Effect of Particle Size Distribution on Radiative Heat Transfer in High-Temperature Homogeneous Gas-Particle Mixtures

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Abstract: The weighted-sum-of-gray-gas (WSGG) model and Mie theory are applied to study the influents of particle size on the radiative transfer in high temperature homogeneous gas-particle mixtures, such as the flame in aero-engine combustor. The radiative transfer equation is solved by the finite volume method. The particle size is assumed to obey uniform distribution and logarithmic normal (L-N) distribution, respectively. Results reveal that when particle size obeys uniform distribution, increasing particle size with total particle volume fraction f_v unchanged will result in the decreasing of the absolute value of radiative heat transfer properties, and the effect of ignoring particle scattering will also be weakened. Opposite conclusions can be obtained when total particle number concentration N_0 is unchanged. Moreover, if particle size obeys L-N distribution, increasing the narrowness index σ or decreasing the characteristic diameter $\bar{D}$ with the total particle volume fraction f_v unchanged will increase the absolute value of radiative heat transfer properties. With total particle number concentration N_0 unchanged, opposite conclusions for radiative heat source and incident radiation terms can be obtained except for radiative heat flux term. As a whole, the effects of particle size on the radiative heat transfer in the high-temperature homogeneous gas-particle mixtures are complicated, and the particle scattering cannot be ignoring just according to the particle size.

Key words: particle size distribution; WSGG; radiative heat transfer; gas-particle mixtures

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0 Introduction

The radiative heat transfer in the high-temperature gas-particle mixture plays a crucial role in studying the combustion properties in the furnace, infrared stealth technology for the aero-engine, the radiative transfer in the atmosphere etc.[1-2]. Usually, in the high-temperature gas-particle mixture, except for a large amount of gaseous species, e.g. CO_2 and H_2O, that emit and absorb the radiant energy, the emitting, absorbing and scattering of particles also play an important role in the change of the radiative heat transfer[3-4]. So, to best understand the radiative heat transfer properties of mixture, the radiative properties of gases and particles should be investigated carefully.

Generally, the calculated models used to study the gas radiative properties can be divided into three categories, i.e. Line-By-Line (LBL) model, Band models and Global models[5]. The LBL model can be applied to accurately predict the radiative properties of gases by the knowledge of every single spectral line from the high-resolution spectroscopic databases, e.g. CDSD[6] and HITEMP[7]. However, such calculations also require large computer resources and computational time. So, the LBL model is usually used only for benchmark solutions to validate approximate methods, not for the practical engineering applications[8]. The Band models can simulate the transmissivity of gases medium rather than the fundamental gas absorption coefficient, so they can only be compatible with the radiative trans-

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fer equation (RTE) in integral form, which means various techniques, e.g. discrete ordinates method (DOM), Monte-Carlo method (MCM) and finite volume method (FVM), developed to solve the differential form RTE cannot be used. Unlike the Band models, the aims of the Global models are to calculate the total radiative heat flux or its divergence by using spectrally integrated radiative properties. So, the Global models can be coupled with the techniques mentioned above to solve the differential form RTE [2,9]. The common Global models are the weighted-sum-of-gray-gases (WSGG) model, the full-spectrum K-distribution (FSK) model and spectral-line-based weighted-sum-of-gray-gases (SLW) model, etc. Among these models, the WSGG model, originally introduced by Hottel and Sarofim[10], has attracted widespread attentions for its efficiency and improved accuracy over the gray gas model, especially after Modest' work about the model for any RTE solver[11]. Moreover, the WSGG model have been successfully incorporated into the flow and temperature field calculations in a fully coupled fashion. Yu et al.[12] presented an extension of WSGG model to a mixture of nongray gas and gray particles. And the DOM was used to solve the calculation of radiative heat transfer equation which was coupled with WSGG model. Trivic[13] also used WSGG model to investigate the radiative heat transfer properties of nongray gases-particles mixtures by Zone Method and MCM in a 3-D enclosure geometry.

The particle radiative properties are distinctly different from those of gases. In addition to being able to absorb and emit radiant energy like the gases, the particles also have significant scattering properties. During the last several decades, for single particle with independent scattering, various techniques have been proposed to predict the particle radiative properties, e.g. Mie theory[5], T-matrix[13], discrete dipole approximation (DDA)[14], anomalous diffraction approximation (ADA)[15]; for particle aggregates with dependent scattering, the common calculated models include the superposition T-matrix[16] and the generalized multiparticle Mie-solution (GMM)[17] etc. When studying the effect of particle radiative properties on the gas-particle mixture, the particles are usually treated as single sphere, and many research has focused on the effect of the particle radiation on the temperature and heat transfer of high temperature gas-particle mixture media. Mengüc et al.[18] studied the radiative transfer in a pulverized coal-fired furnace, and pointed out that accurate knowledge of number density, temperature and particle concentration distributions were more critical than the detailed information about the index of refraction of particles and gas concentration distributions. Robert et al.[1] investigated the influence of particle and gas radiation in oxy-fuel combustion, and found that the particle radiation dominates and the gas composition only have a small effect on the total radiation. Daniel et al.[19] studied different particle types existing in a coal flame and found that the contribution of coal/char particles dominates the radiative heat transfer in the investigated cross-section of the flame. By combining the features of FSK model with the WSGG model, Guo et al.[4] proposed a new non-gray particle radiative property model to study the contribution of gases and particles to radiative heat transfer. The work revealed that particle radiative property should be simulated precisely, for the particles radiation played a significant role in the large-scale furnace.

In the present study, the WSGG model combined with the Mie theory is proposed to study the effect of particle size distribution on the radiative heat transfer in the mixture. To simplify the model and make it trackable, the particle in the high-temperature gas-particle mixture is assumed to be single, spherical, gray and independent scattering. The remainder of this research is organized as follows. First, the principles of the RTE and the WSGG model are introduced. Then, the effect of particle size, obeying uniform distribution and logarithmic normal (L-N) distribution, respectively, on the radiative heat flux, incident radiation and radiative heat source are investigated under the total particle volume fraction unchanged or the total particle number concentration unchanged. Finally, the main conclusions and perspectives are provided.

1 RTE and WSGG

For an absorbing, emitting, and scattering gas-particle mixture, the change of radiation intensity is obtained by the sum of the emission, absorption, scattering away from the direction $\boldsymbol{s}$, and scattering into the direction $\boldsymbol{s}$. The gas scattering is ignored normally, due to its small scattering coefficient. Moreover, in order to make the problem mathematically trackable, the particles are assumed to be single, spherical, gray and independent scattering, and the temperature of particle is the same as the gas. Therefore, according to the basic concept of the WSGG model where the total radiative energy is transferred via I different gray gases, the RTE is written as [4,13]

$$\begin{aligned}\sum_{i=1}^{I}\frac{\mathrm{d}I_{\mathrm{m},i}(z,\boldsymbol{s})}{\mathrm{d}z}=&\\ \sum_{i=1}^{I}[\kappa_{\mathrm{g},i}(z)+\kappa_{\mathrm{a,p}}(z)]I_{\mathrm{b}}(z)a_i(T)-&\\ \sum_{i=1}^{I}[\kappa_{\mathrm{g},i}(z)+\kappa_{\mathrm{a,p}}(z)+\kappa_{\mathrm{s,p}}(z)]I_{\mathrm{m},i}(z,\boldsymbol{s})+&\\ \sum_{i=1}^{I}\frac{\kappa_{\mathrm{s,p}}(z)}{4\pi}\int_{4\pi}I_{\mathrm{m},i}(z,\boldsymbol{s})\Phi(\boldsymbol{s}',\boldsymbol{s})\mathrm{d}\Omega'&\end{aligned}\quad(1)$$

