Influence of particles on forward light scattering of air bubbles in water

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ABSTRACT

The properties of light scattering from air bubbles in water have recently attracted considerable attention, but in practical applications such as in underwater detection, submarine imaging etc., we must take account of light scattering from various sizes of particles suspended in water. The situation of air bubbles and particles co-exist in water was studied in the first time. It is known that an air bubble in water is an example of a scatterer for which the refractive index of core (gas) is less than that of surroundings, which differs significantly from that for particles in water. Consequently, the forward light scattering characteristics of both air bubbles and typical particulate assemblages in the ocean are estimated with Mie theory, the result are analyzed and compared to validate the influence of particles on forward light scattering of air bubbles in the ocean. A preliminary laboratory experiment is also carried out to investigate the properties of forward light scattering (scattering angle less than 4 degrees) caused by particles and air bubbles and to illustrate the differences of light scattering between them.

Keywords: air bubble, particle, forward light scattering, Mie theory

1. INTRODUCTION

The scattering properties of collimated laser beams traversing in water (especially seawater) have recently attracted considerable attention. Direct or indirect viewing is necessary to carry out underwater activities such as underwater target-acquisition guidance of submarine, searching for metal ore nodules and marine specimens. The scattering light may results from suspended particles, air bubbles, oceanic turbulence and so on. The interaction between air bubbles and fine particles is central to the flotation process widely used in the recovery of coal and valuable minerals, in the treatment and purification of wastewater, and in the de-inking of wastepaper. Anh V. Nguyen and his partners1 used an atomic force microscope (AFM) probe technique to measure the interaction forces between an air bubble and a hydrophobic/hydrophilic spherical particle. The study made by Dariusz Stramski and Jaroslaw Tegowski2 shows that bubble clouds may influence ocean reflectance and in-water light field characteristics within the surface layer. Darek J. Bogucki3 has examined and compared near-forward light scattering that is caused by turbulence and typical particulate assemblages in the ocean. The purpose of this paper is to give an analysis of two mechanisms (bubbles and particles) that give rise to intense forward scattering of light. The scattering of light from subsurface bubbles in seawater at small-angle is a problem which has received considerable attention in recent years. While solid particles have long been an object of study. The aim of this research is to compare the properties of the forward scattering on suspended particles and air bubbles and to determine the influence of forward light scattering properties of particles on air bubbles'. We first review the forward light scattering on particles, then discuss the forward light scattering on bubbles, and thirdly compare these results from them. A laboratory experiment is also carried out to illustrate the effects of forward light scattering of particles on bubbles.

2. THEORY

2.1. Modeling of light scattering by particles

The definition of the volume scattering function (VSF) $\beta(\theta)$ of suspended particulate matter in water at small angle is first given before we discuss the approach to model light scattering by marine particles. The importance of this definition lies in the fact that more than half of the scattered radiant intensity is scattered at angle less than $3^{\circ}$ from the incident main beam. Examination of Kullenberg’s data5 shows that 86% of the scattered light at 655 nm is

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scattered at angles less than $10^\circ$. Previous works have obtained scattering curves which differed significantly from the theoretical value at small angles ($\theta < 1^\circ$). In our detection system the scattering angles $\theta$ are less than $4^\circ$. The VSF describes the angular distribution of scattered radiation as the scattered radiant intensity $dI(\theta)$ in a direction $\theta$ from scattering volume $dV$ divided by the incident irradiance $E_0$.

$$\sigma(\theta) = \frac{dI(\theta)}{E_0 dV}$$  \hspace{1cm} (1)

The total scattering coefficient $b$ describes how much light has been scattered in all directions from the incident plane wave beam, which was defined as

$$b = 2\pi \int_{\theta} \sigma(\theta) \sin(\theta) d\theta$$  \hspace{1cm} (2)

The magnitude of $b$ only depends on the substances presenting in the water and is independent of the geometric structure of the various light fields that may pervade it. When several substances are present in the medium, the total VSF is the superimposition of all constituents’ VSF under the condition that the single-scattering assumption is fulfilled. We are interested in modeling the irradiance scattered within the angle $4^\circ$ from the forward direction by a group of spheres with relative refraction index $m$. The theoretical representation of scattering of electromagnetic waves by spherical, non-absorb particles was presented by Mie. Two important parameters in Mie theory are the relative refractive index $m$ and particle diameter scaled by light wavelength. According to Mie theory, when a isotropic, homogeneous sphere particle with diameter $D$ was illuminated by a collimating beam with the wave length $\lambda$ and the intensity $I$, the scattering intensity is given by

$$I(\theta) = \frac{\lambda^2}{8\pi r^2} (i_1 + i_2)$$  \hspace{1cm} (3)

