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Numerical investigation of measurement error of the integrating sphere based on the Monte-Carlo method

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HIGHLIGHTS

- Simulate the radiation transfer of multiple reflections inside integrating sphere using MCM.
- Investigate the effects of nonideal spherical structure of real integrating sphere.
- Correct the measured reflectance according to its simulation result.
- Propose the idea to optimize reflectance of coating and standard white plate.

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ABSTRACT

To accurately measure the directional-hemispherical reflectance of a material surface using an integrating sphere, we investigated the effects of the integrating sphere's interior structure and coating properties on the measured data by numerical simulation. The results showed that the integrating sphere's structure and the reflectance of the coating codetermine the accuracy of the measured results. When the integrating sphere's structure is fixed, choosing an appropriate internal coating using the method proposed in this paper ensures the accuracy of the results. If a proper coating is not available, we propose a method to effectively correct the measured results.

1. Introduction

With the increasing demand for new materials in aerospace, new energy utilization, biomedicine, machining, and so on, processing and manufacturing of materials are rapidly developing [1–3]. However, utilization of new materials cannot be performed without accurate characterization of the materials' properties. As an important radiation property parameter, the accurate measurement of reflectance is extremely important [4–6]. There are various methods to measure the reflectance of materials [7–9], and the d irectional–hemispherical reflectance is frequently measured by an integrating sphere [10–13]. Investigation of the integrating sphere is also common. Symons [14] et al. designed a new apparatus to perform measurements of the solar transmittance of planar and nonplanar transparent samples for various angles of incidence. Dam [15] et al. presented a new method to extract the optical properties from integrating sphere measurements of thin biological samples based on multivariate calibration techniques, multiple polynomial regression, and a Newton-Raphson algorithm for solving nonlinear equation systems. Bittar and Hamlin [16] designed a normal incidence absolute reflectometer based on an integrating sphere that allows accuracies of ±0.2% to be achieved over the 350–750 nm wavelength range. Prokhorov [17] et al. described a newly developed algorithm that substantially improves the convergence by calculating the direct source-induced irradiation for every point of the diffuse reflection of rays traced, and applied this to design an integrating sphere reflectometer for visible and infrared spectral ranges.

In an error study of the integrating sphere, Kim and Philpot [18] presented a new integrating sphere configuration for measuring back scattering using a semispherical cuvette, avoiding the error because of total internal reflection. Davies and Zagieboylo [19] proposed an improved integrating sphere that can determine the average reflectance and transmittance, using the low average reflectance of the coating (pure aluminum oxide) to reduce the error owing to non-uniform spectral response. Hanssen [20]

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Nomenclature

MCM	Monte-Carlo method
λ	wavelength
$i_{\lambda,sample}$	current value of corresponding detector for the sample at a wavelength of λ
$i_{\lambda,white}$	current value of corresponding detector for the standard white plate at a wavelength of λ
E_{in}	radiant energy of irradiation light entering the integrating sphere
E_{out}	radiant energy reaching the detector
fa	area of a certain open pore in the integrating sphere divided by the total area of its inner wall
fa_1	area of the detectors in the sphere divided by the total area of its inner wall
R_θ	uniformly distributed random Number of Zenith Angle θ

Greek symbols

$\rho_{\lambda,sample}$	spectral reflectance of the sample at a wavelength of λ
$\rho_{\lambda,white}$	spectral reflectance of the standard white plate at a wavelength of λ
ρ	reflectance of the integrating sphere's inner wall
$\rho^*_{\lambda,sample}$	sample spectral reflectance at a wavelength of λ

investigated the error caused by non-Lambertian scattering of the interior wall of an integrating sphere through a model for measurement of directional-hemispherical reflectance. Park and co-workers [21–23] reported a series of studies on error correction of the integrating sphere. They realized differential spectral responsivity measurement using a light-emitting diode (LED)-based integrating sphere source and corrected the error caused by the lock-in detection spatial irradiance distribution and broad spectral bandwidth of the LEDs. In addition, they designed a six-port integrating sphere photometer and validated its capability of reducing systematic error because of spatial mismatch between the reference source and the source under test in the measurement of the total luminous flux.

When measuring the directional–hemispherical reflectance of solid materials, the light reflected from the sample surface in all directions needs to be concentrated on the photoelectric detector. One common method is realized by integrating spheres, which is also often used for measuring the lighting source. The practical performance of integrating spheres may not be desirable because of many effects and restrictions when it is used to accurately measure the sample spectral reflectance [24]. Thus, it is necessary to analyze the accuracy of the measurement, determine whether it is acceptable, and possibly correct the measured value. On the other hand, it is very difficult to simulate the measurement using the method of solving discrete equations. So random sampling by Monte-Carlo method is often used to achieve this, and relative investigation is also extensive now [25–26]. Li [27] et al. presented a backward Monte Carlo method based on radiation distribution factor to compute the apparent directional emissivity of one-dimensional absorbing-emitting-scattering semitransparent slab with specular semitransparent surface and opaque diffuse substrate. Parviainen and Muinonen [28] explored the distribution of the reflectance over the scattering hemisphere in particulate porous random media with macroscale surface roughness using Monte-Carlo ray tracing. Xiong and Shi [29] applied the polarized Monte Carlo ray tracing technique to the computer generated bicontinuous medium, so that the snow surface albedo, bidirectional reflectance distribution function can be simulated. Wan and Guo [30] did a numerical study for measuring cerebral blood oxygen saturation noninvasively using optical reflectance ratio of dual wavelengths, and used Monte Carlo method to simulate reflectance measurements in a model neck tissue.

In this study, a Monte-Carlo method (MCM) is used to perform a numerical simulation of the geometry construction of a typical integrating sphere system. According to simulations of different reflectance backgrounds, we first built an error correction model of the reflectance for this integrating sphere system. We then measured the surface hemispherical reflectance of various typical construction material samples, and effectively corrected the measured values using this model. Finally, based on comparison between the corrected and measured results, we analyzed the relationship between the coating reflectance and the measurement error for this system, and determined the optimal integrating sphere coating properties.

2. Experimental system and measurements

The main part of the integrating sphere is a spherical cavity with a coating of high diffuse reflectance on its inner wall. There are several open pores in the wall to allow irradiation light in, place the material samples, place the photoelectric detector, and so on. The sample reflects the irradiation light, which is repeatedly reflected by the spherical cavity's inner wall. This produces diffuse light of uniform luminance in the inner wall, some of which enters the photoelectric detector.

Fig. 1 shows the experimental reflectance measurement system used in this study, and Fig. 2 shows a schematic diagram of its structure. The composite lamp composed of a deuterium lamp and a tungsten lamp can provide sustainable light with a continuous spectrum in the wavelength range 200–2500 nm. The wave chopper performs pulse modulation of the irradiation light, transforming the sustainable light into pulsed light, which is then converted by the filter wheel and the monochromator into monochromatic light with a narrow wavelength range. The monochromatic light reaches the standard white plate or sample wafer after entering the integrating sphere, and the light repeatedly reflected by the inner coating is transformed into a current signal by the detector. Finally, the current signal from the detector and the synchronizing signal from the chopper are exported to the lock-in amplifier, and the data are exported to the computer for post-processing.

Fig. 3 shows the size and structure of the integrating sphere in this system. The open pore at the bottom of the spherical cavity is the entrance port for the irradiation light, and the pore at the top is

Fig. 1. Experimental reflectance measurement system.