Optical Characterization Studies of a Low-Cost Particle Sensor

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ABSTRACT

Compact low-cost sensors for measuring particulate matter (PM) concentrations are receiving significant attention as they can be used in larger numbers and in a distributed manner. Most low-cost particle sensors work on optical scattering measurements from the aerosol. To ensure accurate and reliable determination of PM mass concentrations, a relationship of the scattering signal to mass concentration should be established. The scattering signal depends on the aerosol size distributions and particle refractive index. A systematic calibration of a low-cost particle sensor (Sharp GP2Y1010AU0F) was carried out by both experimental and computational studies. Sodium chloride, silica, and sucrose aerosols were used as test cases with size distributions measured using a scanning mobility particle sizer (SMPS). The mass concentration was estimated using the measured size distribution and density of the particles. Calculations of the scattered light intensity were done using these measured size distributions and known refractive index of the particles. The calculated scattered light intensity showed better linearity with the sensor signal compared to the mass concentration. To obtain a more accurate mass concentration estimation, a model was developed to determine a calibration factor (K). K is not universal for all aerosols, but depends on the size distribution and refractive index. To improve accuracy in estimation of mass concentration, an expression for K as a function of geometric mean diameter, geometric standard deviation, and refractive index is proposed. This approach not only provides a more accurate estimation of PM concentration, but also provides an estimate of the aerosol number concentration.

Keywords: Sensor calibration; Calibration linearity; Number concentration; Mass concentration.

INTRODUCTION

Particulate matter (PM) is ubiquitous in the environment and is receiving significant attention due to potential impacts on health (Pope 3rd et al., 1995; Brunekeef and Holgate, 2002; Biswas and Wu, 2005; Oberdörster et al., 2005). Outdoor PM pollution can be attributed to gasoline exhaust, diesel emissions, biomass burning, traffic-related pollutions, and industrial emissions (Chow, 2001; Zheng et al., 2002; Donaldson et al., 2005; Edney et al., 2005). Indoor PM is generally emitted from tobacco smoking, cooking, wood burning, medical treatment, and outdoor PM penetration (Monn et al., 1995; Tuckett et al., 1998; Long et al., 2000; Tucker, 2000; He et al., 2004; Liu et al., 2016; Wang et al., 2017). Developing countries, such as India and China, had to cope with a challenging situation due to the adverse effect of high PM level (Brook et al., 2010; Cheng et al., 2013; Smith and Sagar, 2014; Tripathi et al., 2015; Liu et al., 2016; Sagar et al., 2016). For example, recent studies have indicated that ambient air pollution accounts for 1.6 million deaths every year in China (Cheng et al., 2013; Rohde and Muller, 2015) and 4–6% of the Indian national burden of disease (Smith, 2000).

Indoor PM pollution increases the potential risk for chronic obstructive pulmonary disease and acute respiratory infections (Bruce et al., 2000; Smith et al., 2000; Brunekeef and Holgate, 2002). Most buildings have HVAC (heating, ventilation and air conditioner) systems that filter the air in the indoor environment. However, most systems do not take into account the concentration of pollutants indoors, which may fluctuate over time (Leavey et al., 2015). By developing a real-time air quality monitoring system, the HVAC system can operate more efficiently. Therefore, distributed and real-time particle concentration measurements are necessary to identify hotspots indoors and provide information for the HVAC system (Kim et al., 2010; Bhattacharyya et al., 2012).