Where $r$ is the distance from observation point to particle center ($r >> D$), $\theta$ is the scattering angle, $i(\theta)$ is the scattering intensity at the scattering-angle $\theta$ which resulted from a unit strength acted by a polarization incidence light. The subscript 1 denoted that the vector $\vec{E}$ of the polarization incidence light is normal to the observation plane, while the subscript 2 denoted that vector $\vec{E}$ of the polarization incidence light is parallel to the observation plane. $P_n(\lambda)$ is indicative of Legendre polynomial and the Mie-scattering coefficients, $A_n$ and $B_n$ were taken from C. F. Bohren and D. R. Hoffman in the form

$$A_n = \frac{m\psi_n(\beta)\psi_n'(\alpha) - \psi_n(\alpha)\psi_n'(\beta)}{m\psi_n(\beta)\xi_n(\alpha) - \xi_n(\alpha)\psi_n'(\beta)}$$  \hspace{1cm} (6)

$$B_n = \frac{\psi_n(\beta)\psi_n'(\alpha) - m\psi_n(\alpha)\psi_n'(\beta)}{\psi_n(\beta)\xi_n(\alpha) - m\xi_n(\alpha)\psi_n'(\beta)}$$  \hspace{1cm} (7)

$$x = -\cos(\theta)$$  \hspace{1cm} (8)

$$m = \frac{n_p}{n_w}$$  \hspace{1cm} (9)

$$\alpha = \frac{\pi n_p D}{\lambda}$$  \hspace{1cm} (10)

$$\beta = \frac{\pi n_w D}{\lambda}$$  \hspace{1cm} (11)

Where $n_p$ and $n_w$ indicate the refractive index of particle and water respectively, $m$ is the relative refractive index (here after, for suspended particles and water denoted as $m_p$ for bubble and water denoted as $m_b$), $\psi(mx)$ and $\xi(x)$ are Riccati-Bessel function and Riccati-Hankel function respectively.
Considering that seawater contains particles of various sizes and shapes, our purpose now is to obtain reasonable estimates of the magnitude of the VSF in the forward directions scattering associated with typical assemblages of marine particles by use of Mie-scattering calculations. We restricted these calculations to a homochromatic light at 632.8 nm. This assumption is sufficient for our purposes because such calculations provide us with an approximate magnitude of the VSF that can be expected to occur over the entire visible spectral region. Before embarking on the Mie calculations, we first made some hypothesis as following: the first, the scattering with shape of sphere surrounded by a homogeneous dielectric medium (water). The second, the particles are non-absorb, thus the imaginary part of the refractive index of particles is zero. This is because absorption has a comparatively small effect on near-forward scattering, and most marine particles exhibit weak absorption. The third, the particles are many and their distributions are random in addition to single scattering, which implies incoherent and single scattering. Based on the above theoretical result to the laboratory result $m$ is chosen to be 1.16. However, according to scalar diffraction theory the scattering amplitude in the forward direction is proportional to the cross-section area of particles, regardless of its shape, and is independent of refractive index $m$. In this paper in order to match the theoretical result to the laboratory result $m$ is chosen to be 1.16.

We constructed a particle size distribution to emulate VSF data taken in seawater. Numerous particle size measurements with a Coulter counter showed that, for particle diameters $D$ greater than approximately 1 µm, the distribution can be approximated by a power function with a slope being a negative number. Generally, the slopes are steeper for larger particles and less steep in the small size range, for this reason the segmented description is often required to obtain the best fit to the Coulter counter data over the broad range of particle diameters extending to several tens of micrometers or so. Considerable simplification can be resulted if we choose the most typical value $-4$ for the differential particle size distribution. To fulfill the condition of single scattering the determination of the concentration of particles greater than 1 µm in diameter is 7 × 10$^{10}$ particles m$^{-3}$. In this paper in order to match the theoretical result to the laboratory result $m$ is chosen to be 1.16.

