Optics Communications 389 (2017) 258–264

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

A forward-angle-scattering method for the determination of optical constants and particle size distribution by collimated laser irradiation

Yatao Ren, Hong Qi*, Xiaoying Yu, Liming Ruan*

School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, P.R. China

ARTICLE INFO

Keywords:
Optical constants
Particle size distribution
Forward-angle-scattering method
Quantum particle swarm optimization

ABSTRACT

This study examined the feasibility of using a secondary optimization technique and forward-angle-scattering method to retrieve optical constants (or complex refractive indices) and particle size distribution (PSD) simultaneously. In this work, two continuous wave lasers of different wavelengths were applied to irradiate the participating samples, and the scattered light of samples with different acceptance angles was obtained. First, the scattered signals within different acceptance angles were calculated by solving the radiative transfer equation. Then, the complex refractive index and PSD were retrieved simultaneously by applying quantum particle swarm optimization. However, the estimated results of PSD were inaccurate. Thus, a secondary optimization, which using the directional radiative intensity as input, was performed to improve the accuracy of PSD based on the first optimization process. Four commonly used kinds of monomodal PSD functions, i.e., the Rosin-Rammler, standard Normal, Logarithmic Normal, and Junge distribution, were retrieved. All results showed that the proposed technique can estimate the complex refractive index and PSD accurately.

1. Introduction

Researches into the microphysical properties of particle systems, such as optical properties and particle size distributions (PSDs), can elucidate the radiative transfer processes in environmental monitoring [1], polarization imaging [2], biofuel production [3], chemical industry [4], and ocean optics [5]. An accurate analysis of radiative heat transfer in these systems requires accounting of the effects of particles thoroughly. Unfortunately, optical constants of particles are not known with sufficient accuracy to perform reliable heat transfer calculations for these practical problems of interest. The estimation of the optical properties and PSDs of particle systems has attracted considerable attention in the last two decades [6–14]. However, we believe that most of the studies concentrate on the measurement of the optical properties or PSDs with the condition that *a priori* information about the other one is known beforehand. In 2016, Kolgotin et al. [15] developed an explicit method to determine the optical constant of aerosols based in the measurement data of lidar. However, the particle size distribution was assumed to be known. Very few methods that try to simultaneously determine the optical constants (or complex refractive indices) and PSDs are based on library method [16], which is very time-consuming. The experimental equipment is also expensive, and the measurement process is very complex. Hence, this work aims to develop a simple and accurate method that can obtain the complex refractive index and PSD simultaneously.

The forward-angle-scattering method, which is based on the measurement of scattered light within different acceptance angles, has been successfully applied to estimate the particle mean size, concentrations, and real refractive indices through Beer's law [17,18]. It has been proved to have many advantages, and it only requires simple optical and electronic systems [17,19]. In the present work, we attempted to extend this method to the estimation of PSDs and complex refractive indices based on the solution of the radiative transfer equation (RTE).

In addition to the measurement of the radiative signals, inversion techniques need to be investigated when estimating the properties of the particle systems. Inverse problem theory has been widely developed within the past decades partly because of the importance of its applications, the arrival on the scene of powerful computers, and the reliable numerical methods. In general, inversion techniques can be roughly classified into two categories [20]: (1) gradient-based techniques, such as Gauss–Newton [21,22], Levenberg–Marquardt [23], and Conjugate Gradient methods [24]; (2) stochastic heuristic intelligent optimization techniques, such as generic algorithm [25–27], particle swarm optimization (PSO) [28–32], and ant colony optimization [20,33]. The intelligent optimization techniques are usually proved to be powerful techniques for the inverse problems in many areas [34,35]. Moreover, the derivatives of the optical characteristics with respect to

* Corresponding authors.
E-mail addresses: qihong@hit.edu.cn (H. Qi), ruanlm@hit.edu.cn (L. Ruan).

http://dx.doi.org/10.1016/j.optcom.2016.12.060
Received 15 November 2016; Received in revised form 1 December 2016; Accepted 24 December 2016

the real and imaginary parts of the refractive index are also extremely difficult to obtain for the complex refractive index reconstruction problems. Therefore, in this work, we studied the possibility of retrieving the complex refractive index and PSD simultaneously through quantum PSO (QPSO) algorithm, which has been recently proved effective and robust in solving inverse radiation problems [36].

