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GPU-accelerated inverse identification of radiative properties of particle suspensions in liquid by the Monte Carlo method

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ABSTRACT

Inverse identification of radiative properties of participating media is usually time consuming. In this paper, a GPU accelerated inverse identification model is presented to obtain the radiative properties of particle suspensions. The sample medium is placed in a cuvette and a narrow light beam is irradiated normally from the side. The forward three-dimensional radiative transfer problem is solved using a massive parallel Monte Carlo method implemented on graphics processing unit (GPU), and particle swarm optimization algorithm is applied to inversely identify the radiative properties of particle suspensions based on the measured bidirectional scattering distribution function (BSDF). The GPU-accelerated Monte Carlo simulation significantly reduces the solution time of the radiative transfer simulation and hence greatly accelerates the inverse identification process. Hundreds of speedup is achieved as compared to the CPU implementation. It is demonstrated using both simulated BSDF and experimentally measured BSDF of micro-algae suspensions that the radiative properties of particle suspensions can be effectively identified based on the GPU-accelerated algorithm with three-dimensional radiative transfer modelling.

1. Introduction

Radiative properties, including absorption coefficient, scattering coefficient and scattering phase function are the basic parameters used to analyze radiative transfer in particle suspensions, such as the microalgae suspensions [1,2] and nanofluids [3–5], both are potential candidates for applications in solar energy harvesting. The radiative properties are function of wavelength and dependent on particle shape and size distribution. It is usually difficult or impractical to simulate these parameters from electromagnetic theory due to the lack of particle morphology information and the size distribution [6].

Generally, there are two ways to determine the radiative properties of participating media experimentally. One is by the direct experimental measurements [7,8], and the other is by inverse identification algorithm based on the measured scattering signal [9–18], such as transmittance and reflectance, bidirectional reflection distribution function (BRDF), etc. The direct measurement method requires the optical thickness τ of the sample to be in the range of single scattering regime, namely, $\tau \ll 1$. Furthermore, immersion detector has to be used to reduce the error due to container reflection for particle suspensions in liquid. Hence special equipment has to be designed to conduct the measurement. As for the inverse identification method, general equipment for the measurement of transmittance and reflectance or

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BRDF can be used to do the measurement, which is very convenient and economical for practical applications. Radiative transfer in particle suspensions placed in a container is inherent a three-dimensional problem, the solution of this forward radiative transfer problem is time consuming. As accurate radiative transfer modeling is critical for the inverse identification, it is very appealing that efficient and fast algorithm can be developed for modeling the three-dimensional radiative transfer process in the particle suspensions placed in test container.

Parallelization is an effective way to improve the computational speed. Traditional parallelization algorithm is based on CPU, which often requires huge computer clusters to realize massive parallelization computation. In recent years, the GPU usually used for graphics processing, has been applied to general computation. The Compute Unified Device Architecture (CUDA) technology proposed in 2006 by NVIDIA [19,20] is the most successful for GPU general computation. A GPU has hundreds to thousands of computational cores, hence it naturally supports massive parallelization, and can be easily implemented over a personal computer. Parallel algorithm based on GPU has achieved hundreds of speedup in many areas, such as computational biology [21,22], computational fluid dynamics [23], etc. Parallelization based on GPU has also been applied to radiative transfer modeling and significant speedup has been obtained [24–27]. It is thus very promising to apply the GPU based massive parallelization to the computational intensive problem of inversely identifying the radiative properties.

In this paper, a GPU accelerated inverse identification model is presented to simultaneously obtain the extinction coefficient, scattering coefficient and single scattering phase function of particle suspensions. During the measurement, the sample medium is placed in a cuvette and a narrow light beam is irradiated normally from the side. The forward three-dimensional radiative transfer problem is solved using a massive parallel Monte Carlo method implemented on GPU. The particle swarm optimization algorithm [28,29] is applied to inversely identify the radiative properties of particle suspensions based on the BSDF. A sensitivity analysis of the inverse model is presented. Several test cases are presented to evaluate the accuracy and efficiency of the inverse identification model. Finally, an application of the algorithm to experimentally identify the radiative properties of an example microalgae, i.e. *Chlorella vulgaris*, is presented.

