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多重散射对含有气体和颗粒的燃烧介质中辐射传热的影响

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EFFECTS OF MULTIPLE SCATTERING ON RADIATIVE TRANSFER IN GAS-PARTICLES MEDIA

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ABSTRACT: To study radiative transfer in a participating medium composed of gas and particles, with arbitrary concentrations of particles, a Monte Carlo simulation has been developed. After validation by comparing with other methods, effects of multiple scattering on radiative transfer are investigated. A critical volume fraction f_v^c is defined to distinguish two radiative flux behaviors versus particles volume fractions : a single scattering zone and a multiple scattering zone. The emissive flux of the slab rises steeply and is dominated by gas and particle single scattering in the single scattering zone, while it approaches a constant value and is dominated by absorption and multiple scattering of particles in the multiple scattering zone.

KEY WORDS: Thermal power engineering; Gas-particles; Multiple scattering; Emissive flux; Thermal radiation

摘要：该文采用蒙特卡洛方法研究包括吸收性气体和具有一定浓度颗粒的燃烧环境中的辐射传热。在蒙特卡洛程序被验证之后，研究了多重散射对辐射传热的影响。定义了一个临界颗粒体积份额 f_v^c，作为区分单次散射区和多重散射区的分界。当颗粒云的体积份额位于单次散射区和多重散射区时，其辐射通量的变化表现出不同的行为。在单次散射区，平板的辐射通量随着离子浓度增加而剧烈增长，辐射行为受到颗粒单次散射的影响。在多重散射区，离子浓度的增加不会引起辐射通量的增长，辐射通量趋近于一个固定值，辐射行为受到气体吸收和多重散射的双重影响。

关键词：热能工程；气体-颗粒；多重散射；辐射通量；热辐射

1 INTRODUCTION

Radiative transfer in participating media has an important influence on combustion and other industrial processes. The radiative transfer in a medium including spectral gas and polydisperse particles affects by emission, absorption and scattering of gas and particles. In the recent decade, various methods to solve the radiative transfer equation (RTE) in participating medium have been developed, and different factors of influence on the radiative transfer were studied.

Goodwin *et al*. [1] reported the spectral values of the optical complex refractive index of coal fly ash, and investigated the effects of size distribution of fly ash particle on radiative transfer. They predicted that the emittance of a slab is independent on size distribution, while the transmittance is dependent on size distribution. The effect of anisotropic scattering of the individual particle on radiative transfer has been studied by Liu *et al*. [2] and the result indicated that this effect on radiative transfer can be neglected, if the particle has a highly forward scattering phase function. Kokhanovsky *et al*. [3] studied the influence of the particle shape in a weakly absorbing, optically thick layer and pointed out the differences between different particle nonsphericities. Bhattacharya [4] presented an analysis of the influence of complex refractive index and particle size on the radiative properties and heat transfer involving ash clouds which indicates that the estimation of the imaginary part of the index has a larger influence than the real part. The authors of this paper have done some research on the inverse radiation transfer in recent years[5-8].

Much of the attention of the prior investigations focuses on the configurations where single scattering is dominant. This paper considers the configurations where multiple scattering can be dominant. The Monte Carlo technique is considered as an accurate and convenient method for numerical resolution of the radiative transfer equation [9-10]. In this work, a Monte Carlo program for radiative transfer in a participating medium is developed. We analyze effects of multiple scattering on radiative transfer.

2 MONTE CARLO TECHNIQUE AND ITS VALIDATION

During the last decade, the authors developed a Monte Carlo program which had been applied to different studies [11-13], but in configuration without emission. In this paper, the program has been extended to take into account the own emission of studied media. The developed Monte Carlo program allows to analyze the radiative transfer in an inhomogeneous non-gray one-dimension slab. The configuration under study corresponds to the case previously studied by Farmer [9]. Between two cold (T_w =0), black walls separated by a 5m distance (as shown in Fig.1), the medium consists of gas (carbon dioxide and nitrogen) and various concentrations of carbon particles. The total gas pressure was specified to 1 atm, and the partial pressure of carbon dioxide is 0.21 atm, independent on the particles concentrations. The optical refractive index of carbon particles in Ref. [14] is used to calculate scattering coefficients, absorption coefficients and the phase functions of the particles according to Mie theory. The slab is divided into 36 identical subregions, and the photons number sent by each subregion is 10^6. Wave number range varies from 835 to 10000 cm^{-1}, sampled every 10 cm^{-1}.