where $I_{\mathrm{m},i}(z,\boldsymbol{s})$ is the radiation intensity in direction $\boldsymbol{s}$ at location z for the 'i' gray gas-particle mixture; $\kappa_{\mathrm{g},i}=\kappa_{\mathrm{g,p},i}p_{\mathrm{g},i}$ is the 'i' gray gas absorption coefficient, and $\kappa_{\mathrm{g,p},i}$, $p_{\mathrm{g},i}$ denote the spectral pressure absorption coefficient and partial pressure of 'i' gray gas; $\kappa_{\mathrm{a,p}}$, $\kappa_{\mathrm{s,p}}$ and $\Phi(\boldsymbol{s}',\boldsymbol{s})$ are the absorption coefficient, scattering coefficient of particles and scattering phase function of mixture media, which can be expressed as[4]

$$\begin{aligned}\kappa_{\mathrm{a,p}}=1.5\sum_{i=1}^{M}Q_{\mathrm{abs}}(D_i)\frac{f_{\mathrm{v}}\cdot F(D_i)}{D_i}=&\\ \frac{\pi}{4}\sum_{i=1}^{M}Q_{\mathrm{abs}}(D_i)\cdot D_i^2\cdot N_0\cdot F(D_i)&\end{aligned}\quad(2)$$

$$\begin{aligned}\kappa_{\mathrm{s,p}}=1.5\sum_{i=1}^{M}Q_{\mathrm{sca}}(D_i)\frac{f_{\mathrm{v}}\cdot F(D_i)}{D_i}=&\\ \frac{\pi}{4}\sum_{i=1}^{M}Q_{\mathrm{sca}}(D_i)\cdot D_i^2\cdot N_0\cdot F(D_i)&\end{aligned}\quad(3)$$

$$\begin{aligned}\Phi(\boldsymbol{s}',\boldsymbol{s})=\frac{3}{2\kappa_{\mathrm{s,p}}}\sum_{i=1}^{M}\frac{f_{\mathrm{v}}\cdot F(D_i)}{D_i}Q_{\mathrm{sca}}(D_i)\Phi_{\mathrm{p},i}(\boldsymbol{s}',\boldsymbol{s})=&\\ \frac{\pi}{4\kappa_{\mathrm{s,p}}}\sum_{i=1}^{M}N_0\cdot D_i^2\cdot F(D_i)Q_{\mathrm{sca}}(D_i)\Phi_{\mathrm{p},i}(\boldsymbol{s}',\boldsymbol{s})&\end{aligned}\quad(4)$$

where f_{v} is the total particle volume fraction; N_0 denotes the total particle number concentration; $F(D_i)$ is the normalized volume frequency distribution of the particle system with diameter D_i, $\sum_{i=1}^{M}F(D_i)=1$; Q_{abs}, Q_{sca} and Φ_{p} are the absorption factor, scattering factor and scattering phase of single particle, respectively, which can be predicted by the Mie theory[5].

In the present study, the emission weighted factors polynomial coefficients and the pressure based absorption coefficients were taken from both formulations of Dorigon et al.[21], which were obtained by fitting total emissivity from the lasted HITEMP2010 molecular spectroscopic experimental database[7], and not repeated here.

For I gray gases, the I values of the weighting factors should be evaluated. A common and easy representation of the temperature dependency of the emissivity weighting factors is a polynomial. The physical interpretation of the weighting factor $a_i(T)$ is the fractional amount of black body energy in the regions of spectrum where gray gas having absorption coefficient $\kappa_{\mathrm{g},i}$ exists, and it can be derived as follows[21]

$$a_i(T)=\sum_{j=1}^{N}b_{i,j}T_j\quad(5)$$

where $b_{i,j}$ is the polynomial coefficients of jth order for the ith gray gas. For the weighting factors must sum to unity and also must have positive values, the weighting factor for the transparent windows is set as $a_0(T)=1-\sum_{i=1}^{I}a_i$.

Considering black walls with known temperatures, the boundary conditions in this case can be expressed as follows[2]

$$\begin{aligned}\sum_{i=1}^{N}I_{\mathrm{m},i}(z,\boldsymbol{s})=\sum_{j=1}^{N}\varepsilon(z)I_{\mathrm{b}}(z,\boldsymbol{s})a_i(T)+&\\ \sum_{i=1}^{N}\frac{1-\varepsilon(z)}{\pi}\int_{4\pi}I_{\mathrm{m},i}(z,\boldsymbol{s}')\left|\boldsymbol{s}'\cdot\boldsymbol{n}\right|\mathrm{d}\Omega'&\end{aligned}\quad(6)$$

where ε denotes the emitting rate of the boundary, and $\varepsilon=1$ for the black wall; $\boldsymbol{n}$ is the outer normal direction of the wall. The RTE is solved by FVM, which is a kind of accurate radiative transfer algorithms and can provide the most flexible trade-off between precision and computation time. By solving the RTE, the incident radiation coming from all directions can be derived as[13]

$$G_m(z)=\sum_{i=1}^{N}G_{m,i}(z)=\sum_{i=1}^{N}\int_{4\pi}I_{m,i}(z,s)\mathrm{d}\Omega \quad (7)$$

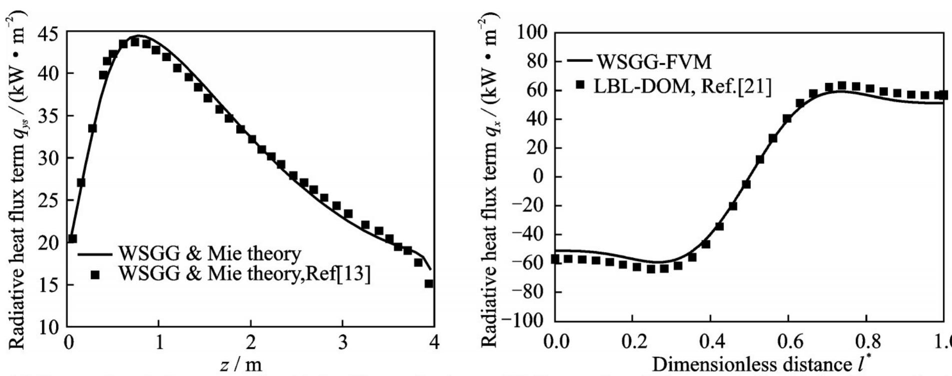
The radiative heat flux q_m and radiative heat source $\nabla\cdot q_m$ for all gas-particle mixtures are expressed as

$$q_m(z)=\sum_{i=1}^{N}q_{m,i}(z)=\sum_{i=1}^{N}\int_{4\pi}I_{m,i}(z,s)(s\times \boldsymbol{i})\mathrm{d}\Omega \quad \boldsymbol{i}=[e_x, e_y, e_z]^{\mathrm{T}} \quad (8)$$

$$\nabla\cdot q_m(z)=\sum_{i=1}^{N}\nabla\cdot q_{m,i}(z)=\sum_{i=1}^{N}[\kappa_{g,i}(z)+\kappa_{a,p}(z)][4\pi a_i(T)I_b(z)-G_{m,i}(z)] \quad (9)$$

where $\boldsymbol{i}$ is the direction vector.

