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Review

Light scattering: A review of particle characterization applications

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ABSTRACT

This review covers the progress of light scattering applications in the field of particle characterization in the past decade. The review addresses static light scattering (the measurement of scattering intensities due to light–particle interaction at various spatial locations), dynamic light scattering (the measurement of scattering due to light–particle interaction as a function of time), and scattering tracking analysis (the tracking of particle movement through scattering measurement).

Contents

Introduction

The science and technology of light scattering touches a very broad range of fields, from cosmology, meteorology, and oceanography, all the way to nanotechnology, and produces an enormous amount of research and application literature. Excluding some cases of surface scattering, most light scattering occurs with particles of various origins, sizes, and shapes in various environments from planets to micelles. A Google Scholar search of "light scattering" yielded about 840,000 entries for papers published between 2003 and 2013 and a similar search for "light scattering" and "particle" found about 121,000 entries for the same period. Because of the unique nature of scattering phenomena in each branch of science, the terminology, theoretical and experimental methodologies, instrumentation and data interpretations for light–matter interaction are all different. A monograph of particle scattering in marine science references few papers on industrial particle characterization (Jonasz & Fournier, 2007), a person in the light scattering instrument industry may know nothing about the scattering of light by planets (Xu, 2000), and a book chapter on polymer science may cover a broad range of scattering measurement techniques (Berry, 2013).

During the past decade, several light scattering technologies used for particle characterization, such as laser diffraction (LD) technology, have matured and even become commoditized. Demands from users for measurements that are more reproducible

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Abbreviations: CCD, charge-coupled device; CMOS, complementary metal-oxide-semiconductor; DDA, discrete dipole approximation; DLS, dynamic light scattering; ELS, electrophoretic light scattering; FDTD, finite-difference time domain; FFF, field-flow fractionation; LD, laser diffraction; LD–PD, laser diode–photodiode; MALS, multiangle light scattering; OPC, optical particle counter; PALS, phase analysis light scattering; PIDS, polarization intensity differential scattering; PMT, photomultiplier tube; PTA, particle tracking analysis; SEC, size-exclusion chromatography; SLS, static light scattering; SPM, scanning probe microscopy.

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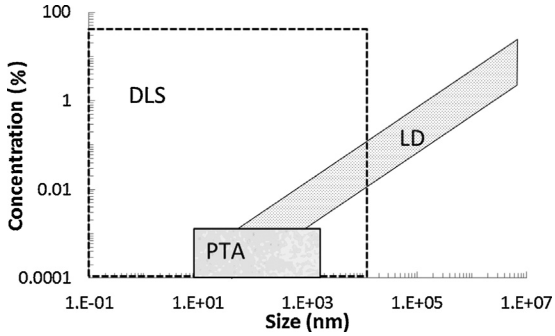

Fig. 1. Approximate concentration and size ranges of a few scattering technologies. DLS, dynamic light scattering; LD, laser diffraction; PTA, particle tracking analysis.

and quicker have driven instrument manufacturers to make more rugged, easier to use, and lower cost instruments. On the other hand, simple physical parameters, such as spherical equivalent diameter and particle count, are no longer sufficient for many applications. Demands for a lower sizing range down to sub-nanometer, three-dimensional information on individual particles, characterization of powder mixtures and even composite particles, and new applications such as the measurement of airborne particles in environmental monitoring, the study of fine bubbles and the detection of nanomaterial waste all require the further development of light scattering technologies. Fig. 1 shows current approximate size and concentration ranges of popular scattering technologies.

This review covers the progress made in light scattering applications in the field of particle characterization in the past decade. Even with this restriction, the review covers a large amount of literature. It is thus unavoidable that some papers have been missed or omitted. This review is divided into three sections: static light scattering (SLS, the measurement of scattering intensities due to light-particle interaction at various spatial locations), dynamic light scattering (DLS, the measurement of scattering due to light–particle interaction as a function of time), and scattering tracking analysis (STA, tracking of particle movement through scattering measurement).