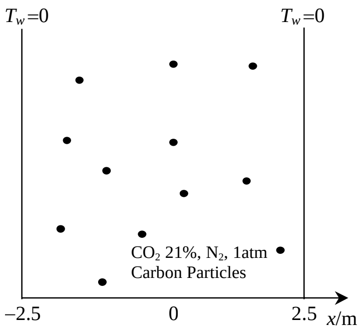
In the gas, only CO_2 plays an important role in emission and absorption. A combined Elsasser narrow-band and Edwards wide-band model [15] is used to determine the spectral absorption coefficient of CO_2. The absorption coefficients for each wave number are given by

$$k_{a\eta} = \rho(S_c/\delta)[\sinh(\pi\beta/2)/\{\cosh(\pi\beta/2)-\cos[2\pi(\eta-\eta_c)/\delta]\}] \tag{1}$$

where ρ is the density of gas, S_c is the mean line-intensity, δ is the line spacing, β is the pressure broadening parameter. The subscript c represents the band center. All these parameters are summarized in Table 1(a) of Ref. [15].

In the Monte Carlo procedure, energy bundles (called photons for convenience) are sent from emissive sources (gas and particles) and encounter different events before leaving the slab or being absorbed. Each event is characterized by a probability, calculated according to the corresponding physical law[16].

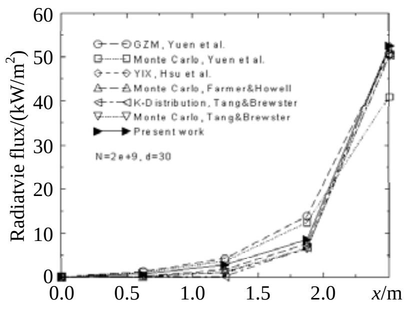
Firstly we assume that particles concentration N equals to 2.0×10^9 particles/m^3, and the diameter of spherical particles d is 30μm, to compare our predictions with the results of 6 differents methods in Ref.[17]. Fig.2 shows that our results are in agreement with those of Ref. [17], validating the developed code.



注：宽度 5m，CO_2 的分压力 0.21atm，碳粒的复折射率 1.92-0.45i

图 1 含有气体和颗粒的平板

Fig.1 Geometry of a gas-particles slab



注：浓度 N=2.0×10^9 颗粒/ m^3，粒径 d=30μm, T_g=T_p=1000K

图 2 本文结果与其它方法的比较

Fig.2 Comparisons with other methods

3 RESULTS AND DISCUSSIONS

3.1 Introduction

The study by Farmer [9] indicated that an increase of the carbon particles concentration produced significantly higher emissive flux (in this paper, emissive flux refers to the radiative flux exiting from one side of the slab), but the concentration was limited to 2.0×10^9 particles/m^3. For such concentrations, the gas emission and the particles single scattering are dominant, leading to the conclusion that an increase of particles concentration generates an increase of the emissive flux out of the slab. In fact, the particles scattering phenomenon in the participating medium is strongly linked to the particles volume fraction f_v (here, f_v is defined as the ratio of the particles volume and the total volume of gas-particles medium) [18], and the scattering effects are very different for various concentrations of particles. When f_v is low, the single scattering dominates. When f_v grows, multiple scattering becomes important. For large values of f_v, say 5% or 10%, dependent scattering may appear. These different scattering behaviors must be taken into account in a radiative transfer model, because their effects on emissive flux are not the same.

Guidt et al. defined a dimensionless criterion r in Ref. [19]

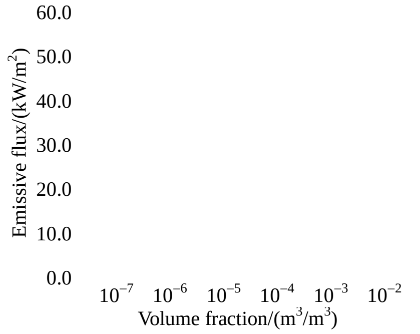
$$r = d\sqrt{Q_{ext}}N^{1/3} \tag{2}$$

where Q_{ext} is the extinction efficiency factor. They referred to r =1/2 for dependent scattering. A simple calculation with carbon particles gives the smallest volume fraction for dependent scattering : 2×10^{-2} m^3/m^3 ($N = 1.45\times10^{12}$ particles/m^3). Because this paper is not concerned with the dependent scattering, we explore only the variation of the emissive flux when f_v increases from 2×10^{-8} m^3/m^3 to 2×10^{-2} m^3/m^3.

The increase of particles concentrations in a gas-particles medium leads to two effects : transition from single scattering to multiple scattering, and transition from gas-predominance to particles-predominance. So the variation of emissive flux with particles concentrations is affected by these two factors at the same time.

3.2 Influence of multiple scattering and absorption of particles

In section (3.1) , the gas is assumed to be transparent, to study the influence of multiple scattering and absorption of particles. The emissive flux with different volume fractions are shown in Fig.3.



