PARTICLE DIAGNOSTICS IN THE THERMAL DUSTY PLASMA FLOWS

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Here we present a combination of optical methods for determining the particle temperature, T_p, mean size, D_{32}, concentration, N_p, and refractive index, $m(\lambda)=n(\lambda)-ik(\lambda)$, in high-temperature flows. The unknown particle parameters are obtained by minimizing a mean-square error between the measured and calculated data. Calculations were performed by using the Mie theory [1].

1. Theory

1.1. Determination of Particle Temperature.

The temperature of particles can be obtained from emission-absorption measurements in an emission line of the gas. A restoration of several unknown parameters from measurements on a gas emission line is a complicated diagnostic problem which requires measurements in narrow band spectral region and considerable efforts in order to avoid significant experimental errors [2-4]. Therefore, it is preferable to measure the particle temperature, T_p, and their parameters in a wide wavelength range beyond the gas emission line. The classic pyrometric two-color method can be employed for the determination of T_p in optically grey medium.

We consider the temperature measurements for particles which are optically non- grey at the experimental wavelengths. The general difficulties for this task are related to the necessity of a knowledge of the spectral emissivity, $\varepsilon(\lambda)$. Determination of $\varepsilon(\lambda)$ requires *a priori* information of the particle parameters. In many cases of practical interest, however, these quantities are not known. The temperature of particles can be obtained by the spectroscopic method involving the approximate relationships for $\varepsilon(\lambda)$ [5]. This method is based on solving a system of radiative transfer equations for light intensity measurements of the signals of reference lamp plus flame, S_{pl}, flame only, S_p, and lamp, S_l in the absence of the flame at several wavelengths λ_i ($i=1$-N). Assuming that multiple in-scattering is negligible yields:

$$\varepsilon(\lambda) = (1-\omega(\lambda))(1-\exp\{-\tau(\lambda)\}) \quad (1)$$

Here, $\omega(\lambda)$ is the single scattering albedo, $\tau(\lambda)$ is the optical depth. The case of turbid media was detailed in [4]. The error estimate $\delta^{(k=0)}$ of the emissivity $\varepsilon(\lambda)$ (Eq. 1) from neglecting the in-scattered radiation (k>0) can be easily calculated using the value of the measured optical depth, $\tau(\lambda)$ [4,6]. For confined scattering medium with $\tau(\lambda) < 0.9$-1.2, the $\delta^{(k=o)}$ value is less then 2% for particles with the size parameters $\rho \geq 1$ [4]. In this case a problem can be reduced to choosing an appropriate model for the spectral dependence of single albedo $\omega(\lambda)$. We consider the spectral approximation $W(\lambda)$ for the function $\{1-\omega(\lambda)\}$ (Eq. 1) as

$$W(\lambda) = c / \{\lambda^a \ \tau(\lambda)^b\} \quad (2)$$

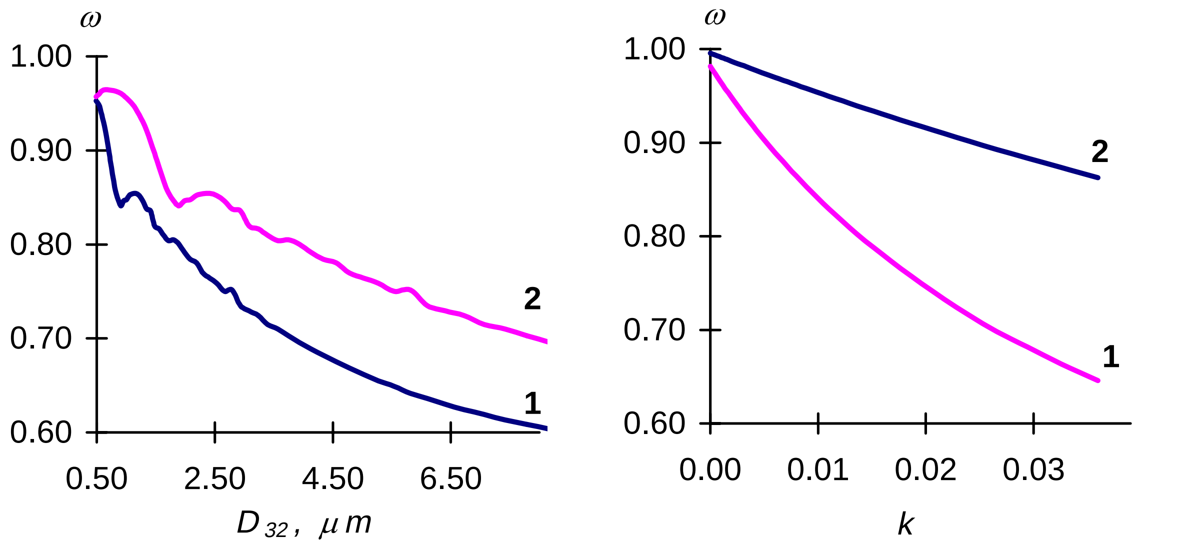
Here, a, b, c are some coefficients, the values of which are independent of the wavelengths. The relative measurements eliminate the c value from consideration. Then the particle temperature, T_p, as well as the appropriate approximation of $\varepsilon(\lambda)$, (i.e. coefficients a, b) are obtained by minimizing a mean-square error between the experimental and calculated data.