Since it is important to monitor PM concentrations, many instruments have been developed, ranging from accurate and expensive laboratory scale instruments (Wang and Flagan, 1990; Chen et al., 1998) to portable instruments for field measurements (Yanosky et al., 2002; Rees and Connolly,
Field and laboratory instruments that are compact typically rely on the measurement of the optical scattering intensity of particles. The governing principles of these instruments can be divided into either single particle light scattering measurements or total particle light scattering measurements; and they report either the number or the mass concentration, respectively. Portable instruments sacrifice some accuracy, but they are more convenient and practical for field measurements. The TSI SidePak<sup>TM</sup> AM510, weighing 0.46 kg, uses a 670 nm laser to sample aerosol mass concentration from 0.001 to 20 mg m<sup>–3</sup> (Rees and Connolly, 2006; Jiang et al., 2011). The P-Trak<sup>®</sup>, whose longest dimension is 27 cm, uses isopropanol as the working fluid to monitor 0.02 to 1 μm particle number concentrations, ranging from 0 to 5 × 10<sup>5</sup> particles cm<sup>–3</sup> (Chao et al., 2003; Zhu et al., 2006). These portable aerosol instruments with light weight provide reasonable accurate estimations of either the number or the mass concentration. While several portable instruments are available, cost is still the major concern for deploying such real-time monitoring network systems for indoor and outdoor air quality measurements. Recently, a series of low-cost particle sensors that operate by measuring the total particle light scattering intensity are being touted for use. Their low price (device cost in the range of USD 10 each) alleviates the economic concerns in making widespread measurements in large-scale environments, and their compact size makes them readily portable. These units could be assembled for a total cost of USD 50 and used in a distributed manner. In controlled laboratory tests, low-cost particle sensors have shown high linearity and stability in comparison with commercial instruments with a known particle size and composition (Wang et al., 2015; Manikonda et al., 2016; Sousan et al., 2016, 2017; Zikova et al., 2017). Several studies in the literature have reported the combination of low-cost particle sensors with “smart” home devices (e.g., temperature, humidity, carbon monoxide sensors, cameras) to provide more comfortable and energy-efficient homes and workplaces (Ivanov et al., 2002; Chung and Oh, 2006; Kim et al., 2010; Bhattacharyya et al., 2012; Kim et al., 2014). Moreover, a few studies also applied multiple sensors for outdoor or indoor air quality measurements (Rajasegarar et al., 2014; Patel et al., 2017). One of the disadvantages is that the response of the low-cost particle sensors varies with particle composition and size distributions, which requires repeated calibration to ensure reliable estimations of mass concentration. This disadvantage has been reported by several groups (Wang et al., 2015; Sousan et al., 2016). However, there is no sufficient study of the reasons and quantification for such variations; nor approaches proposed to enhance the accuracy.

To overcome these limitations, an evaluation of the relationship between particle composition, size, and signal outputs of a low-cost particle sensor is reported in this paper. Sharp GP2Y1010AU0F (Model GP2Y) was selected as the representative low-cost particle sensor due to its high linearity and long-time operational stability in comparison with reference instruments as established in a former study (Wang et al., 2015). To accomplish this, first, experimental studies for calibration were conducted in a chamber with known aerosols. Second, Mie and Rayleigh scattering expressions (Laven, 2006) were used along with the particle size distributions to predict the measured signals of the low-cost particle sensors. The sensor signal output was correlated to the integrated information from more sophisticated size distribution measurement instruments to evaluate accuracy. Finally, based on the light scattering theory, an expression for a calibration factor (K) dependent on refractive index and size distribution parameters (geometric mean diameter, d<sub>pp</sub> and geometric standard deviation, σ<sub>d</sub>) was derived to predict the mass concentration and number concentration from the sensor signal output.

**METHODS**

**Major Components of the Wireless Sensor**

Fig. 1(a) shows the schematic diagram of the wireless sensor setup. Sharp GP2Y with a fan (Fig. 1(b)) was evaluated in this study. Sharp GP2Y contains an infrared emitting diode (IRED) and a phototransistor. The IRED illuminates particles in the air flow with a 10 ms pulse-driven waveform whose duty ratio is 0.032. Scattered light intensity is converted to a 0–3.5 V analog signal by the phototransistor. The analog signal becomes fully developed within 0.28 ms, so the voltage on the phototransistor is recorded at exactly 0.28 ms. A 5 V, 2 × 2 cm<sup>2</sup> brushless mini fan (Mini Cooling Radiator, 2510S) was attached to the back of the sensor to allow air flow through the aperture. Since the sensor was attached on the wall, the natural airflow convection of the sensor design is limited. Therefore, the fan was equipped with the sensor to direct the air flow through the unit that introduces the particles to the sensing region.

The communication module used in this experiment is an XBee Series 2 (Fig. 1(c)). Its operating frequency is 2.4 GHz, and the transmission power output is 2 mW. The range of indoor transmission is 30 meters, and the outdoor free air range is 100 meters. In this study, the XBee was placed on the circuit board as shown in Fig. 1(a). The microcontroller used in this work was an Arduino Nano ATmega328P (Fig. 1(d)), which accurately coordinated the data timing between the sensor and the XBee module. In the loop, the Arduino powered the IRED in the sensor with an accurate 10 ms square waveform and then sampled the voltage signal at 0.28 ms after the leading edge of the waveform was detected. After this, the microcontroller converted the analog voltage signal into a digital signal that can be sent by the XBee module. In these experiments, the sampling interval of the microcontroller (Arduino) was set to 2.5 seconds, and every four samples were averaged before sent to the computer through XBee. Therefore, the log file stored on the computer recorded signal every ten seconds.