2. The forward problem

The sample of particle suspensions is placed into a rectangular cuvette as shown in Fig. 1. A narrow light beam is irradiated normally from the left side. The optical configuration features three finite-sized semitransparent layers, namely, one sample liquid layer surrounded by two glass layers. The particle suspensions are assumed homogeneous and the glass layer is assumed non-scattering.

The forward problem is to obtain the BSDF based on simulation of radiative transfer in the sample liquid. The

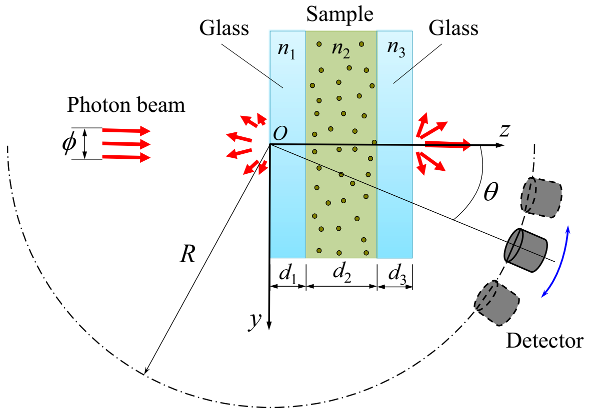

Fig. 1. Schematic of the configuration of the forward problem of light transfer in sample particle suspensions contained in a cuvette.

equation of radiative transfer in the particle suspensions can be written as follows [30],

$$\mathbf{s}\cdot\nabla I(\mathbf{r},\mathbf{s})+\beta I(\mathbf{r},\mathbf{s})=\frac{\kappa_s}{4\pi}\int_{\Omega'=4\pi} I(\mathbf{r},\mathbf{s})\Phi(\mathbf{s}'\rightarrow\mathbf{s})\mathrm{d}\Omega' \tag{1}$$

where I is the radiative intensity, $\mathbf{s}$ is the direction vector, κ_s is the scattering coefficient, $\beta=\kappa_a+\kappa_s$ is the extinction coefficient, κ_a is the absorption coefficient, $\Phi(\mathbf{s}',\mathbf{s})$ is the scattering phase function and Ω' is the solid angle. Here, the one parameter Henyey–Greenstein (H–G) phase function is used to approximate the scattering phase function of particle suspensions, namely,

$$\Phi(\mathbf{s}'\rightarrow\mathbf{s})=\Phi(\cos\Theta)=\frac{1-g^2}{(1+g^2-2g\cos\Theta)^{3/2}} \tag{2}$$

where $g\in[-1,1]$ is the asymmetry factor. The H–G phase function is widely used as an approximate phase function for its simplicity and its ability to capture a wide range of scattering behavior from strongly backward to strongly forward. It has been used to approximate the scattering phase function of solid particle suspensions [13,14], blood cell [31] and microalgae cell suspensions [2,32]. Berberoglu et al. [32] showed that the H–G phase function is a good approximation of the scattering phase function of *Chlorella* sp. and other two kinds of microalgae.

The Monte Carlo method is applied to simulate the radiative transfer in the cuvette containing particle suspensions and to obtain the BSDF with considering the real detector configuration. When a photon bundle transports in the suspensions, it will be absorbed and scattered, the free path length is calculated as [30]

$$\Delta s=-\frac{1}{\beta}\ln\xi \tag{3}$$

where ξ is a uniformly distributed random number within (0,1]. The photon bundle is scattered if $\xi_\omega<\omega$ and otherwise absorbed, where ξ_ω is a uniformly distributed random number within (0,1]. The polar angle of photon scattering direction for the H–G scattering phase function