In order to ensure the reliability of the research method used in this paper, two examples from published papers are selected to verify the method. Firstly, the radiative heat flux for mixtures of soot particle with H_2O and CO_2 in a 3-D enclosure geometry for y-direction, q_{ys}, at the middle of south wall (x=1.0 m, y=1.0 m) along z-direction with P_{H_2O}=0.2, P_{CO_2}=0.1, $f_{v,soot}=2.001\times10^{-6}$ was simulated. The detailed introduction can be seen in Ref. [13]. Secondly, the distributions of local radiative heat flux in 1D media mixed with H_2O and CO_2 also was simulated. The temperature and molar concentration of CO_2, H_2O distributions obey $T(l^*)=400+1\,400\sin^2(\pi l^*)$, $Y_{CO_2}(l^*)=0.2\sin^2(\pi l^*)$, $Y_{H_2O}(l^*)=2\times0.2\sin^2(\pi l^*)$, respectively. The l^* is dimensionless distance and $l^*=x/L$, the x is position coordinate and the path length L is 0.5 m. Fig.1 (a) shows the computed result, and it is obvious that there is a good agreement between the result calculated in Ref.[13], which means it is feasible to use the WSGG model and Mie theory to calculate the radiative properties of high temperature gas-particle mixture. Fig.1(b) also shows the simulated result, and it is obvious that there is a reasonable agreement between the result calculated by the LBL-DOM in the Ref.[21] and those by the WSGG-FVM in the present study. Therefore, the radiative properties of gases and particle mixtures were studied by WSGG available in the Ref. [21] and Mie theory.



(a) Comparison between results obtained by method used in this study and the results of Ref.[13]

(b) Comparison between results obtained by method used in this study and the results of Ref.[21]

Fig.1 Model validations

2 Numerical Simulation

To simplify the problem and save computation time, the gray approximation for the suspension of particles is taken. According to particles studied in the Ref. [13], the complex refractive index of particle are set as m=2.29+1.49i (soot particle), and the corresponding radiative properties at a mean wavelength λ_m, which calculates from the equal energy division relation for blackbody radiation and represents the spectral distribution of the incident radiation energy, is studied. The mean wavelength λ_m is derived as[5,10]

$$\lambda_m T_m = 4\,107.0\ \mu\text{m}\cdot\text{K} \quad (10)$$

$$T_m^4=\sum_{i=1}^{N'}V_iT_i^4\Big/\sum_{i=1}^{N'}V_i \quad (11)$$

where V and N' denote the control volume and the number of control volume in the FVM, respectively. To evaluate the effect of particle radiative properties on the radiative transfer in the homogeneous gas-particle mixtures, distribution of local incident radiation, local radiative heat source terms and local radiative heat fluxes are calculated in a 2D rectangular enclosure with 1 m in the x-direction and 0.5 m in the y-direction. The wall are also kept at a cold temperature of 0 K, and the temperature profile in the domain is expressed as[22-24]

$$T(x,y)=\begin{cases}(14\,000x-400)(1-3y_0^2+2y_0^3)+800 & x\leqslant 0.1\\ -10\,000/9(x-1)(1-3y_0^2+2y_0^3)+800 & x\geqslant 0.1\end{cases} \tag{12}$$

where $y_0=\left|y-0.25\right|/0.25$.

Fig.2 displays the current pre-defined temperature distribution field. It is very similar to the temperature distribution around a flame. Besides, this temperature distribution has been used many times to study the radiative model and numerical scheme of radiative transfer equation (RTE) solutions in hydrocarbon combustion environments[22-24]. Fig.3 shows the contours of incident radiation G_m, local radiative heat source terms $\nabla\cdot q_m$, and local radiative heat fluxes along x-direction q_x and y-direction q_y in the medium with a uniform gaseous mixture of 10% CO_2, 20% H_2O and 70% N_2. The total pressure is 1.0×10^5 Pa.

Moreover, two particle size distributions (PSDs), i.e. the uniform distribution and the L-N distribution, are studied, and the mathematical representations of the distribution functions are expressed as follows[25-26]

$$F_{\text{uniform}}(D)=1 \tag{13}$$

$$F_{\text{L-N}}(D)=\frac{1}{\sqrt{2\pi}\,D\cdot\ln\sigma}\times \exp\left[-\frac{1}{2}\left(\frac{\ln D-\ln\bar{D}}{\ln\sigma}\right)^2\right] \tag{14}$$

where $\bar{D}$ and σ are the characteristic diameter and the narrowness index of the distribution function, respectively. All investigated cases are summarized in Table 1 (PSDs obeying the uniform distribution). The dotted lines shown in Fig.2 are the central line in x plane, i.e. along (x, 0.25), and the central line in y plane, i.e. along (0.5, y), which indicate the locations for which the radiative heat transfer properties are simulated.

The cases 1.1—1.3 are used to study the effects of particle size on the radiative heat transfer properties with the total particle volume fraction f_v unchanged. The diameters of particle are set as 1, 3, 6 μm, respectively.

Fig.4 shows the calculated results of radiative heat flux, incident radiation and radiative heat source along (0.5, y) in the media. The relative errors between the cases with particle scattering and without particle scattering are also evaluated. From Figs.4(b, d, f), it can be found that when the total particle volume fraction f_v is unchanged, increasing the particle size will result in the decreasing of the

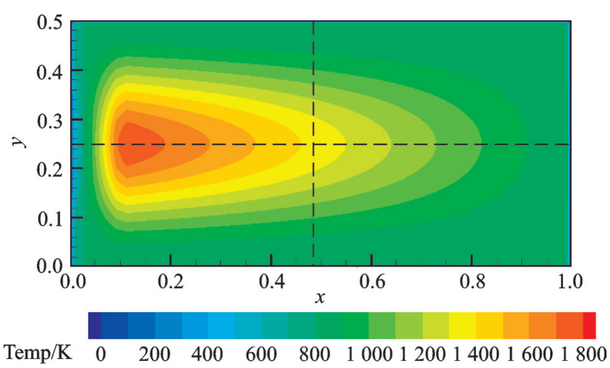


Fig.2 Contours of temperature for 2D model with Eq. (12)

Table 1 Investigated cases for evaluating effect of particle size obeying uniform distribution on radiative transfer properties in gas-particle mixtures

Case	T/K	N_0/m^{-3}	f_v	$F(D)$	p_{H_2O}	p_{CO_2}	p_{N_2}
1.1	Eq.(12)		2.0×10^{-6}	Eq.(13), D=1 μm	0.2	0.1	0.7
1.2	Eq.(12)		2.0×10^{-6}	Eq.(13), D=3 μm	0.2	0.1	0.7
1.3	Eq.(12)		2.0×10^{-6}	Eq.(13), D=6 μm	0.2	0.1	0.7
1.4	Eq.(12)	3.00×10^{11}		Eq.(13), D=1 μm	0.2	0.1	0.7
1.5	Eq.(12)	3.00×10^{11}		Eq.(13), D=3 μm	0.2	0.1	0.7
1.6	Eq.(12)	3.00×10^{11}		Eq.(13), D=6 μm	0.2	0.1	0.7

