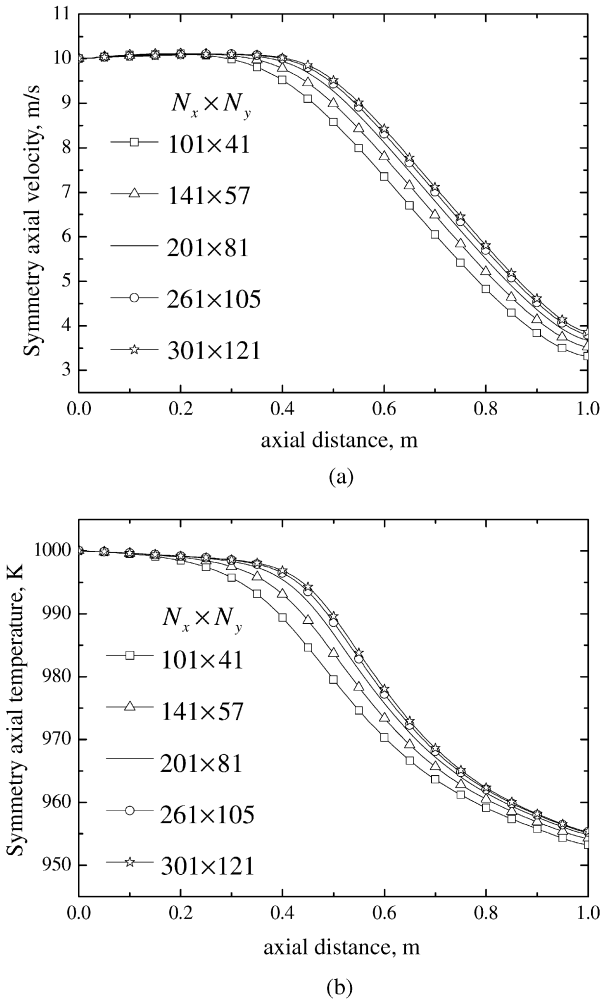

Fig. 2. Distribution of gas velocity and temperature on symmetry axis for different nodes: (a) axial velocity; (b) temperature.

3.1. Distribution of entropy generation

In this section we analyze the distribution of entropy generation due to heat conduction and convection, viscous dissipation and radiative transfer in the system for the case of $Re_d = 78298$ and $\varepsilon = 1.0$. The volumetric entropy generation rate due to heat conduction and convection and that due to viscous dissipation are related to the distributions of temperature and velocity, respectively. Fig. 3 shows the typical flow structure of the turbulent confined jet. The computed contour lines of temperature and velocity are depicted in Figs. 4 and 5, respectively. Figs. 6 and 7 depict the distribution of volumetric entropy generation rate due to heat conduction and convection and that due to viscous dissipation, respectively. As shown in Figs. 6 and 7, generally the volumetric entropy generation rate due to heat conduction and convection is larger than that due to viscous dissipation in the case considered in this paper.

As shown in Fig. 4, the temperature gradient can be neglected at the jet core zone where the gas temperature is kept the same as the inlet gas temperature. At the beginning section of the mixing layer, the strong turbulent perturbation owing to gas entrainment leads to large temperature gradients. The

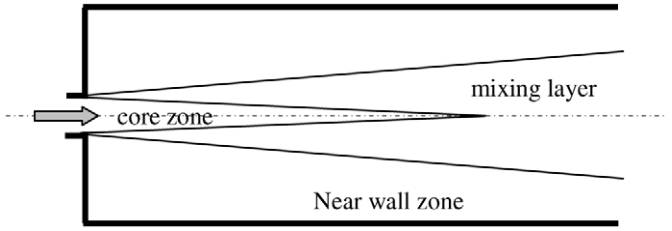

Fig. 3. Flow structure of the turbulent confined jet.