Static light scattering

The exact scattering solution for a dielectric spherical particle with a homogenous optical property and smooth surface under a plane wave was derived by Mie (1908) more than a century ago. Since then, many more solutions for scattering from particles having symmetric geometries, such as cylinders and spheroids, in electromagnetic radiation have been derived (Bohren & Huffman, 1983; Kerker, 1969; van de Hurst, 1981). Various forms and extensions of the Mie theory for different shapes of light beam have been extensively and continuously developed in response to new challenges (Gouesbet & Lock, 2013; Hergert & Wriedt, 2012). For particles having arbitrary shape and/or optical inhomogeneity, there are no exact analytical solutions but matrix and numerical methods. The most commonly used methods are the T-matrix method based on an expansion in vector spherical harmonics (Barber & Hill, 1990; Mishchenko, Travis, & Mackowski, 2010; Waterman, 1971), the finite-difference time domain (FDTD) method using grids to numerically solve Maxwell's equations (Shlager & Schneider, 1995; Yee, 1966), and the discrete dipole approximation (DDA) method in which a particle is decomposed into small sections (dipoles) (Draine & Flatau, 1994; Purcell & Pennypacker, 1973).

During the last decade, computing power has advanced rapidly following Moore's law; i.e., the number of transistors in an affordable central processing unit doubles every two years, from 37.5 million in 2000 to 2.5 billion in 2011. This has boosted scattering modeling using various methods for particles of arbitrary shapes and various sizes in beams other than plane waves. In addition, information technology such as cloud computing and server capabilities has made the comparison, sharing and validation of computing code much easier (Wriedt, 2012).

Single spherical particle scattering has been computed using various methods, such as the expanded Mie theory for spheres having radially anisotropic permittivity and permeability (Fan, Shen, & Luk'yanchuk, 2010) and non-concentric core–shell spheres (Ross & Sigel, 2012) and the FDTD method for coated spheres in absorbing medium (Sun, Loeb, & Fu, 2004). The retrieval of particle shape information of a distribution of non-spherical particles modeled as homogeneous spheroids has been attempted using the DDA method to compute reference phase matrices of symmetric model particles and using the T-matrix method to compute particle phase matrices (Nousiainen, Kahnert, & Lindqvist, 2011).

Even though modeling single particle scattering has become easier, success in the inversion process of obtaining properties of distributions of scatterers from scattering intensity measurement, which is the purpose of most industrial applications of light scattering measurements, is still fairly limited, mostly to spherical model particles. A combination of light scattering intensity measurement and turbidity measurement to resolve the inverse problem and obtain particle size distributions has been reported (Vega, Gugliotta, Gugliotta, & Elicabe, 2003). The particle distribution and volume percentage of concentrated polydisperse particles embedded in a solid polymer matrix were obtained using the Vrij scattering model (Vrij, 1979) under the Percus–Yevick hardsphere approximation, even though the volume fraction so derived from the relative intensity measurement deviated greatly from the scanning electron microscopy measurement (Otero, Frontini, & Elicabe, 2010). Lagasse and Richards (2003) used a commercial LD instrument to measure the angular pattern of the scattering intensity and used a linear regularization technique for the inversion under the assumption that the core–shell diameter ratio is a constant and the size distribution is a linear combination of B-splines. Simultaneous retrieval of the core–shell particle size distribution and the core size distribution, the projections of a 3D distribution onto the axial planes of the particle size and core size, respectively, was achieved through a numerical analysis of light scattering angular intensity for both simulated examples and experimental examples. In this approach, the generalized second-order Tikhonov regularization method together with a steepest-descent optimization algorithm (sequential quadratic programming) employing an optimum searching strategy (particle swarm optimization) was used to resolve the ill-posed inversion problem. In using this approach, no a priori assumption on the distribution shape is required, the computation is easily implemented and automated, and no user intervention for the regularization parameter is needed (Clementi, Vega, Gugliotta, & Quirantes, 2012).

Instruments for measuring light scattering intensity can be categorized into three main types: optical particle counters (OPCs) that measure scattering from individual particles; granulometers or goniometers, which are often referred to as multiangle light scattering (MALS) or SLS that measure particles in liquid suspension in a broad angular range, typically continuously from near 0° to 180° using a rotating arm or fixed detectors throughout the entire angular range (Peters, 2000); and angular scattering intensity measurement instruments, commonly known as LD instruments, which measure dry powders, sprays, or particles in liquid using a set of fixed detectors at small angles with some additional detectors at large angles. Because the intended uses in research and industrial applications are different, the three types of instruments are designed differently. Particle counters, even though they can size

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