**Experimental Set up**

As stated previously, it is important to ensure that the signal output can be accurately used to determine the mass concentration by a calibration factor. The signal from the Sharp GP2Y is dependent on the particle composition and...
size distribution. Our earlier work has demonstrated that for the same mass concentration of different particle types (e.g., NaCl, sucrose, and NH₄NO₃) and size distributions (e.g., 300 nm, 600 nm, and 900 nm polystyrene latex particles), the sensor signal outputs were different (Wang et al., 2015). However, the patterns of the change, together with the necessity of calibration, has not been clearly presented. Therefore, it is crucial to explain the reason for such difference qualitatively or quantitatively with a systematically study, which is addressed in this study. In this work, a systematical calibration of a Sharp GP2Y was carried out experimentally. Then, with a proposed model, the response of the sensor as a function of particle composition and size distribution parameters was studied.

Initial experiments were done with laboratory generated NaCl, sucrose, and SiO₂ particles. Different sets of tests with various solution concentrations were done to determine the effect of varying size distributions on the measured signal outputs. The experimental system is shown in Fig. 2. Different concentrations of NaCl solutions, sucrose solutions, and SiO₂ solutions were added in a constant output atomizer (TSI Model 3076) to generate test aerosols with different size distributions. NaCl solutions (0.507 mg mL⁻¹, 1.087 mg mL⁻¹, and 1.892 mg mL⁻¹) and sucrose solutions (1.150 mg mL⁻¹, 3.325 mg mL⁻¹, 4.315 mg mL⁻¹) were prepared by dissolving NaCl (reagent grade ≥ 98%, +80 mesh, Sigma-Aldrich) and sucrose (≥ 99.5%, Sigma Ultra, Sigma-Aldrich) in deionized water. SiO₂ solutions (10 wt. % suspension in H₂O, LUDOX® TM-40 colloidal silica, Sigma-Aldrich) were prepared with deionized water. The atomized particles were passing through a diffusion drier to remove the water contents in the particles. Then, the dried particles were sent to a cubic chamber (58 cm × 58 cm × 58 cm) through the inlet tube at the top of the chamber. On the right side of the chamber, a Sharp GP2Y sensor and a sampling tube that connected the chamber with a scanning mobility particle sizer (SMPS, size range 14.6 nm to 661.2 nm, TSI Model 3080) were placed close to each other at the middle of the right panel. The distance between the Sharp GP2Y center and the sampling tube was around 5 cm, small in comparison to the width of the chamber (58 cm). Thus, the PM sampled by the SMPS was assumed to be the same as that detected by the Sharp GP2Y. The SMPS was operated with a three-minute sampling interval to measure the size distributions (n(dₚ)) of the generated particles in the chamber. And as mentioned before, the data log file of the Sharp GP2Y had a 10-second sampling interval. Therefore, every eighteen samples from the Sharp GP2Y will be averaged to match the sampling interval of the SMPS.

Characteristic size distributions from different solutions are shown in Fig. 3. Two critical parameters, the geometric mean diameter (dₚ) and the geometric standard deviation (σₚ) of each size distribution are reported in Table 1. The difference was not large among the size distributions of particles generated from atomizing sucrose and SiO₂ solution. This is mainly caused by the larger standard deviations of the size distributions as shown in Table 1, so that the size distributions were broadened, covering each other.

With the experimental setup, we can obtain the signal output from sensor and the size distribution from SMPS, which is necessary to calculate the mass concentration and the total scattered light intensity. The detailed expressions of the mass concentration and the total scattered light intensity are presented in the next section.

**Mass Concentration (m_{total}) and Calculated Total Scattered Light Intensity (I)**

The mass concentrations (m_{total}) were calculated based on the size distribution function, n(dₚ), assuming that all
Fig. 2. Schematic diagram of systems used to compare the performance of the wireless sensor with that of standard aerosol instruments. Constant output atomizer 3076 producing small particles \(d_p < 600\,\text{nm}\) with an SMPS reference instrument.

