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Simultaneous measurements of two-dimensional temperature and particle concentration distribution from the image of the pulverized-coal flame

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ABSTRACT

This paper presented a model for simultaneously measuring the two-dimensional temperature and particle concentration distribution from the images of the flame. In order to determine the relationship between a point in the three-dimensional space and its image in the camera, the optical image-formation process was analyzed. The inverse problem of the radiation transfer in the participating medium was studied. The mathematics method to simultaneously solve the temperature and the particle concentration was discussed. To validate the model presented in this paper, a test furnace with the fuels mixed by pulverized-coal and oil was set up. The temperature and particle concentration of a cross section were measured under different coal feed rates. The comparison between the measured temperature by the pyrometer and the calculated temperature according to the flame image proved that the two-dimensional distribution of temperature can be obtained accurately. The particle concentration distribution was reasonable under different cases.

1. Introduction

Many advances in the thermal sciences depend on accurate determination of temperature and particle concentration distribution. To measure the temperature and the particle concentration of the flame, the emission of the flame or the extinction of the laser was detected by the sensors [1], but the previous measurements were mainly restricted to time-average "point" measurements.

Recently, the investigations have been focused on the reconstruction of temperature profile in target space according to its boundary heat flux, which is a kind of inverse problem of radiation. Li [2,3] and Liu [4,5] have reconstructed the temperature profiles in plane-parallel, spherical, cylindrical, semitransparent, gray media by the inverse analysis from the data of the radiation intensities exiting the boundaries. Silvaneto [6] presented an inverse radiation analysis for simultaneous estimation of optical thickness, single scattering albedo and the coefficients of phase function for an anisotropic scattering plane-parallel medium.

Temperature reconstruction using Charge-Coupled Device (CCD) camera is a typical application of the radiative inverse problem, which has made significant progress in recent years. Keanini [7] described a method for measuring time-varying temperature distribution using high frame rate visible imaging CCD cameras. Zhou [8,9] deduced the temperature distribution in the pulverized-coal furnace using CCD camera. An imaging-based instrumentation system for three-dimensional temperature measurement of a combustion flame was presented by Yan [10]. Simultaneous measurement of flame temperature and soot concentration was conducted by Lu et al. [11].

However, the radiation absorption coefficient, which is decided by the particle concentration in the flame, always was considered as a known constant in the previous work. If this method is applied in a real situation, the concentration distribution of particles in the medium is generally not known, and the resulting absorption and scattering coefficients are not available as inputs to temperature reconstruction.

This paper describes a model that the temperature and the particle concentration are both considered as the unknowns. The solving method to temperature and particle concentration is discussed. The two-dimensional distributions of the temperature and the particle concentration in the pulverized-coal flame are calculated simultaneously with four CCD cameras.

2. Theory

Two processes should be considered for the image-formation of three-dimensional flame on the target of CCD camera. The first one is optical process which determines the original emission point in the three-dimensional flame space for each pixel in the flame image in the CCD camera. The next one is radiative transfer process which describes the variations of the radiation energy during propagation in the participating medium.

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2.1. Optical model of the flame image-formation

There are some differences between the image-formation of the flame and common object. In the flame image-formation, the space between the flame and the lens of the camera is filled with participating medium. Every point in the space is almost emitting point and there is no clear object plane.

According to geometrical optics, the relationship between object plane and image surface can be described as:

$$x \cdot x' = f \cdot f' \tag{1}$$

where f is object focus, f' is image focus, x is the distance between object plane and object focus and x' is the distance between image plane and image focus.

For a fixed optical system, the focus and the position of the image plane are always known, so x can be obtained by Eq. (1). A virtual object plane in the position of x can be considered in the participating medium and each point on this plane corresponds to a certain determining point in the image. However, the point on the virtual object plane is not the real emitting point. The emission from this point to the target of the camera is the sum of radiations in a solid angle through this point, as shown in Fig. 1.

The aperture angle U is defined to describe this angle, which was determined by the following equation:

$$U = tg^{-1}\left(\frac{d/2 - L \cdot tg\theta}{L}\right) + tg^{-1}\left(\frac{d/2 + L \cdot tg\theta}{L}\right) \tag{2}$$

where d is the lens diameter, L is the distance between the virtual plane and lens, θ is the view angle.

If the aperture angle is small enough, the total emission in the angle U can be considered a ray through this point. According to the optical parameters of the image fiber used in this paper (d = 6 mm; L = 1 m; θ = 0–45°), the aperture angle U are shown in Fig. 2. It can be seen that the aperture angle is between 0.16° and 0.36°. So the total emission in the angle U can be simplified to a single ray through a point in the virtual object plane. Thus the direction of each ray which arrives at the each pixel can be determined.