A one-dimensional (1-D) radiative transfer model in a spherical particle system was established to test the performance of the proposed method. Two experimental samples with different thicknesses were applied to retrieve the complex refractive indices and PSDs. Then, the two samples (Samples 1 and 2) were separately exposed to two continuous wave lasers (Lasers 1 and 2) of different wavelengths. The scattered signals within different acceptance angles were predicted with the direct model under all the conditions, namely, (1) Sample 1 exposed to Laser 1, (2) Sample 1 exposed to Laser 2, (3) Sample 2 exposed to Laser 1, (4) Sample 2 exposed to Laser 2. Finally, the complex refractive indices and PSDs were retrieved simultaneously with QPSO algorithm. For precision, the unknown complex refractive indices and PSDs varied in the direct model calculations until the best agreement with the measurements was achieved. Additionally, the sensitivity of the radiative signals to the complex refractive indices and PSDs was calculated and analyzed, based on which the optimal thicknesses for the samples were chosen. The remainder of this paper is organized as follows. First, the direct model of the radiative transfer in a spherical particle system is introduced in Section 2. Consequently, the inverse problem is presented. In Section 3, the inverse procedure is explained in detail and the corresponding analysis is carried out. Finally, the main conclusions are listed in Section 4.

2. Theory

2.1. Direct model

A 1-D absorbing, scattering, and non-emitting particulate system is under consideration (see Fig. 1). In the present work, the slab is a glass container with mono-disperse microalgae and the influence of the container is not considered for the sake of simplicity. The left side of the system is exposed to a continuous-wave laser beam. Given the short interaction time and low laser intensity, the media are presumably cold without considering the thermal effect caused by the laser irradiation. The RTE in a 1-D particulate system can be expressed as follows [37]:

$$\frac{\partial I(z,\theta)}{\partial z} = -\beta_\lambda I(z,\theta) + \frac{\sigma_{s\lambda}}{2}\int_0^\pi I(z,\theta')\Phi_\lambda(\theta',\theta)\sin\theta' d\theta' \tag{1}$$

where I is the intensity in direction θ at location z. The extinction coefficient is denoted by β_λ, which is equal to $\kappa_\lambda + \sigma_{s\lambda}$, where κ_λ and $\sigma_{s\lambda}$ are spectral absorption and scattering coefficients, respectively. The subscript λ stands for the wavelength of incident laser. The scattering phase function $\Phi_\lambda(\theta',\theta)$ represents the probability that the radiation that propagates from the incoming direction θ' will be scattered into the direction θ which is calculated with Mie theory [38] in the present work.

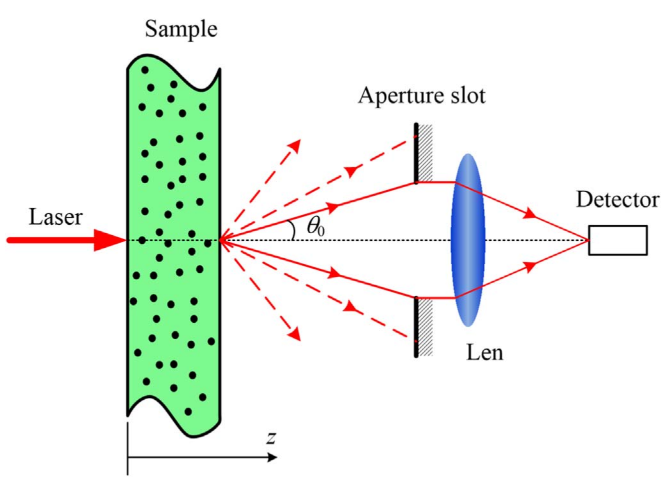

Fig. 1. Schematic of a 1-D slab absorbing, scattering, and non-emitting particle system exposed to a collimated continuous wave laser.

