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Simulation study on radiative imaging of combustion flame in furnace*

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Abstract: Radiative imaging of combustion flame in furnace of power plant plays an increasingly important role in combustion diagnosis. This paper presents a new method for calculating the radiative imaging of three-dimensional (3D) combustion flame based on Monte Carlo method and optical lens imaging. Numerical simulation case was used in this study. Radiative images were calculated and images obtained can not only present the energy distribution on the charge-coupled device (CCD) camera target plane but also reflect the energy distribution condition in the simulation furnace. Finally the relationships between volume elements and energy shares were also discussed.

Key words: Combustion flame, Radiative imaging, Charge-coupled device (CCD) cameras, Energy share, Furnace

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INTRODUCTION

In recent years many studies have been conducted on combustion diagnosis based on radiative images captured by charge-coupled device (CCD) cameras, such as those for monitoring and characterization of pulverized coal flames (Yan *et al*., 2002; Lu *et al*., 2004), 3D temperature distribution reconstruction (Zhou *et al*., 2002; Wang *et al*., 2004; Huang *et al*., 2005; Brisley *et al*., 2005), prediction of unburnt carbon of coal fired utility boiler (Shimoda *et al*., 1990), estimation for NO_x emissive concentration of the pulverized coal boiler (Wang *et al*., 2002).

At present combustion flame imaging calculation methods are almost restricted to traditional pinhole imaging, for example, the works of Wang *et al*. (2004), Zhou *et al*.(2002) and Lou *et al*.(2002). From the point of actual imaging process, pinhole imaging is primary and experimental. In pinhole imaging process, all the radiative rays within a certain angle are simplified to a single ray which passes the optical center, so in real application pinhole imaging is a simplified imaging model. However, the lens of a real CCD camera functions as convex lens. The imaging of CCD camera should be lens imaging instead of pinhole imaging.

Until now little work has been carried out on calculating radiative image through optical lens imaging. The main aim of this paper is to present a numerical method for calculating radiative images of combustion flame using Monte Carlo method and optical lens imaging and then analyze the relationships between volume element and energy share which will be defined in Section 4.

IMAGING CHARACTERISTICS OF COMBUSTION FLAME IN FURNACE

Combustion flame in furnace can be considered as an absorbing, emitting and anisotropically scattering medium with high temperature. The space full of participating medium is in front of CCD cameras

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and almost each point in space is luminous point. In actual industrial application, the optical systems of CCD cameras are fixed and cannot be regulated easily. Thus there is no determinate image plane for this kind of participating medium imaging clearly.

The energy of radiative ray is continually absorbed by absorbing gas and particles during propagation. The direction of radiative ray can also be changed due to scattering by particles. Therefore some rays, which can originally arrive at CCD cameras and image, may change their directions due to scattering and cannot image at last. However, some rays, which originally cannot image, may change their directions due to scattering and can image finally, as shown in Fig.1.

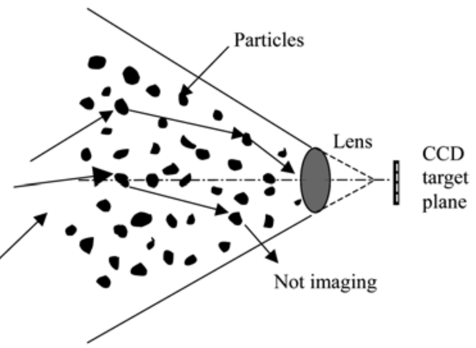

Fig.1 Combustion flame imaging

Monte Carlo method was adopted to simulate and track radiative rays in participating medium and optical lens imaging was used to calculate imaging. Monte Carlo method is not the emphasis of this paper and will not be discussed. Details are available in (Farmer and Howell, 1994).

LENS IMAGING CALCULATION OF COMBUSTION FLAME

System description

A 3D simulation furnace with 0.4 m×0.4 m×0.4 m size was divided into 7×7×7 volume elements, as shown in Fig.2. The origin of the coordinate system was in the center of system. The CCD target plane was divided into 30×30 elements. Four CCD cameras (No. 1~No. 4) were chosen to obtain four radiative energy images.

The simulation system was full of CO_2, N_2 and

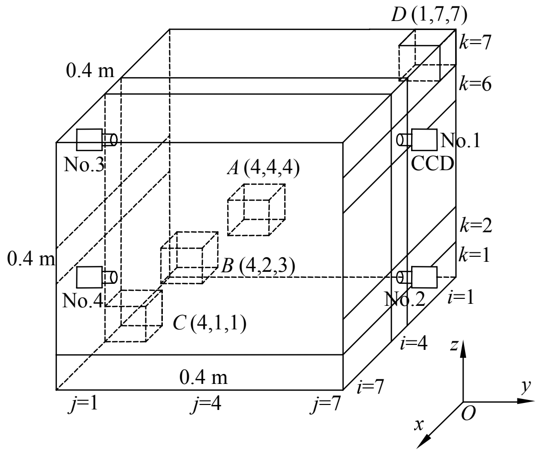

Fig.2 Simulation system

carbon particles. The enclosures were considered to be black. In this simulation case, the response wavelength range of the CCD camera was 0.4~0.7 μm which is the wavelength range of visible light. Spectral absorption coefficients of CO_2 are considered to be zero in this wavelength range. In each volume element, average scattering coefficient and extinction coefficient of particles were assumed to be 0.18 m^{-1} and 0.29 m^{-1}, respectively.