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As already mentioned, the calculations of VSF which represents our particle size distribution were made for $\lambda = 632.8$ nm for particles with refractive index $m = 1.16$ and the scattering angle $\theta = 170^\circ$. We adopt the method that Darek J. Bogucki used to achieve the VSF. In order to obtain the calculation, the size distribution was divided into 38 size classes and calculated the VSF respectively. At the mean time the midpoint diameters of the size classes were used as input in these calculations. The resultant VSF was obtained as the sum of contributions of all size classes. The results for scattering angles as high as 170$^\circ$ are presented in Fig. 1.

2.2. Modeling of light scattering by air bubbles

For both air bubbles and suspended particles in water are scatterers, the computation formulas used to calculate the VSF of air bubbles is just the same as those used in section A. the only difference is the relative refractive index $m$. As mentioned in the above section we are interested in modeling the irradiance scattered within the scattering-angle $\theta < 4^\circ$ by assemblages of sphere with a relative reference index $m = 0.75$. In despite of the fact that when the diameter of bubbles large than 300 µm the oblateness will strongly affect the details of the optical backscattering pattern, but the forward light scattering is less dependent on the shape, so our calculations were primarily carried out for spheres. Another simplification is the omission of thin insoluble films on the surface of bubble, which are though to stabilize some micro-bubbles in the ocean, for the fact that most scattering phenomena are relatively weakly affected by the
film except the Brewster angle scattering under the condition that the film is thinner than a few µm.

The bulk optical properties of bubbles in the ocean was carried out by Stramski\textsuperscript{14}, who studied the light-scattering capability of clean bubble population with a size distribution following the \textasciitilde4th power law for radii between 10 and 150 µm. To address our hypothesis that we put forward in this paper, an approach similar to that used by Stramski\textsuperscript{2} was introduced in this study. The bubble size distribution we used based on both the available \textit{in situ} bubble measurements in the ocean and our laboratory instrument, so we select bubbles in the size range form 0.001 to 3000 µm. In our study we interested in the bubble ranged from 0.01 µm to 80 µm. Once the bubble clouds are formed, the bubbles evolve by such processes as dissolution, rise and gas expansion, all of which are a function of bubbles size. Therefore these processes regulate the bubbles bubble distribution function (BDF) with respect to size. The \textit{in situ} observations support, in general, two types of bubbles density functions. One has a plateau with the bubble concentration dropping off rapidly on both sides of the plateau. The other exhibits a monotonic increase as the bubbles radius decreases. The bubble size distribution obtained by optical methods and simulated numerical models seem to support the former. Here we use the expressions which given by Xiaodong Zhang\textsuperscript{15}

\[
N(r) = N_0 P(r) = \begin{cases} 
N_0 c_1 r^4 & 0 \leq r < r_a \\
N_0 c_2 r & r_a \leq r < r_b \\
N_0 c_3 r^{-4} & r_b \leq r 
\end{cases}
\]  

(12)

Where \(r_a\) and \(r_b\) are the radii of bubbles that define the limits of the plateau, \(c_1, c_2\) and \(c_3\) are uniquely depends on the peak position. In the following study in order to simplify the calculation we chosen \(c_1 = c_2 = c_3 = 1\), where \(N_0 (\text{m}^{-3})\) is the total bubble number density in a unit volume of water and \(P(r)\) is the bubble probability density function at radius \(r\), where \(N_0\) with value \(2 \times 10^{10}\) which was determined by our interested bubble distribution. We select \(r_a = 1 \mu m, r_b = 10 \mu m\) to present the full-range of bubble population we interested in seawater, without regard to the specific generating mechanism.

With the distribution and the index of refraction of bubbles we can calculate the VSF of bubble shown by Fig. 2 by the method applied in section 2.1.

![Fig. 2. VSF calculated from Mie-theory for 0.01-80µm and 1-2000µm air bubbles.](image)

![Fig. 3. Comparison of VSF calculated from Mie-theory for air bubbles with VSF calculated from Mie-theory for particles, along with the sum VSF of particles and bubbles](image)

2.3. Comparison of volume-scattering function for particles and air bubbles

The VSF corresponding to particles can be compared with the VSF corresponding to air bubbles, as shown in Fig. 3. We are interested in the near forward light scattering property of the bubbles with medium size. Therefore, in what follows, we just discuss the influence of particles ranged from 0.01-80µm on the bubbles with size of 0.01-80µm. We can see from the graph that the magnitude of VSF of bubbles and of particles are kept unchanged when the scattering angle \(\theta\) is less than \(\theta_1\), but the VSF of bubbles is also approximately held unaltered while the VSF of particles decreasing gradually when \(\theta\) ranged from \(\theta_1\) to \(\theta_2\). This should attract our attention that in this scattering angles range the differentiation of VSF between bubbles and particles is distinct. Thus the dominant effect of the particles at very
small angles seems to be a fairly universal fact. For comparison, the sum of VSF calculated from Mie-theory of particles and bubbles is also plotted, this curve lead us to the same conclusion that the particles has more influence on bubbles in the study of forward light scattering of bubbles when the scattering angle is less than one degree.