mixing layer expands along the direction of jet flow, and the temperature gradient gradually decreases. Therefore, as shown in Fig. 6, the volumetric entropy generation rate due to heat conduction and convection gradually decreases from the center to the edge of mixing layer. The volumetric entropy generation rate due to heat conduction and convection in the center of mixing layer is larger than 100 $W/(m^3\,K)$, and the maximum value of volumetric entropy generation rate due to heat conduction and convection is 789.32$W/(m^3\,K)$. From the edge of mixing layer to solid wall, due to the effect of boundary layer, the temperature gradient and hence the volumetric entropy generation rate due to heat conduction and convection increase gradually. The volumetric entropy generation rate due to heat conduction and convection is larger than 1000 $W/(m^3\,K)$ in the narrow zone close to the isothermal wall, and the maximum value of volumetric entropy generation rate is 8236.16 $W/(m^3\,K)$. The thickness of this narrow zone is about 3.846×10^{-3} m and the entropy generation due to heat conduction and convection in this zone is about 80.88% of the total entropy generation due to heat conduction and convection. The volumetric entropy generation due to heat conduction and convection is small and less than 20 $W/(m^3\,K)$ in the most zones of the computational domain.

As shown in Figs. 5 and 7, because of low velocity gradient the volumetric entropy generation rate due to viscous dissipation is small at the jet core zone. Similar to heat conduction and convection processes, owing to the gas entrainment phenomena the velocity gradient is large at the center of mixing layer. This indicates that the volumetric entropy generation rate due to viscous dissipation is larger in the center of mixing layer than that at the other zones. From the center to the edge of mixing layer, the velocity gradient decreases gradually. Therefore, the volumetric entropy generation rate due to viscous dissipation gradually decreases from the center to the edge of mixing layer.

Fig. 8 shows the distribution of volumetric radiation entropy generation rate. The largest value of volumetric radiation entropy generation rate is located at the jet core zone, in which the temperature difference between gas and solid wall is the larger than that at the other zones. By comparison with Figs. 6, 7 and 8, it can be seen that, generally, the volumetric entropy generation due to heat conduction and convection is larger than that due to the radiative transfer in gas and the viscous dissipation near boundary layer. However, the volumetric radiation entropy generation is not small in whole zone.

The entropy generation due to heat conduction and convection dominates in the case of $Re_d = 78298$ and $\varepsilon = 1$, which is 67.97% of total entropy generation of the system considered

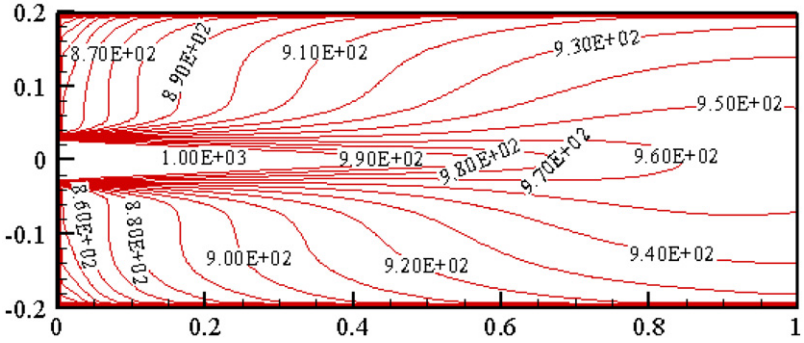

Fig. 4. Computed contour lines of gas temperature (K).