2.2. The radiative transfer along one ray

For an absorption, scattering and emission participating medium, radiative transfer equation (RTE) is as following [12]:

$$\frac{dI_\lambda}{dS} = -K_{ext,\lambda} I_\lambda + K_{abs,\lambda} I_{b\lambda} + \frac{K_{sca,\lambda}}{4\pi}\int_{4\pi} I_\lambda(\bar{S}')P(\bar{S},\bar{S}')d\omega \tag{3}$$

where $K_{ext,\lambda}$ is the extinction coefficient, $K_{abs,\lambda}$ is the absorption coefficient, $K_{sca,\lambda}$ is the scattering coefficient, $K_{ext,\lambda} = K_{abs,\lambda} + K_{sca,\lambda}$, P is

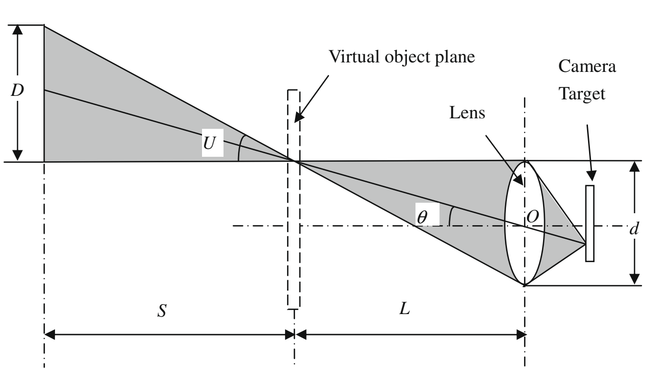

Fig. 1. Image-formation process in the participating medium.

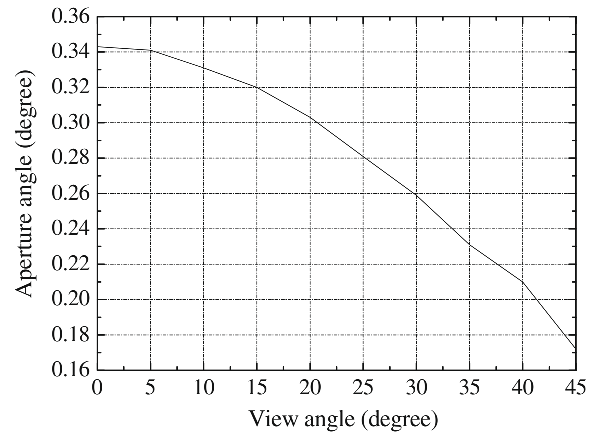

Fig. 2. Variation of aperture angle with view angle.

the scattering phase function, $I_{b\lambda}$ is the local blackbody intensity. The left hand term represents the change of the energy, the first term in the right hand represents the energy attenuation due to the medium absorption and out-scattering, the second term in the right hand represents the energy augmentation due to the medium emission, and the third term in the right hand represents the energy augmentation due to the medium in-scattering.

To most area in the pulverized coal–fired boiler, the ignoring of the particle scattering brings error less than 7% [13]. Hence, the scattering is ignored in this study, $K_{ext,\lambda} = K_{abs,\lambda} + K_{sca,\lambda} = K_{abs,\lambda}$, so the radiative transfer equation will be simplified as:

$$\frac{dI_\lambda}{dS} = -K_{abs,\lambda} I_\lambda + K_{abs,\lambda} I_{b\lambda}. \tag{4}$$

According to Planck law, $I_{b\lambda}$, the black radiation spectral intensity under a specified temperature and at a specified wavelength, has the relation with the temperature T as following:

$$I_{b\lambda} = \frac{C_1 \lambda^{-5}}{\pi[e^{C_2/(\lambda T)} - 1]} \tag{5}$$

where C_1 and C_2 is the first and the second Planck constant, respectively, $C_1 = 3.741 \times 10^{-16}(\mathrm{w\ m^2})$, $C_2 = 1.43879 \times 10^{-2}(\mathrm{m\ K})$.

The participating medium in the pulverized coal–fired furnace consists of gases such as CO_2, H_2O and particles such as carbon particle and fly ash.

A homochromous filter centered at 0.56 μm was mounted in the front of the camera in this study. Therefore, the radiation intensity captured by the camera is the homochromous radiation intensity at 0.56 μm. At this wavelength, almost all the gases in the furnace can be considered as transparent medium. As for the particle, the main test object we considered here is in the outlet area of the pulverized-coal burner in the boiler, where the concentration of carbon particles is high and fly ash is low. Therefore, the contribution of fly ash in the absorption coefficient is ignored and the carbon particles are only considered.

According to Mie theory, the absorption coefficient of the particle cloud with a size distribution can be obtained according to the following equation:

$$K_{abs} = 1.5 f_v \overline{Q}_{abs} / D_{32} \tag{6}$$

where D_{32} is Sauter Mean Diameter, which is determined by size distribution:

$$D_{32} = \frac{\int_0^\infty N(D)D^3 dD}{\int_0^\infty N(D)D^2 dD} \tag{7}$$