Fig. 3. Characteristic size distributions of particles generated by the constant output atomizer with different solutions.

Table 1. Densities and size distribution parameters of the particles generated from different solutions.

<table>
<thead>
<tr>
<th>Solution conc. mg cc(^{-1})</th>
<th>Test number</th>
<th>Particle density g cc(^{-1})</th>
<th>Size distributions from SMPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. NaCl</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.507</td>
<td>1</td>
<td>2.16</td>
<td>92.02 1.77</td>
</tr>
<tr>
<td>1.087*</td>
<td>2</td>
<td>119.55 1.69</td>
<td></td>
</tr>
<tr>
<td>1.892</td>
<td>3</td>
<td>156.95 1.48</td>
<td></td>
</tr>
<tr>
<td>II. Sucrose</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.150</td>
<td>4</td>
<td>115.78 1.91</td>
<td></td>
</tr>
<tr>
<td>3.325</td>
<td>5</td>
<td>126.99 1.99</td>
<td></td>
</tr>
<tr>
<td>4.315</td>
<td>6</td>
<td>155.57 1.87</td>
<td></td>
</tr>
<tr>
<td>III. SiO(_2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1%</td>
<td>7</td>
<td>150.93 2.07</td>
<td></td>
</tr>
<tr>
<td>2%</td>
<td>8</td>
<td>176.06 1.91</td>
<td></td>
</tr>
</tbody>
</table>

particles are spherical (Friedlander, 2000):

\[
m_{\text{total}} = \int \rho_p \frac{\pi d_p^4}{6} n_A(d_p) \cdot d(d_p),
\]

where \(\rho_p\) is the particle density, \(d_p\) is the particle diameter. In this work, \(n_A(d_p)\) was measured by the SMPS as described in the experimental set up section.

The total scattered light intensity \(I\), was calculated based on the working principle of the Sharp GP2Y sensor, as shown in Fig. 4. Total scattered light intensity is a summation of the product of the scattered light intensity of a single particle, \(i_{dp}\), and the size distribution function, \(n_A(d_p)\), as Eq. (2) (Friedlander, 2000).

\[
I = \int i_{dp} n_A(d_p) \cdot d(d_p),
\]
Fig. 4. Working principle and critical parameters of the Sharp GP2Y low-cost particle sensor. “PT” and “IRED” represent the phototransistor and the infrared emitting diode respectively.

(θ), the distance between the illuminated particles and the phototransistor (R), the wavelength of light source (λ), and the incident light intensity (I₀). Particle properties include the particle size (dₚ) and the refractive index (m). The refractive index can be expressed as a combination of real and imaginary terms (m = m_{real} – m_{img}i). However, practically, particles would pass the measuring point as a combination of different particle diameters with different number concentrations, rather than pass through the measuring point one by one, which is the situation shown in the left side of Fig. 4. Therefore, i_{dₚ} needs to be coupled with n_{d}(dₚ) · d(dₚ), the number concentration of particles whose size is dₚ. Then, it needs to be integrated from the minimum size to the maximum size.

In this study, the sensor parameters are, θ = 60°, R = 2 cm, λ = 860 nm, and m = 1.536 (NaCl particles), 1.5376 (sucrose particles), and 1.486 (SiO₂ particles) (Hand and Kreidenweis, 2002). MiePlot V4.5 (Laven, 2006) was used to calculate the scattered light intensity of a single particle (i_{dₚ}) as a function of particle diameter (dₚ) with the mentioned constraints.

Expression for Calibration Factor (K) to Relate Sensor Signal Output (S) to Mass Concentration (m_{total}) from Experiments

A calibration factor (K) linking the mass concentration (m_{total}) with the sensor signal output (S) is defined as follows:

\[ m_{total} = K(S - S_0) \quad (3) \]

\[ S_0 \] is a signal output obtained at a particle concentration of zero due to a certain drift in the electronics of the system. In the following section, there will be: \( K_{exp} \), \( K_{eq,6} \), and \( K_{eq,12} \), representing the calibration factor fitted from the experimental results (\( K_{exp} \)) or calculated from the proposed model (\( K_{eq,6} \) and \( K_{eq,12} \)).

In the experiments, mass concentration (m_{total}) can be calculated from Eq. (1) with the \( n_{d}(d_p) \) measured by the SMPS and the \( \rho_p \) reported in Table 1. The sensor signal output (S) was recorded in the log file on the computer. So, \( K_{exp} \) can be obtained by fitting experimental results into Eq. (3).