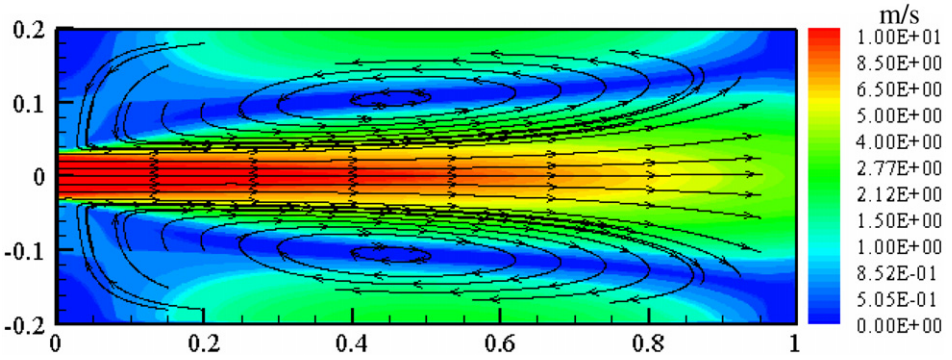

Fig. 5. Distribution of gas velocity and the stream lines.

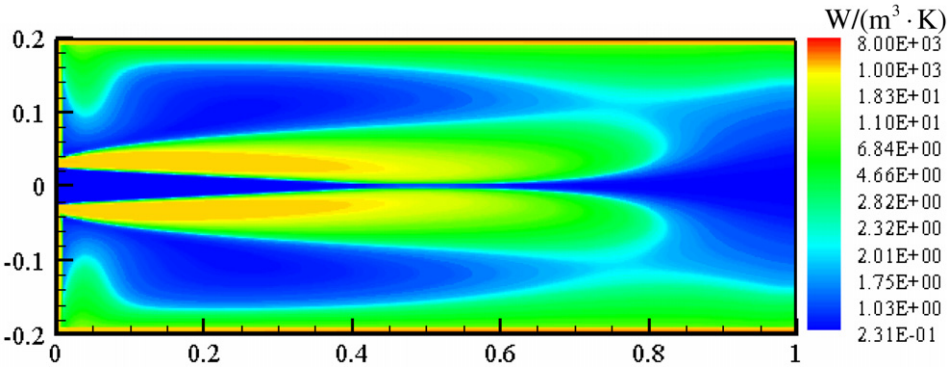

Fig. 6. Distribution of volumetric entropy generation rate due to heat conduction and convection.

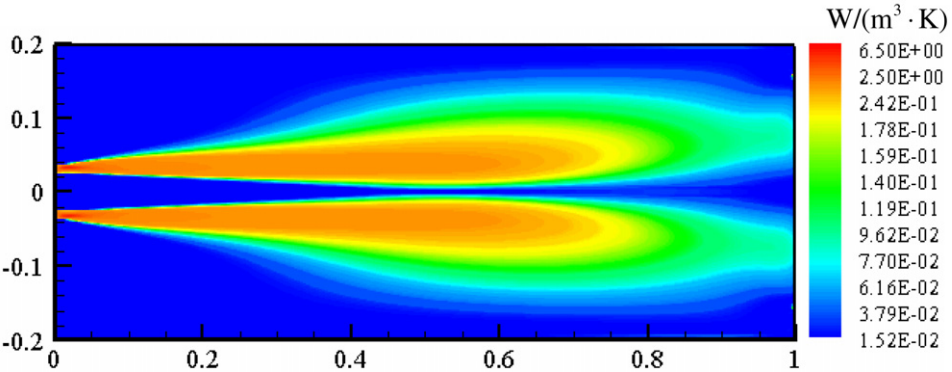

Fig. 7. Distribution of volumetric entropy generation rate due to viscous dissipation.