1.2. Determination of Particle Mean Sizes and Refractive Index.

The spectral dependence of $\varepsilon(\lambda)$ can be obtained from the following equation:

$$S_p(\lambda)/S_l(\lambda) = \varepsilon(\lambda)\, B(T_p, \lambda)/B(T_l,\lambda) \quad (3)$$

where $B(T_p, \lambda)$ is the Planck blackbody function, T_l is the temperature of the reference lamp. For the case of $<\rho> > 5$, $\varepsilon(\lambda)$ is dependent on D_{32} only, and is weakly dependent on m for absorbing particles with $k > 0.4$ [5]. Then the $\varepsilon(\lambda)$ measurements can be inverted for D_{32} and k of particles with $0.001 < k < 0.1$. The lower limit on the k value results from insignificant emissivity for particles with $<\rho> > 1$. Assuming single scattering, the problem can be reduced to empirical inversion of $\omega(\lambda)$ [5]. Dependencies of the albedo $\omega(\lambda_o)$ on the particle Sauter mean diameter, D_{32}, and absorption index k are shown in Figs. 1a,b for the Gaussian distribution with the standard deviation δ_G = 25%. The spectral distribution of the albedo, $\omega(\lambda)$ is determined by the particle sizes provided that the refractive index is weakly dependent on λ. The $\omega(\lambda)$ value at $\lambda=\lambda_o$ is uniquely determined by the k value. Therefore, with the known particle sizes and real refractive index, the spectral absorption index, $k(\lambda)$, can be easy measured.



a) b)

Figure 1. Dependencies of the albedo ω on the particle mean diameter D_{32} (a) and the image refractive index k; (b) for the Gaussian distribution with the standard deviation δ_G =25%: a) m=1.7-0.01i, λ: 1- 0.5 μm, 2- 1.0 μm; b) n=1.7, D_{32}: 1- 0.5 μm, 2- 1.0 μm

For determination of the particle mean size, concentration, and real refractive index, we use a technique based on measurements of forward angle scattering transmittance (FAST) at different aperture angles of the detector [7-8]. Because of the detector's finite field of view, the contribution from forward-scattered light to the detector irradiance can not be completely eliminated, even when multiple scattering can be neglected. In this case, true optical depth, τ, is distinguished from the apparent (measured) optical depth, τ*. Taking into account that some light scattered at angels $\theta < \theta_d$ reaches the detector, the relative value of measured extinction cross section can be expressed as follows

$$q(\theta_d, m, D_{32}) = \tau^* / \tau \tag{4}$$

By varying the detector aperture (θ_d), one can measure an angular distribution of $q(\theta_d, m, D_{32})$. In order for the least mean-square fit to provide the correct determining of the particle diameters D_{32}, it is necessary that

$$\theta_d < \theta^* \approx 0.96/<\rho> \tag{5}$$

In many cases of practical interest the determination of D_{32} can be made from FAST measurements at angles $\theta_d < \theta^*$ without knowledge of the PSD and the refractive index, m.

2. Experiment

The polydispersions of particles of SiO_2, CeO_2, and ash in a flow of a propane-air flame combustion products were studied in the spectral range from 0.5 to 1.1 μm. The particles were introduced in the inner flame of the Mekker combustor. The flame temperature was varied from 1800 to 2250 K. The measured optical depth $\tau(\lambda) < 0.35$, because the multiple scattering was negligible [5]. The particle temperature, (T_p), number density, (N_p), complex refractive index, ($m=n-ik$), and mean diameter (D_{32}), were obtained. The results of measurements are given in Table 1.

Particles	№	D_1, μm	D_2, μm	n	a	b	T_p, K	T_g, K
CeO_2	1	1.23	1.17	2.05	0.20	≅1	2020	2025
	2	1.17	1.20	1.98	0.22	≅1	2230	2240
	3	0.33	-	-	0.85	0.85	1810	1820
	4	0.30	-	-	0.81	0.81	1905	1912
ash	5	1.65	1.73	1.68	0.32	≅1	1922	1930
	6	1.57	1.64	1.68	0.32	≅1	2090	2095

Table 1. Results of Measurements of the Mean Size, D_{32}, the Real Refractive Index n, the Temperature, T_p, and the Retrieved Coefficients, a, b (Eq. 2) for CeO_2, and Ash Particles

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