Before performing imaging calculation of combustion flame the temperature distribution in simulation system was required. A temperature distribution in (Farmer and Howell, 1994) was often used so it was adopted and modified here:

$$T(x,y,z)$$
$$=T_0\left[\left(1-2\frac{|x-0.4/7|}{W}\right)\left(1-2\frac{|y+0.4/7|}{L}\right)\left(1-2\frac{|z|}{H}\right)+1\right],$$

where T_0=950 K and x, y, z were defined in Fig.2.

Imaging calculation

The coordinate systems were divided into space coordinate system XYZ and image coordinate system $X'Y'Z$, as shown in Fig.3. The CCD target plane was on the plane $X'O'Y'$. Set $|OO'|=L$.

(1) Determine if the ray arrives at the lens of CCD camera.

As shown in Fig.3, if the ray arrived at the lens, the arriving position M can be determined by the Monte Carlo process mentioned above. The distance $|MO|$ between point M and point O (the center of lens of CCD camera) was then calculated. Let lens

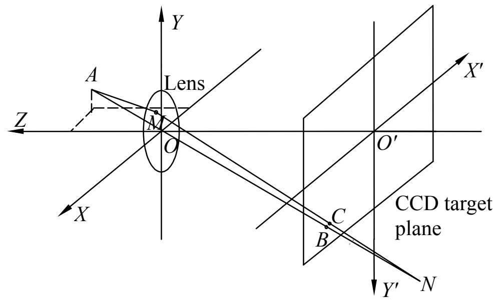

Fig.3 Imaging calculation

radius be r. If $|MO|>r$, the ray cannot arrive at the lens. If $|MO|\le r$, the ray can arrive at the lens.

(2) Determine if the luminous point (the last scattering point) is within the viewing angle of CCD camera.

In Fig.3 let the included angle between line AM and optical line OZ be α. The point A and point M can be obtained by Monte Carlo process mentioned above. Let the viewing angle be β. Compare α and $\beta/2$ then determine if the luminous point is within the viewing angle of CCD camera.

(3) Image formation calculation after the ray enters lens.

The emission point of a ray was assumed to be point A and the emission ray was AM. The process to form an imaging point on the CCD target plane was as follows:

1) Clear imaging point of point A was assumed to be point N, which means that imaging point N of emission point A was located after target plane (Other imaging conditions can be considered in the same way so they were not all listed here). The point of intersection between line MN and the target area was assumed to be point C.

2) Let lens focus be f and then secondary optical axis focus was calculated by $f'=f/\cos\alpha$. Let d be image distance of imaging point N. It can be calculated by optical equation $1/f'=1/d+1/s$, where s is object distance and can be obtained by point A. After d was obtained, point N coordinates were obtained.

3) Incidence point M coordinates were determined by the Monte Carlo process above and then the line MN equation was obtained. So the intersection point C can be derived from the line MN equation and plane $X'O'Y'$ equation according to geometry space analysis. The point C was the imaging point on the CCD target plane. Thus, the imaging condition of the emission point A has been obtained.

RESULTS AND DISCUSSIONS

Radiative images

The system in Section 3 was used as a simulation case. Fig.4 shows four radiative images of four CCD cameras in Fig.2.

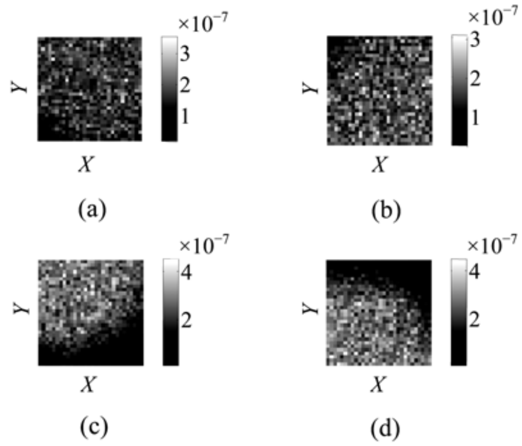

Fig.4 Radiative images. (a) CCD No.1; (b) CCD No.2; (c) CCD No.3; (d) CCD No.4

In Fig.4 it is noted that the radiative images obtained can not only present the energy distributions on the CCD camera target planes but also reflect the energy distribution condition in the simulation system. It is worth noting that radiative images are useful and can be used in the 3D temperature distribution reconstruction in furnace.

Energy share

Energy share $\alpha_{i\to j}$ is defined by the following equation:

$$\alpha_{i\to j}=E_{i\to j}/E_i,$$

where $E_{i\to j}$ is the radiative energy emitted by the volume element i arriving at the pixel j on the CCD target, E_i is the total radiative energy emitted by the volume element i.

Energy share describes how much energy emitted by the volume element i can be accepted by the pixel j.