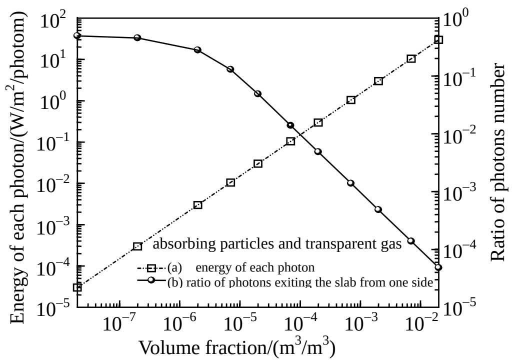
注：介质中含吸收性颗粒和透明气体，T_p=1000K

图 3　辐射通量随浓度 f_v 的变化

Fig.3　Emissive flux versus different volume fractions f_v,

In Fig.3, the curve first rises very steeply, then becomes flatter until it approaches a limiting value. When the volume fraction of particles is low, the emissive flux of the slab increases with the concentration, as it has been previously predicted [9] . If the volume fraction of particles is high, the emissive flux does not continue to rise with particles concentration, but tends to a constant value.

In the Monte Carlo program, the emissive flux is determined by photons number exiting the slab and energy of each photon. Fig.4 shows varieties of these two parameters.



注：介质中含吸收性颗粒和透明气体，d=30μm, T_p=1000K

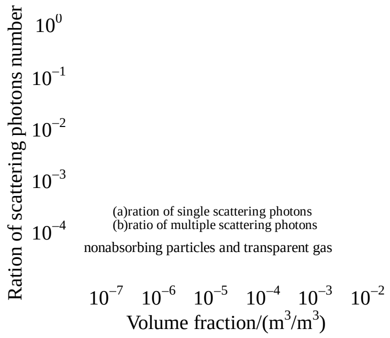
图 4　从平板一侧发射出的射线数和每条射线的能量与颗粒浓度的关系

Fig.4　Photons number exiting the slab from one side and energy of each photon versus particles volume fractions

When the concentration of particles is low, the photons number exiting the slab decreases very slowly

(Fig.4 (b)), and the energy of each photon goes up more quickly (Fig.4 (a)), so the emissive flux increases (Fig.3). Then, when the concentration is high, the increase of energy of each photon (Fig.4 (a)) is completely compensated by the decrease of photons number exiting the slab (Fig.4 (b)), as a result, the emissive flux tends to a constant, as shown in Fig.3.

The effects of scattering and absorption of particles are shown in Fig.5 and Fig.6, respectively for nonabsorbing and absorbing particles. The single scattering photons number is the photons number exiting the slab after only one scattering, and the multiple scattering photons number is the photons number exiting the slab whose scattering times are more than one.



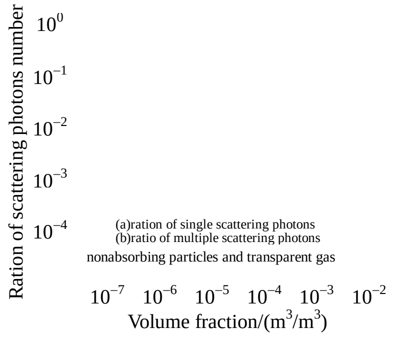
注：介质中含非吸收性颗粒和透明气体，d=30μm, T_g=T_p=1000K

图 5 单次散射和多次散射的射线数随颗粒浓度的变化

Fig.5 Photons number of single scattering and multiple scattering versus particles volume fractions

The particles are assumed to be nonabsorbing in Fig.5. When the particles concentration is low, the number of photons exiting the slab due to single scattering is much larger than that due to multiple scattering. With the increase of particles concentration, the photons number of multiple scattering rises rapidly, while the photons number of single scattering decreases after reaching a maximal value. When the particles concentration is high, the number of photons exiting the slab due to multiple scattering is much larger than that due to single scattering. This process has been previously described in Ref. [18].

Fig.6 shows the significant effects of particles absorption on the multiple scattering photons number, for absorbing particles. When the particles concentration is low, the single scattering predominates in a similar way observed when there is no absorption. When the particles concentration is high, because of the absorption of particles, the photons number of multiple scattering does not rise continuously but decrease with the particles volume fraction, as the single scattering photons number does. The multiple scattering leads to significantly higher absorption in the absorbing medium.