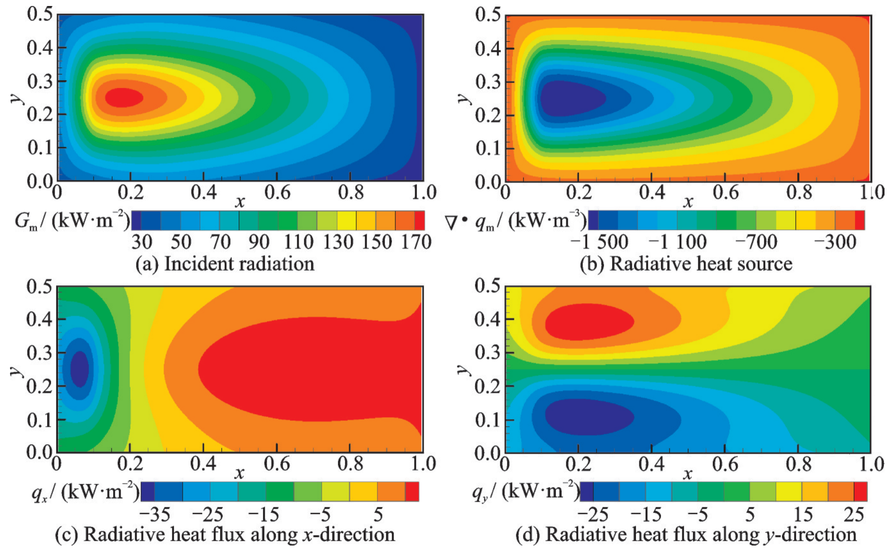


Fig.3 Contours of radiative heat flux, incident radiation and radiative heat source terms in gaseous mixtures of the 2D rectangular enclosure with 10% CO_2, 20% H_2O and 70% N_2

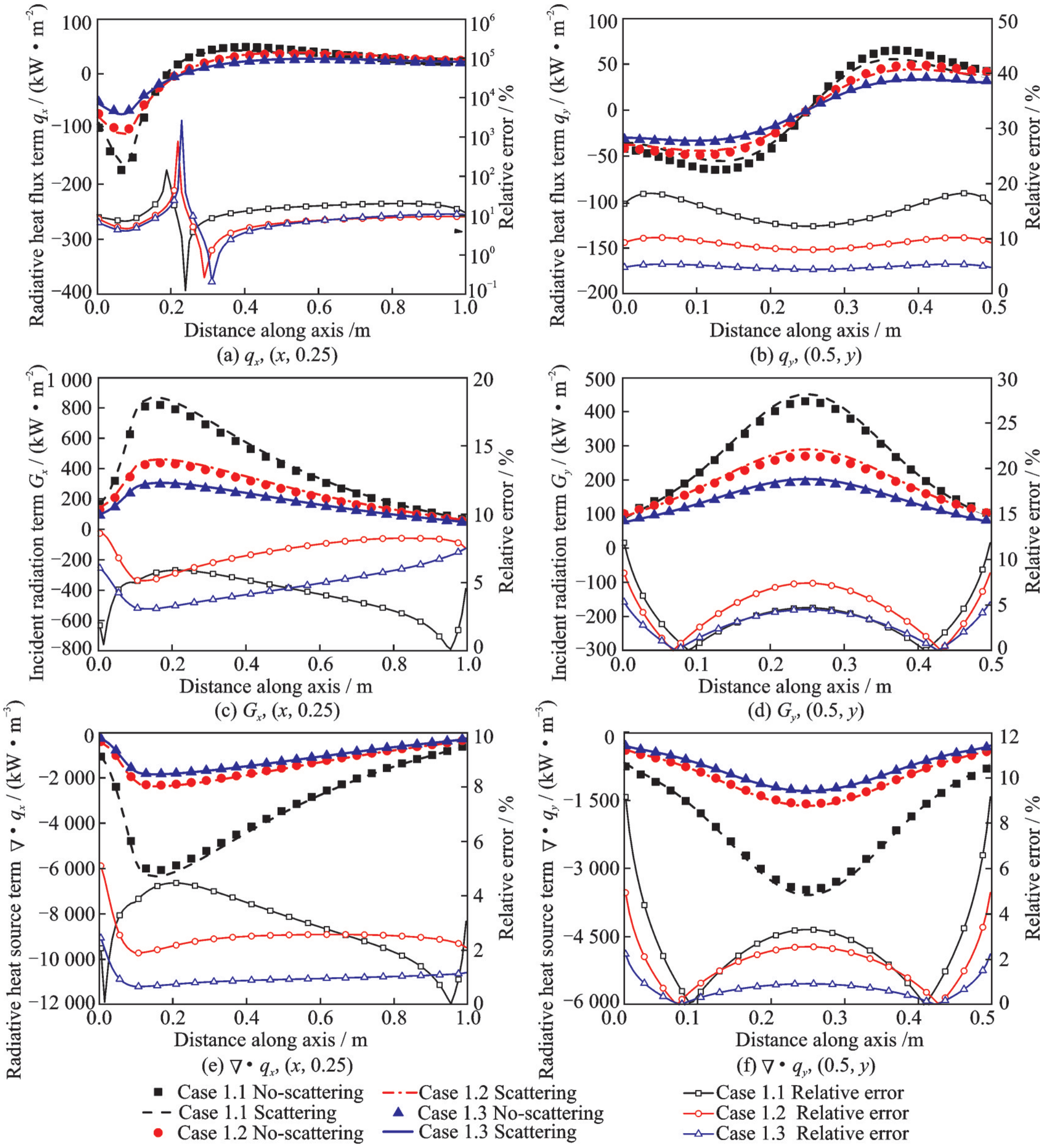


Fig.4 Radiative heat transfer properties in the gas-particle media with particle volume fraction f_v unchanged

absolute value of the radiative heat flux term q_y, the incident radiative term G_y and radiative heat source term $\nabla\cdot q_y$ along (0.5, y). The absolute value of radiative heat flux term calculated without particle scattering is larger than that with particle scattering, while the absolute values of incident radiative term and radiative heat source term calculated without particle scattering is smaller than that with particle scattering. The phenomenon indicates that irrespective of particle scattering, the value of radiative heat flux will be over predicted, while the incident radiative term and radiative heat source term will be underestimated. Moreover, comparing the maximum value of the relative errors between the results with particle scattering and those without particle scattering (e.g. the relative errors in simulating radiative heat flux term for D=1 ,3 , 6 μm are about 19%, 10.1% and 5.4%), it can be found that when total particle volume fraction f_v is unchanged and the particle size is small, the effect of particle scattering on the radiative heat flux term, the incident radiative term and radiative heat source term should not be ignored. When it comes to studying the radiative heat transfer properties along (x, 0.05), the conclusions show slight difference from that obtained along (0.5, y), especially at the location in the media with higher temperature. However, the overall results obtained along (x, 0.05) are consistent with those obtained along (0.5, y).

The cases 1.4—1.6 are used to study the effects of particle size on the radiative heat transfer properties with the total particle number concentration N_0 unchanged. The PSDs are also assumed as the uniform distribution, and the diameters are also set as 1,3, 6 μm, respectively. Fig.5 shows the corresponding calculated results. Compared with the results obtained from cases 1.1—1.3, many different conclusions can be obtained. From Figs.5(b,d,f), it can be found that when the total number concentration N_0 is unchanged, increasing the particle size will increase the maximum absolute value of the radiative heat flux term q_y, the incident radiative term G_y and radiative heat source term $\nabla\cdot q_y$ along (0.5, y). Moreover, comparing the maximum value of the relative errors between the results with particle scattering and that without particle scattering (e.g. the relative errors in simulating radiative heat flux term for D=1, 3, 6 μm are about 0.9%, 22% and 54%), it can be found that when the total number concentration N_0 is unchanged and the particle size is large, the effect of particle scattering on the radiative heat flux term, the incident radiative term and radiative heat source term should not be ignored. When it comes to studying the radiative heat transfer properties along (x, 0.25), the conclusions show slight difference from those obtained along (0.5, y), especially at the location in the media with higher temperature. However, the overall results obtained along (x, 0.05) are also consistent with those obtained along (0.5, y).