The scattered light within different acceptance angles (see Fig. 1) $T_{mea}(\theta_0)$ and the collimated transmittance T_c can be expressed as follows:

$$T_{mea}(\theta_0) = \frac{1}{I_0}\left[2\pi\int_0^{\theta_0} I(L,\theta)\cos\theta\sin\theta\ d\theta + I_c(L,0)\right] \tag{2}$$

$$T_c = I_c(L,0)/I_0 \tag{3}$$

where I_0 is the intensity of the incident laser, and I_c is the intensity of the collimated light, which can be calculated with Beer's law. And the I_c can be measured by using a very small acceptance angle.

The absorption coefficient κ_λ and scattering coefficient $\sigma_{s\lambda}$ for a particle system must be known to solve the forward model, and these coefficients can be calculated with the following equations:

$$\kappa_\lambda = \int_0^\infty C_{a\lambda}(D)N(D)\mathrm{d}D \tag{4}$$

$$\sigma_{s\lambda} = \int_0^\infty C_{s\lambda}(D)N(D)\mathrm{d}D \tag{5}$$

where $C_{a\lambda}$ and $C_{s\lambda}$ denote the absorption and scattering cross-section, respectively. For sphere particles, $C_{a\lambda}$ and $C_{s\lambda}$ can be calculated with Mie theory [38]. D is the diameter of the particles. $N(D)$ represents the number density of the particles with diameter D.

In this study, four commonly used monomodal PSD functions, i.e., the Rosin–Rammler (R-R), standard Normal (S-N), and Logarithmic Normal (L-N) distribution, are considered. The mathematical representations of the monomodal volume frequency distribution functions for these four PSDs are expressed as follows [39,40]:

$$f_{R-R}(D) = \frac{\sigma}{\overline{D}} \times \left(\frac{D}{\overline{D}}\right)^{\sigma-1} \times \exp\left[-\left(\frac{D}{\overline{D}}\right)^{\sigma}\right] \tag{6}$$

$$f_{S-N}(D) = \frac{1}{\sqrt{2\pi}\sigma} \times \exp\left[-\frac{(D-\overline{D})^2}{2\sigma^2}\right] \tag{7}$$

$$f_{L-N}(D) = \frac{1}{\sqrt{2\pi}D\ln\sigma} \times \exp\left[-\frac{(\ln D - \ln\overline{D})^2}{2(\ln\sigma)^2}\right] \tag{8}$$

$$f_J(D) = \beta D^{-\alpha} \tag{9}$$

where $\overline{D}$ represents the characteristic diameter parameter, and σ is the dispersion ratio. α and β are characteristic parameter. The volume frequency distribution is denoted by $f(D)$. The concentration of particles is set as a constant value and assumed to be known.

As mentioned, the absorption and scattering cross-section, namely, $C_{a\lambda}$ and $C_{s\lambda}$, are calculated with Mie theory, in which the complex refractive index m must be known to obtain κ_λ and $\sigma_{s\lambda}$. And m can be expressed as $n - ik$, in which n and k represent the real and imaginary part of the complex refractive index, respectively. In the present work, the complex refractive index m is assumed unknown and must be estimated. $C_{a\lambda}$ and $C_{s\lambda}$ can be calculated using a random guessed value in the inverse process. Then, this value is updated with the proceeding of the inverse process until the objective function reaches a small preset value.

2.2. Inverse model

For the inverse problem involved in this work, six parameters need to be obtained, i.e., two sets of complex refractive indices (n_1, k_1, and n_2, k_2), which correspond to different wavelengths, and the PSD parameters of $\overline{D}$ [μm] and σ. Multi-wavelength method was applied