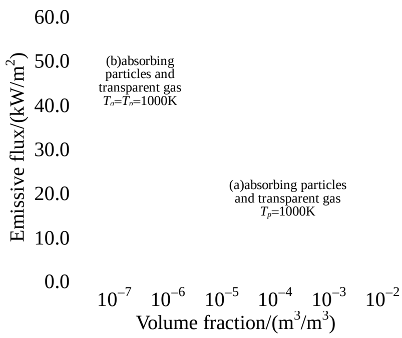
注：介质中含非吸收性颗粒和透明气体，d=30μm, T_g=T_p=1000K

图 6 单次散射和多次散射的射线数随颗粒浓度的变化

Fig.6 Photons number of single scattering and multiple scattering versus particles volume fractions

3.3 Influence of absorbing gas

Fig.7 shows effects of the absorbing gas on the emissive flux. Comparing curve (a) and curve (b) in Fig.7, it indicates that the absorbing gas has the predominant influence on the emissive flux only for low particles volume fraction. When particles concentration is high, the emission, absorption and scattering of particles are much larger than that of gas, the emissive flux is dominated by particles.



注：d=30μm

图 7 气体的吸收性对辐射通量的影响

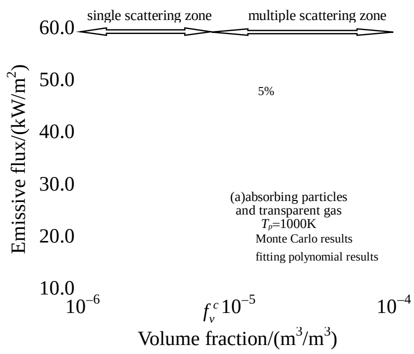
Fig.7 Effects of the absorbing gas on the emissive flux

3.4 Single scattering zone and multiple scattering zone

In Fig.7, the slope of emissive flux curve changes dramatically for different particles volume fractions.

We specify a critical volume fraction f_v^c , which divides the particle volume fractions into two different zones, called the single scattering zone and the multiple scattering zone.

The way to define the critical volume fraction f_v^c for the case in Fig.7 (b) is shown in Fig.8. A polynomial is found to represent the emissive flux for volume fraction ranging from 1×10^{-6} m^3/m^3 to 1×10^{-4} m^3/m^3. The significant change of the emissive flux versus the particles volume fraction is included in this volume fraction range. f_v^c is the volume fraction, where the emissive flux begins to reach 95% of the maximum emissive flux value.



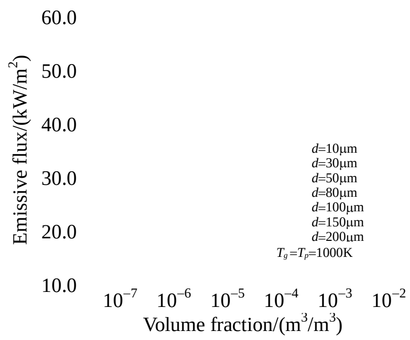
注：d=30μm

图 8　临界颗粒浓度的意义

Fig.8　Definition of critical volume fraction f_v^c

Based on the above definition, the critical volume fraction f_v^c divides the particles volume fractions axis into a single scattering zone and a multiple scattering zone. In the single scattering zone, the emissive flux rises steeply with the increase of particles concentration, and is dominated by gas and particles single scattering. In the multiple scattering zone, the emissive flux becomes flatter, it approaches a limiting value and does no longer change with the particle volume fraction. The emissive flux is dominated by the absorption and multiple scattering of particles in this zone.

Fig.9 shows the emissive flux for different particles diameters. For all the considered sizes, the variations of emissive flux versus particles volume fraction are similar. The particles critical volume fractions f_v^c increases with the particle diameter. In the multiple scattering zone, for carbon particles diameters from 10 to 200μm, the size and concentration of particles have no longer significant effects on the emissive flux.



注：T_g=T_p=1000K

图 9　不同颗粒尺寸时的辐射通量

Fig.9　Emissive flux with different particles Sizes

4　CONCLUSIONS

This paper is focused on the multiple scattering effects in an absorbing, emitting and scattering medium. A Monte Carlo technique has been developed and validated to calculate the radiative transfer in a participating CO_2-carbon medium enclosed in a slab with black and cold boundaries.

The emissive flux exiting from the slab has been calculated versus the particles volume fraction f_v . A critical volume fraction f_v^c is defined to divide the particle volume fractions axis into two different zones, called the single scattering zone and the multiple scattering zone. When the volume fraction is in the single scattering zone, the emissive flux rises with the increase of concentration of the particles, as it has been previously predicted, and the radiative transfer is dominated by gas and single scattering of particles. When the volume fraction is in the multiple scattering zone, the scattering is dominated by the absorption and scattering of particles. Because the multiple scattering leads to significantly higher absorption, the emissive flux does no longer rise with the increase of the particles concentrations, but tends to be constant.

The critical volume fraction f_v^c is a function of particle size, temperature and physical properties of particles. The further research is to find the relationship between them.

5　ACKNOWLEDGEMENT

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