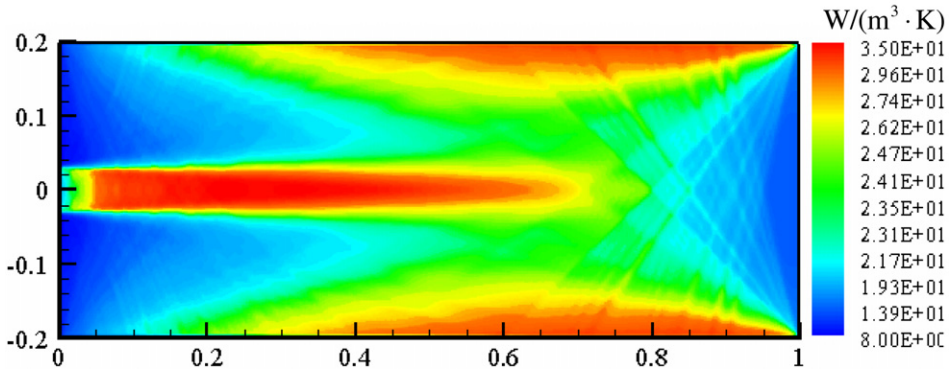

Fig. 8. Distribution of volumetric entropy generation rate due to radiative transfer in gas.

Table 1
Apportioning of total entropy generation and their percents for different jet Reynolds number in the case of wall emissivity $\varepsilon = 1.0$

Re_d	S_G^c/S_G (%)	S_G^f/S_G (%)	S_G^r/S_G (%)	S_G^A/S_G (%)	S_G (W/K)	Ns
7830	27.95	2.03×10^{-4}	26.18	45.86	21.54	0.33
15660	37.31	1.05×10^{-3}	21.70	40.99	31.96	0.25
39149	54.20	9.12×10^{-3}	15.24	30.56	54.91	0.17
78298	67.97	0.04	10.43	21.56	87.66	0.14
117447	75.17	0.11	7.97	16.75	118.81	0.13
156596	79.61	0.21	6.46	13.72	149.51	0.12

Table 2
Apportioning of total entropy generation and their percents for different wall emissivity in the case of jet Reynolds number $Re_d = 78298$

ε	S_G^c/S_G (%)	S_G^f/S_G (%)	S_G^r/S_G (%)	S_G^A/S_G (%)	S_G (W/K)	Ns
0.4	67.10	0.04	13.88	18.97	89.64	0.141
0.6	67.31	0.04	12.42	20.23	88.91	0.140
0.8	67.61	0.04	11.31	21.03	88.25	0.139
1.0	67.97	0.04	10.43	21.56	87.66	0.138

here. Radiation entropy generation includes the entropy generation due to gas radiation process and that due to wall radiation process. The percent of wall radiation entropy generation in the total entropy generation is 21.56%. Unlike the entropy generation due to heat conduction and convection, the volumetric entropy generation rate due to radiative transfer in gas is quite even and larger than 8 W/(m^3 K) in the most zones of the computational domain. The radiation entropy generation in gas is 10.43% of the total entropy generation. Hence the percent of entropy generation due to radiative transfer in the total entropy generation is 31.99%. Therefore, the entropy generation due to radiative transfer cannot be omitted in high-temperature systems such as boilers and furnaces, in which thermal radiation is one of the main modes of heat transfer.

3.2. Effect of jet Reynolds number on entropy generation

To better understand the effect of jet Reynolds number on entropy generation and total entropy generation number, Table 1 shows the apportioning of total entropy generation in the case of $\varepsilon = 1$. Within the Reynolds number region considered in this paper, the entropy generation due to due to viscous dissipation is small, and its percent in total entropy generation of the system is less than 0.5%. The total entropy generation increases quickly with the jet Reynolds number. However, with the increase of the jet Reynolds number, the heat transfer process is enhanced, and hence the total entropy generation number decreases in the case that the temperatures of the inlet gas and the top and bottom are not changed. The percent of the entropy generation due to heat conduction and convection increases with the jet Reynolds number from 27.95 to 79.61%, but the percent of radiation entropy generation decreases with the increase of jet Reynolds number from 72.04 to 20.18%. Even in the case of $Re_d = 156596$, the entropy generation due to radiative heat transfer in the high temperature system still cannot be neglected.