Table 2 lists the cases with PSDs obeying the L-N distribution, and the L-N distributions studied in the manuscript are depicted in Fig.6. In studying cases 2.1—2.8, total particle volume fraction f_v is unchanged, and the effects of the narrowness index σ (cases 2.1—2.4) and characteristic diameter $\overline{D}$ (cases 2.5—2.8) of the distribution function on the radiative heat transfer properties are evaluated. Figs. 7, 8 show the calculated results of radiative heat flux, incident radiation and radiative heat source terms in the media for cases 2.1—2.4 and cases 2.5—2.8. It is obvious that only increasing the narrowness index σ, the absolute values of radiative heat flux, incident radiation and radiative heat source terms will increase. While only increasing the characteristic diameter $\overline{D}$, the absolute values of radiative heat flux, incident radiation and radiative heat source terms will decrease.

The total particle number concentration N_0 is unchanged in cases 2.9—2.16, and effects of the narrowness index σ (cases 2.9—2.12) and characteristic diameter $\overline{D}$ (cases 2.13—2.16) of the distribution function on the radiative heat transfer properties are evaluated in Figs.9, 10. Unlike the conclusions obtained from cases 2.1—2.8, it is obvious that if only increasing the narrowness index σ, the absolute values of incident radiation and radiative heat source terms will decrease, while those of radiative heat

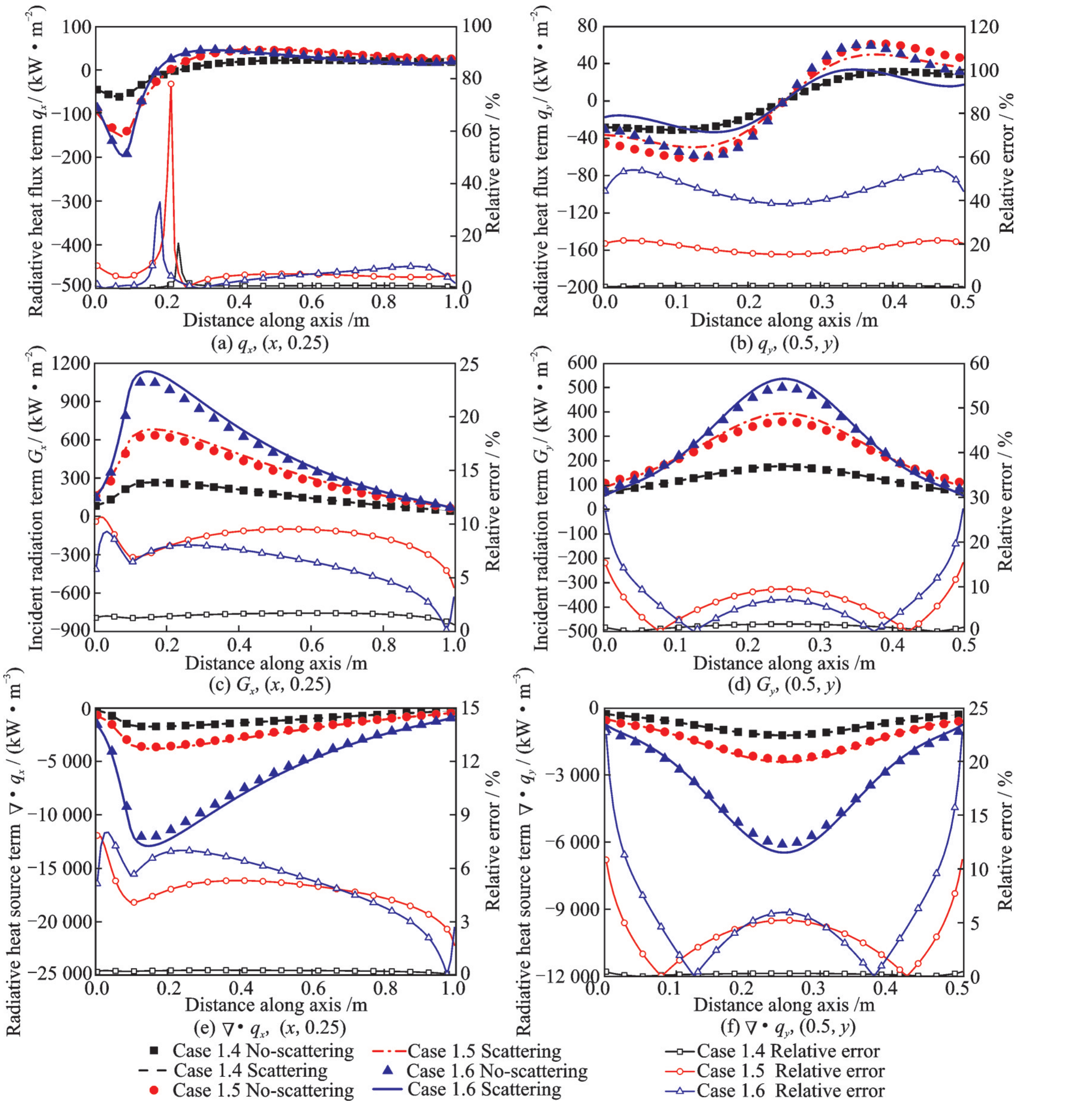
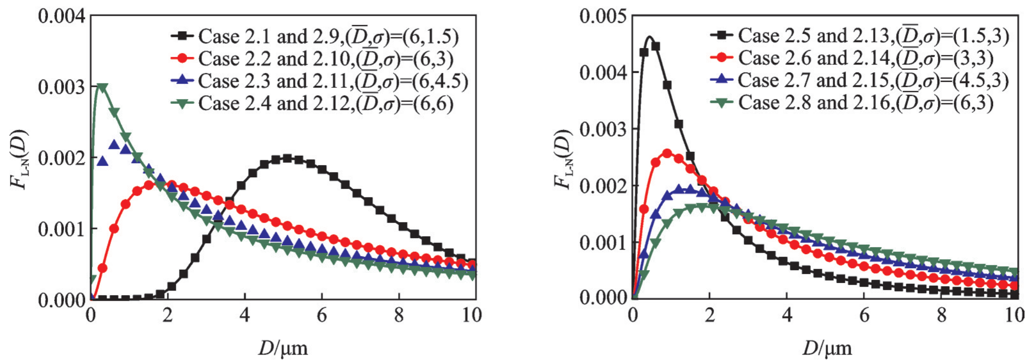


Fig.5 Radiative heat transfer properties in the gas-particle media with particle number concentration N_0 unchanged

Table 2 Investigated cases for evaluating effect of particle size obeying L-N distribution on radiative transfer properties in gas-particle mixtures