3. LABORATORY EXPERIMENT

3.1. Method

We present a method to measure the influence of the particles with the diameter $D_p$ from 40µm to 100µm to the bubbles with the diameter $D_b \in [1\mu m, 2000\mu m]$. The experimental setup is shown Fig. 4. A linear polarized He-Ne beam, with 632.8nm was attenuated and collimated by a collimating system. The intensity of laser beam is adjusted by an alterable attenuator to ensure that the received intensity under that of the CCD saturation. An air bump and ceramics micro-pore bar was used to produce bubbles. The bubble size and concentration was denoted and controlled by the air bump’s pressure. The solid glass beads were chosen as particles, which were spread into the testing tank when needed. The real time measurement system was made up of the CCD data acquisition and the DSP processing. A linear CCD placed at the back focal plane of the Fourier transform lens was used as an optical-electrical converter to collect the light signal which contains the information of the Full Width at Half Magnitude (FWHM) and the peak value of the scattering spectrum distribution. The DSP processing handing the converted electrical signal and gives both values of FWHM and the peak.

![Fig. 4. Experiment setup.](image)

In this way the magnitude of the forward light scattering within 4° is one-to-one correspondence to the output valuation of the pixel of CCD. There is evidence that in our investigation the spectrum distribution is obedient to the Gauss distribution. So the scattering spectrum distribution can be uniquely determined by its FWHM and peak value. Based on this conclusion we can argument the characteristics of the forward light scattering of air bubbles and particles in water by study FWHM and peak value of the Gauss distribution.

3.2. Experiment results

To examine how particles affect the forward light scattering characteristic of air bubbles in water, experiment are done at several conditions. Firstly, the experiment is done in three situations: there are bubbles in water only, bubbles mixed with the particles with an average diameter of 40µm (0°) and of 70µm(2°) respectively. In the experiment, the concentration of the particles is $8.996 \times 10^{-4}$ and the air pump pressure holding to maintain constant concentration of air bubble in water. The received scattering spectrum distributions of Gauss fit are shown in Fig. 5. It is shown that much light was scattered for the existence of particles, and the larger the particles are, the more the scattering light is.

![Fig. 5. Gauss Fit Curve for three situations](image)

Secondly, the experiment is done at constant air pump pressures of 0.01Mpa with gradual rising particles concentration. That is, in the experiment the size and the population of bubbles are invariable, while the quantity of particles is raised gradually. FWHM and the peak values of the Gauss curve are shown in Fig. 6. Form Fig. 6 we can see that more particles will lead to more impact on scattering characteristic of air bubbles’ in water. As
particle density increase, the peak values of scattering spectrum distribution decrease and the FWHM of that increase. In this way the influence of particles at different concentration on the near forward light scattering of air bubbles with a given distribution is determined.

Thirdly we investigate experimentally the effect of particles with gradual increasing concentration on air bubble at different air pressure. The result is shown in Fig. 7. From Fig. 7 it can be conclude that with air pressure increasing, the influence of particle with certain size is decreasing. That is, the particles have more effect on the near light scattering property of smaller air bubbles.

4. CONCLUSIONS AND FUTURE WORK

The Mie code calculation presented here provides a comparison of the forward light scattering characteristics of air bubbles and typical particulate assemblages in the ocean in theory. We also have investigated numerically and experimentally the scattering of light beam at small angles in water in which the particles and air bubbles existing together. Through compared the near forward scattering by typical oceanic particulate assemblages with air bubbles induced scattering, we found that oceanic particulate assemblages have certain influence on air bubbles’ light
scattering property. The preliminary results shown above demonstrate that the scattering induced by particles should be taken into account when the forward scattering characteristic of air bubbles in oceanic water is studied. It can be conclude that if the distribution of particles in the ocean water is homogeneous, the particles’ effect on the scattering of air bubble can be eliminated by certain mathematics method used on our designed system. Future work will demonstrate the influence of both the particle and other noise source such as oceanic turbulence.

REFERENCES