3.3. Effect of wall emissivity on entropy generation

Table 2 shows the constitutions of total entropy generation and their percents for different wall emissivity in the case of the jet Reynolds number $Re_d = 78298$. Both of the total entropy generation and the total entropy generation number decrease with the increase of wall emissivity. However, in the case that the temperatures of the inlet gas and the top and bottom are not changed, the variations of the total entropy generation and the total entropy generation number are small. From Table 2, it can be clearly seen that the percent of entropy generation due to heat

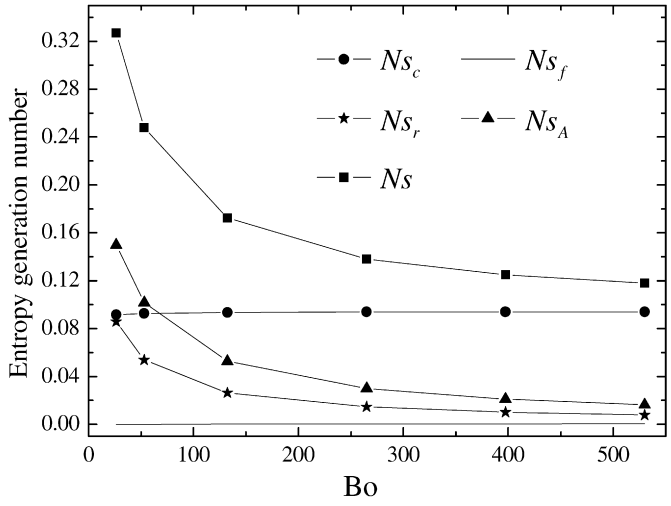

Fig. 9. Effect of Boltzmann number on entropy generation number in the case of $\varepsilon = 1$.

conduction and convection and that due to viscous dissipation varies slowly with the increase of wall emissivity.

3.4. Effect of Boltzmann number on entropy generation

Boltzmann number approximately reflects the ratio of heat convection and radiation, which is defined as

$$Bo = \frac{\rho c_p u_{\text{in}}}{\sigma T_{\text{ref}}^3} \tag{24}$$

Here T_{ref} is the reference temperature, which is selected the same value as the inlet temperature of gas, i.e., $T_{\text{ref}} = 1000$ K. Fig. 9 shows the distribution of entropy generation number with Boltzmann number in the case of $\varepsilon = 1$. With the increase of Boltzmann number, the variation of entropy generation number due to heat conduction and convection and that due to viscous dissipation are negligible, but the entropy generation number due to radiative heat transfer in gas and that due to wall radiation decrease first quickly (in the region of $Bo < 200$) and then decrease slowly (in the region of $Bo > 200$).

From the analysis above, attention should be paid near wall zone and the center of mixing layer where the local heat conduction and convection entropy generation rate per unit volume is large, and radiation entropy generation should be taken into account for enhancing heat transfer and advancing energy conversion efficiency in high-temperature systems. The total entropy generation number would be minimized by adopting large jet Reynolds number and Boltzmann number.

4. Conclusions

Entropy generation is associated with thermodynamic irreversibility, which is present in all heat transfer and fluid flow processes. Based on the radiative entropy generation formula given in Refs. [22,23], we studied the entropy generation in a two-dimensional high-temperature confined jet flow. The computation of combined radiation and convection heat transfer was carried out with the help of CFD code Fluent 6.1.22, and the local entropy generation rates due to heat transfer and fluid friction were calculated as post-processed quantities with the computed data of velocity, temperature and radiative intensity. The main conclusions from present analysis can be summarized as follows:

(1) The entropy generation due to radiative transfer cannot be omitted in high-temperature systems such as boilers and furnaces, in which thermal radiation is one of the main modes of heat transfer.
(2) In the case that the temperatures of the inlet gas and the top and bottom are not changed, the total entropy generation number decreases with the increase of jet Reynolds number and Boltzmann number, respectively.
(3) The effect of wall emissivity on total entropy generation and total entropy generation number is small.
(4) For enhancing heat transfer and advancing energy conversion efficiency, large jet Reynolds number and Boltzmann number should be selected.

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