Case	T/K	N_0/m^{-3}	f_v	$F(D)$	p_{H_2O}	p_{CO_2}	p_{N_2}
2.1	Eq.(12)		2.0×10^{-6}	Eq.(14), $(\overline{D},\sigma)=(6.0, 1.5)$	0.2	0.1	0.7
2.2	Eq.(12)		2.0×10^{-6}	Eq.(14), $(\overline{D},\sigma)=(6.0, 3.0)$	0.2	0.1	0.7
2.3	Eq.(12)		2.0×10^{-6}	Eq.(14), $(\overline{D},\sigma)=(6.0, 4.5)$	0.2	0.1	0.7
2.4	Eq.(12)		2.0×10^{-6}	Eq.(14), $(\overline{D},\sigma)=(6.0, 6.0)$	0.2	0.1	0.7
2.5	Eq.(12)		2.0×10^{-6}	Eq.(14), $(\overline{D},\sigma)=(1.5, 3.0)$	0.2	0.1	0.7
2.6	Eq.(12)		2.0×10^{-6}	Eq.(14), $(\overline{D},\sigma)=(3.0, 3.0)$	0.2	0.1	0.7
2.7	Eq.(12)		2.0×10^{-6}	Eq.(14), $(\overline{D},\sigma)=(4.5, 3.0)$	0.2	0.1	0.7
2.8	Eq.(12)		2.0×10^{-6}	Eq.(14), $(\overline{D},\sigma)=(6.0, 3.0)$	0.2	0.1	0.7
2.9	Eq.(12)	3.00×10^{11}		Eq.(14), $(\overline{D},\sigma)=(6.0, 1.5)$	0.2	0.1	0.7
2.10	Eq.(12)	3.00×10^{11}		Eq.(14), $(\overline{D},\sigma)=(6.0, 3.0)$	0.2	0.1	0.7
2.11	Eq.(12)	3.00×10^{11}		Eq.(14), $(\overline{D},\sigma)=(6.0, 4.5)$	0.2	0.1	0.7
2.12	Eq.(12)	3.00×10^{11}		Eq.(14), $(\overline{D},\sigma)=(6.0, 6.0)$	0.2	0.1	0.7
2.13	Eq.(12)	3.00×10^{11}		Eq.(14), $(\overline{D},\sigma)=(1.5, 3.0)$	0.2	0.1	0.7
2.14	Eq.(12)	3.00×10^{11}		Eq.(14), $(\overline{D},\sigma)=(3.0, 3.0)$	0.2	0.1	0.7
2.15	Eq.(12)	3.00×10^{11}		Eq.(14), $(\overline{D},\sigma)=(4.5, 3.0)$	0.2	0.1	0.7
2.16	Eq.(12)	3.00×10^{11}		Eq.(14), $(\overline{D},\sigma)=(6.0, 3.0)$	0.2	0.1	0.7



(a) The L-N distribution with $\overline{D}$=6 and different σ (b) The L-N distribution with σ=3 and different $\overline{D}$

Fig.6 L-N distribution studied in the paper

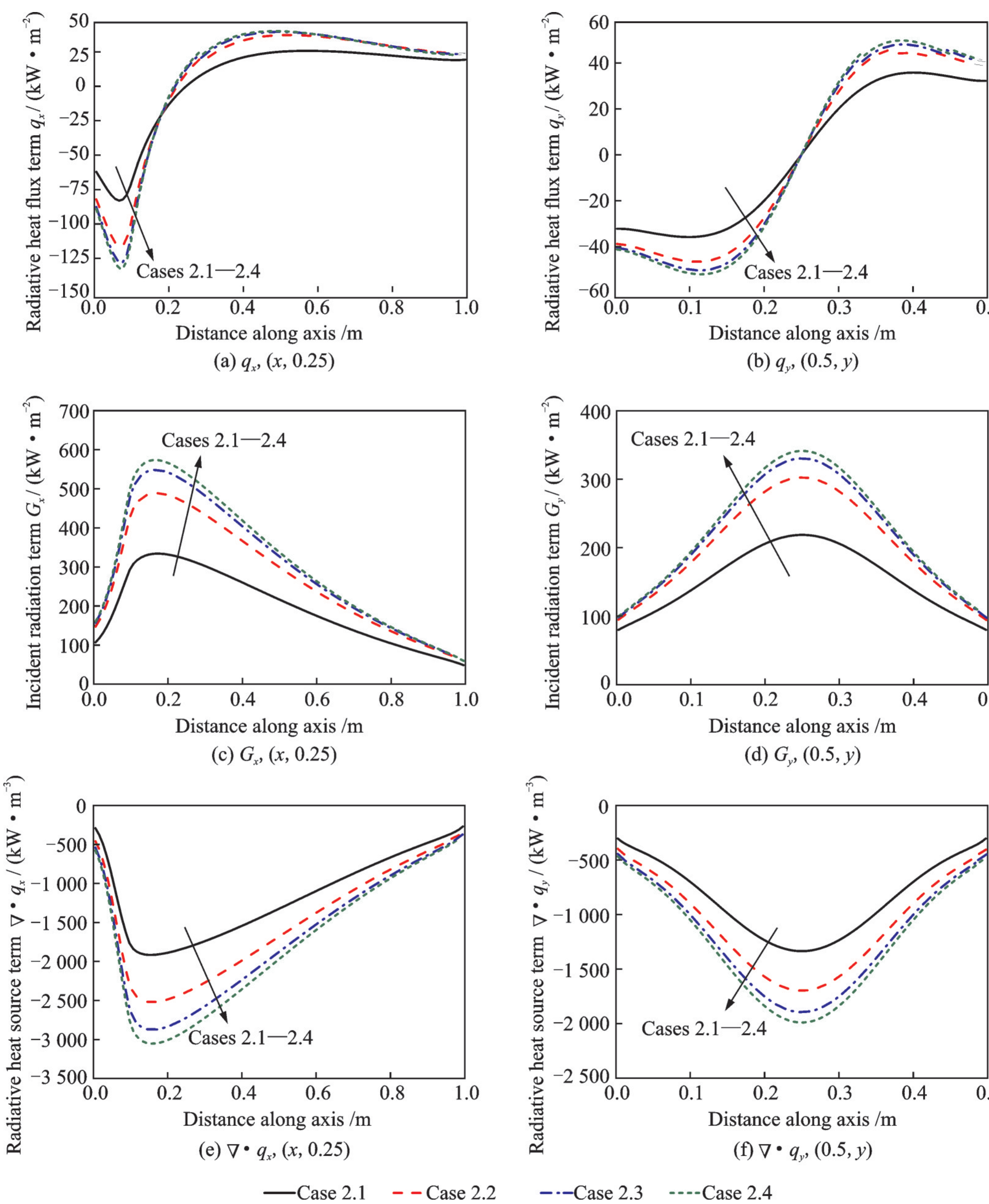


Fig.7 The values of radiative heat flux, incident radiation and radiative heat source terms in gas-particle mixtures with particle volume fraction f_v unchanged and different narrowness indices of L-N distributions (Cases 2.1—2.4)