Energy share $\alpha_{i\to j}$ of four typical volume elements A, B, C and D in Fig.2 are calculated respectively. The energy share distributions on the CCD camera No.1 target planes are illustrated in Fig.5.

In Fig.5, as the distance between volume element

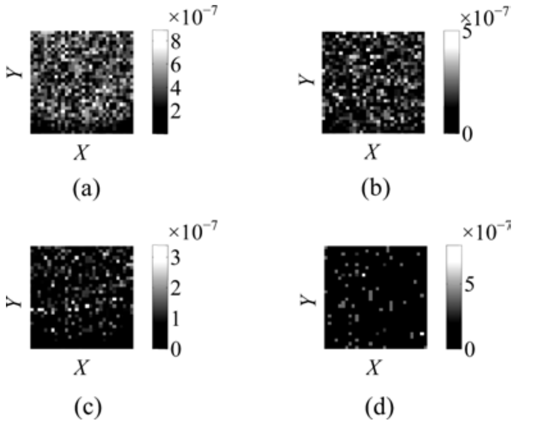

Fig.5 (a)~(d) showing energy shares distributions on the CCD camera No.1 target planes of typical volume elements *A*, *B*, *C* and *D*

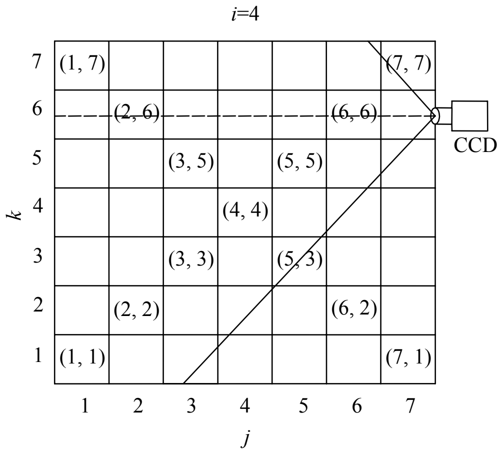

Fig.6 Typical volume elements on cross section *i*=4

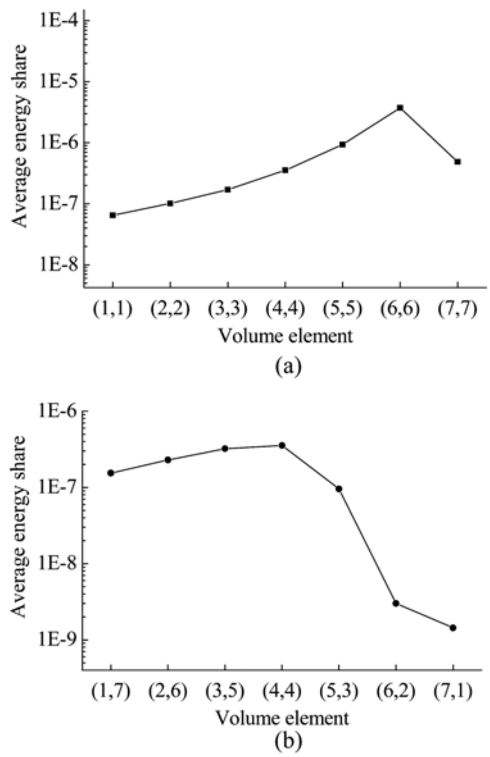

Fig.7 Average energy share of typical volume elements within (a) and without (b) the viewing angle of CCD camera

and CCD camera increases, the number of the pixels which can receive energy from volume elements decreases. It is worth noting that the volume element *D* was out of the viewing angle of CCD camera No. 1 but the pixels of CCD camera No. 1 can still receive energy emitted by the volume element *D*. This should be caused by scattering effect. From this point of view, it is suggested that scattering should be helpful for CCD cameras to get more 3D flame radiative information.

We also define another energy share and call it average energy share $\overline{\alpha}_i$:

$$\overline{\alpha}_i = \overline{E} / E_i,$$

where $\overline{E}$ is the average energy received by all the pixels from the total energy emitted by the volume element *i*.

Typical volume elements on the cross section *i*=4 (position is shown in Fig.2) are shown in Fig.6. The elements on the two diagonals in Fig.6 include not only the elements within the viewing angle of CCD cameras but also those elements out of the viewing angle of CCD cameras. Through calculating average energy shares of these typical volume elements on the two diagonals, the general variations rules can be obtained.

Average energy shares of these volume elements are illustrated in Fig.7a and 7b.

It can be seen from Figs.7a and 7b that when the volume elements are within the viewing angle of CCD camera, the average energy share increases with the decrease of the distance between volume element and CCD camera. This demonstrates that the longer the distance is, the more energy is absorbed by the participating medium. When the volume elements are partial or all out of the viewing angle of CCD camera, the average energy share decreases sharply. It is implied that the longer the distance between volume element and CCD camera is, the more scattering energy is absorbed by the participating medium.

CONCLUSION

A new method for calculating the radiative imaging of combustion flame in furnace has been developed based on Monte Carlo method and optical lens imaging. Radiative images and the relationship between the volume element and energy share were obtained and discussed through a simulation case. Future work will focus on the 3D temperature reconstruction research using radiative images discussed in this paper.

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