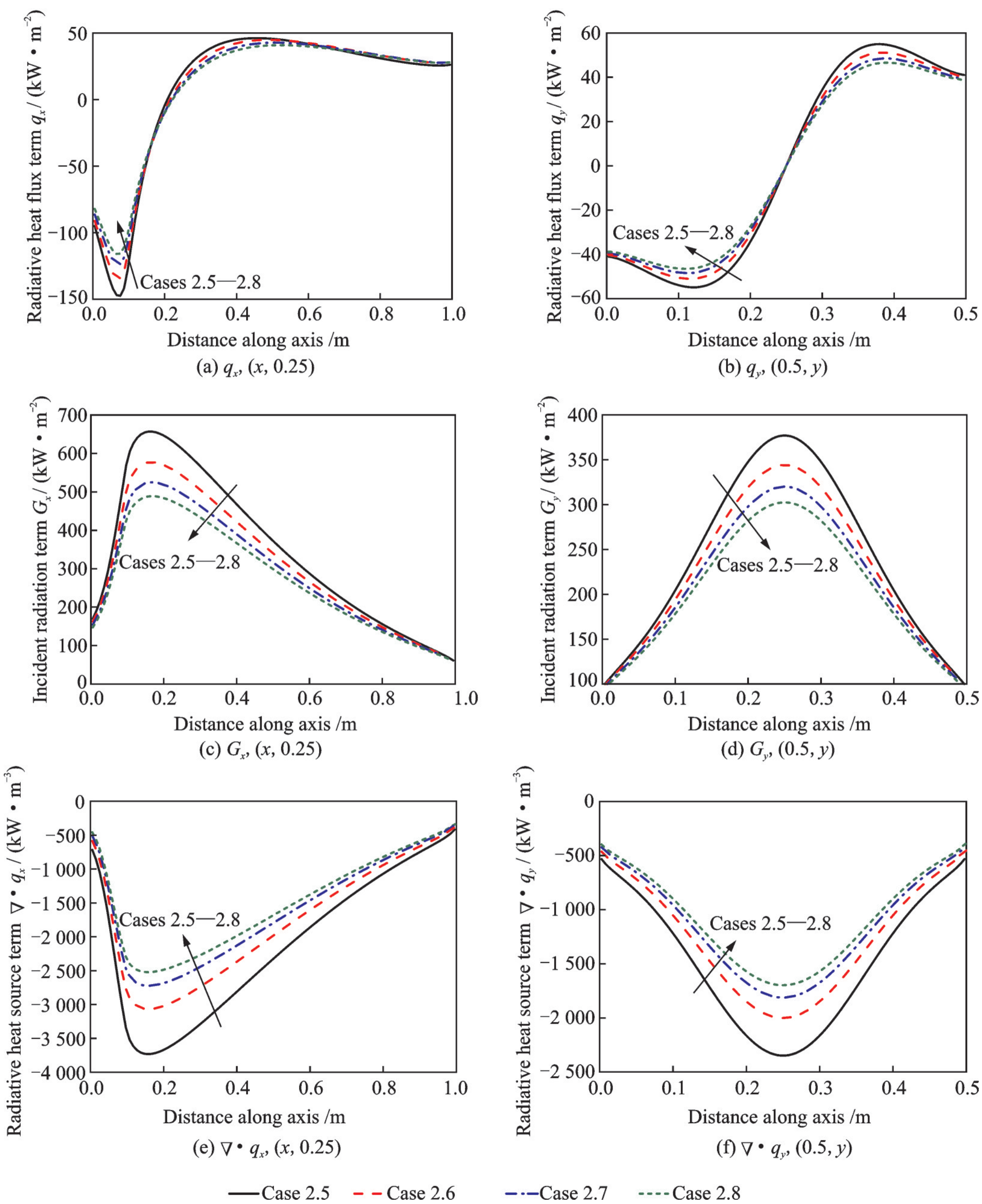
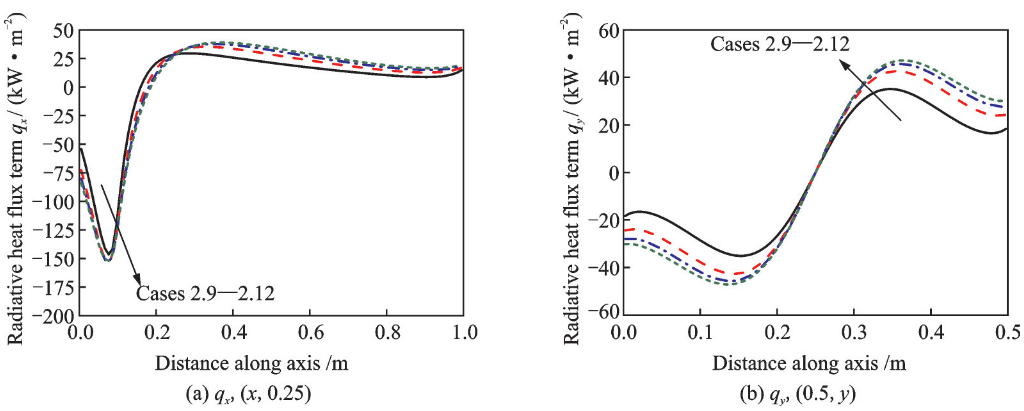


Fig.8 The values of radiative heat flux, incident radiation and radiative heat source terms in gas-particle mixtures with particle volume fraction f_v unchanged and different characteristic diameters of L-N distributions (Cases 2.5—2.8)



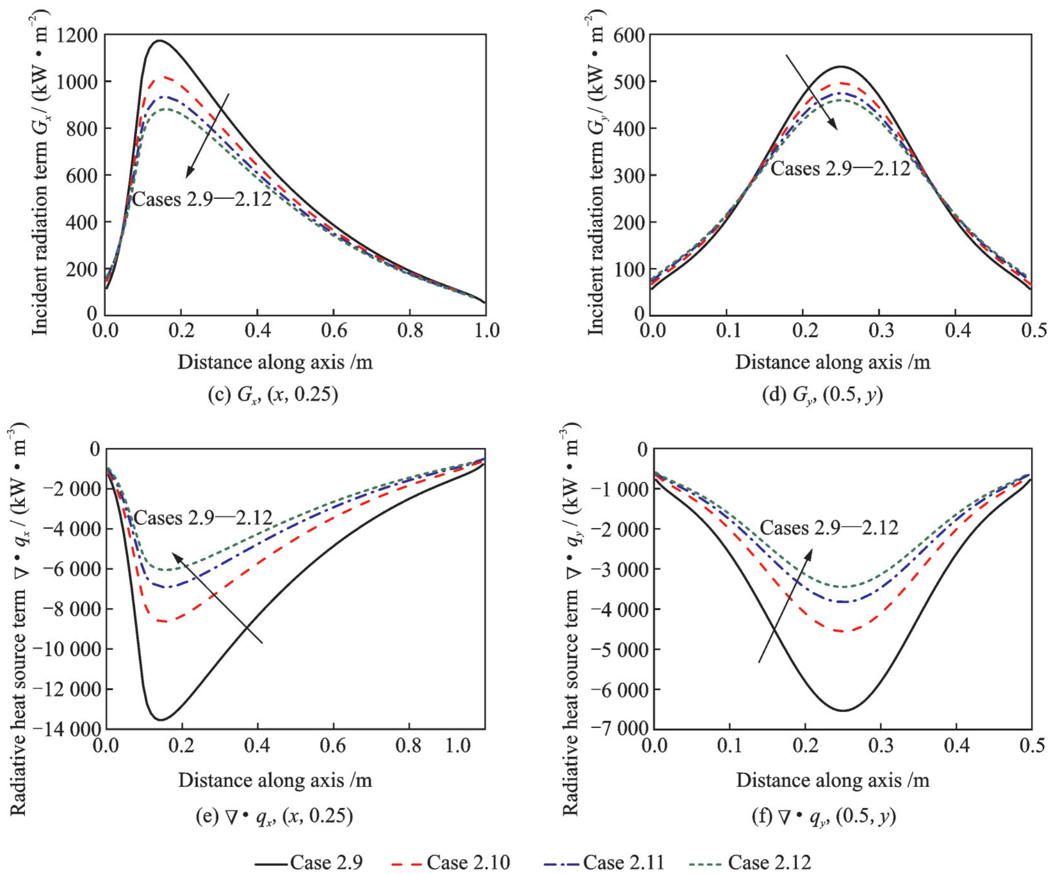
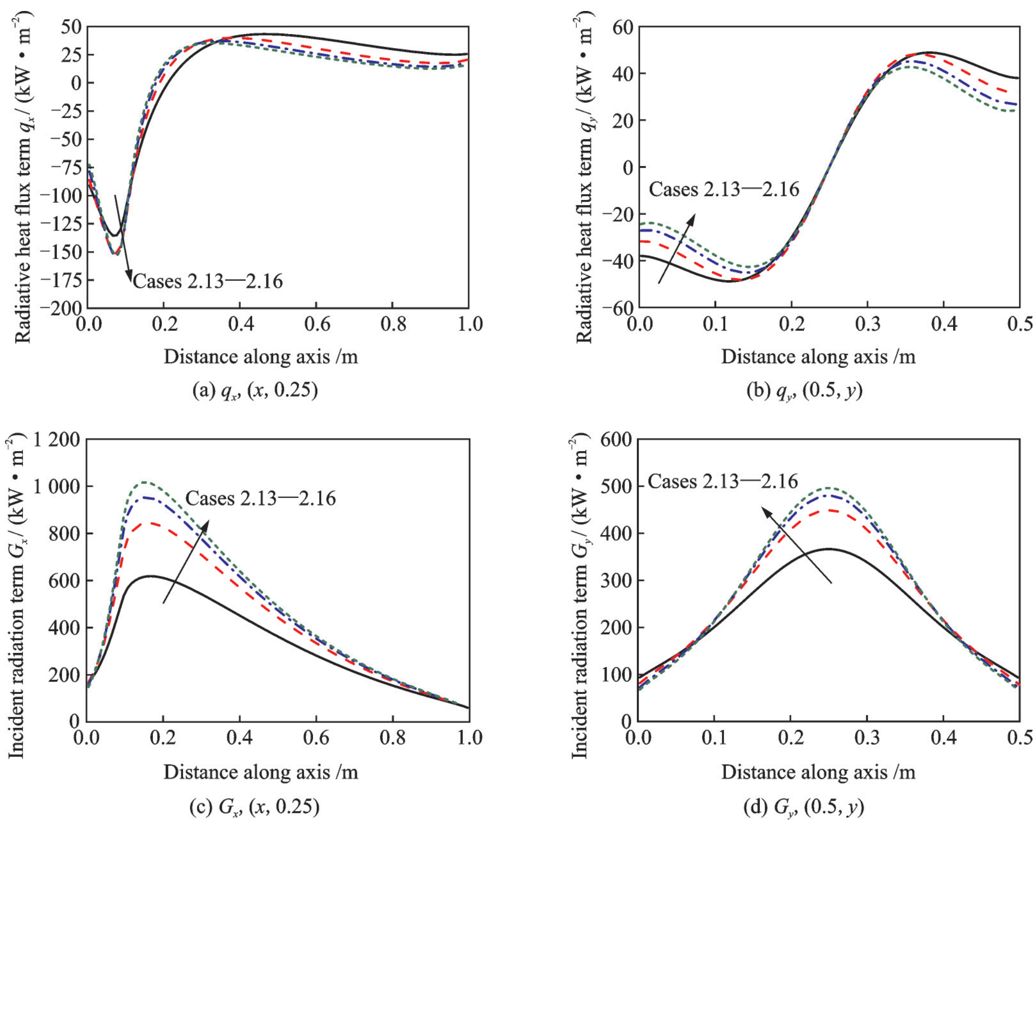


Fig.9 The values of radiative heat flux, incident radiation and radiative source terms in gas-particle mixtures with total particle number concentration N_0 unchanged and different narrowness indices of L-N distributions (Cases 2.9—2.12)



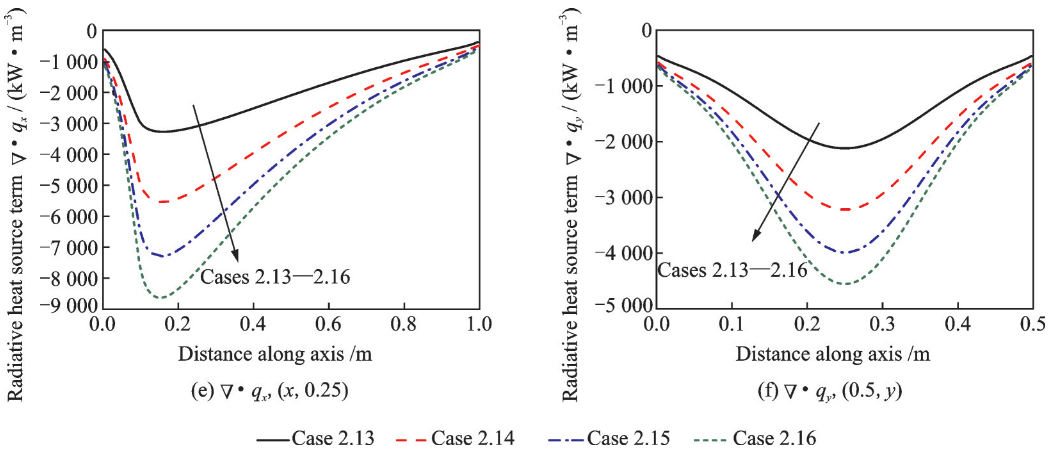


Fig.10 The values of radiative heat flux, incident radiation and radiative source terms in gas-particle mixtures with total particle number concentration N_0 unchanged and different characteristic diameters of L-N distributions (Cases 2.13—2.16)

flux will increase; if only increasing the value of characteristic diameters $\overline{D}$, the absolute value of radiative heat flux along $(x, 0.25)$, incident radiation and radiative heat source terms will increase, while those of radiative heat flux along $(0.5, y)$ will decrease.

3 Conclusions

By applying the WSGG and Mie theory to study the radiative heat transfer properties of gases and particle, the radiative transfer equation of gas-particle mixtures is solved by the FVM, and the effects of particle size, which obeys uniform distribution and L-N distribution, on the radiative transfer properties, i.e. radiative heat flux, radiative heat source and incident radiation, are studied, respectively. The following conclusions can be drawn:

(1) When the particle volume fraction f_v is unchanged and the particle size obeys uniform distribution, increasing particle size will result in the decreasing of absolute value of radiative heat transfer properties, and weaken the effect of particle scattering.

(2) When the particle number concentration N_0 is unchanged and the particle size obeys uniform distribution, increasing particle size will increase the absolute value of radiative heat transfer properties, and enhance the effect of particle scattering.

(3) When the total particle volume fraction f_v is unchanged and the particle size obeys L-N distribution, increasing the narrowness index σ or decreasing the characteristic diameter $\overline{D}$ will increase the absolute value of radiative heat transfer properties.

(4) When the total number concentration N_0 is unchanged and the particle size obeys L-N distribution, increasing the narrowness index σ or decreasing the characteristic diameter $\overline{D}$ will result in the decreasing of the absolute value of radiative heat source and incident radiation terms, while the changing of radiative heat flux is different.

Therefore, in the calculation process of radiation heat transfer of high-temperature gas-particle mixture medium, the importance of different particle size distribution for radiation heat transfer characteristics should be fully considered.

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