Estimation the Calibration Factor (K) with Lognormal Size Distribution

To further analyze how other parameters will influence the calibration factor, \( (S - S_0) \) was expressed as a function of the total scattered light intensity, I

\[ (S - S_0) = \eta I, \quad (4) \]

where \( \eta \) is the response coefficient of the sensor, which is determined by the optical characteristics of the phototransistor. The value of \( \eta \) is determined experimentally by calibration. With Eq. (4), Eq. (3) can be written as

\[ m_{total} = \eta K I \quad (5) \]

According to Eq. (1) and Eq. (2), m_{total} and I are functions of \( n_{d}(d_p) \) and \( i_{dₚ} \). By substituting Eqs. (1–2) into Eq. (5), the calibration factor (\( K_{eq,6} \)) can be expressed as Eq. (6), which is dependent on the properties (density, size distribution, and refractive index) of the measured PM.

\[ K_{eq,6} = \frac{1}{\eta} \int \frac{\rho_p \pi d_p^3}{6} n_d(d_p) \cdot d(d_p) \]

\[ = \frac{1}{\eta} \int i_{dₚ} n_d(d_p) \cdot d(d_p) \]

Eq. (6) indicated that the PM size distribution and the PM properties have a complex influence on the calibration factor. The integration in the numerator and the denominator are too complicated for either qualitative analysis or practical implementation. To simplify the integration, lognormal size distribution assumption and method of moments were applied in the following derivation.

The definition of lognormal size distribution is shown as follows, where \( N_{0ₚ} \), \( \sigma_{dₚ} \), and \( d_{pg} \) represent the total number concentration, the geometric standard deviation, and the geometric mean diameter, respectively (Friedlander, 2000).
\[ n_s(d_p) = \frac{N_s}{(2\pi)^{3/2}d_p\ln \sigma_g} \exp \left( -\frac{(\ln d_p - \ln d_{pg})^2}{2\ln^2 \sigma_g} \right) \quad (7) \]

The method of moments is defined as Eq. (8) (Friedlander, 2000).

\[ M_r = \int d_p n_s(d_p) \cdot d(d_p) \quad (8) \]

where \( M_r \) is the general moment of the particle size distribution, where \( \gamma \) represents the order of the moment. The geometric standard deviation (\( \sigma_g \)) and the geometric mean diameter (\( d_{pg} \)) can be used to express \( M_r \) as shown in Eq. (9). \( M_0 \) is the zeroth moment, which represents total number concentration (Friedlander, 2000) and \( M_0 \) can be cancelled out later.

\[ \ln(M_r / M_0) = \gamma \ln d_{pg} + \frac{\gamma^2}{2} \ln^2 \sigma_g \quad (9) \]

In order to apply the method of moments to Eq. (6), apart from lognormal size distribution assumption, \( \gamma \) needs to be expressed as a polynomial function of particle size \( d_p \). Therefore, we expect to fit the relationship between \( i_{dp} \) and \( d_p \) for the simplification. Eq. (10) was applied to describe the relationship between \( i_{dp} \) and \( d_p \). \( i_{dp} \) was enlarged with a factor of 10\(^{15} \) to increase the accuracy of fitting since \( i_{dp} \) was too small for calculation. The relationship between \( i_{dp} \) and \( d_p \) can be divided into two ranges, proportional to \( d_p^6 \) and \( d_p^2 \) for small particles in the Rayleigh regime and large particles in the geometric scattering regime respectively. Although the transition regime, Mie regime is not included here in Eq. (10), it can still quantitatively cover the light scattering properties in the whole size range. The fitting results of Eq. (10) will be discussed in detail in the Results and Discussion section.

\[ \frac{1}{i_{dp}} = \frac{a}{d_p^6} + \frac{b}{d_p^2} \quad (10) \]

Eq. (10) could be further simplified as Eq. (11) under the following two situations. When most of the measured particles are small, Rayleigh regime will be the dominate regime, and Eq. (10) can be simplified as Eq. (11a). On the contrary, when the measured particles are larger, geometric scattering regime will be the dominant regime. Therefore, Eq. (10) can be simplified as Eq. (11b)

\[ i_{dp} \approx \frac{d_p^6}{b} \quad \text{when } d_p \text{ is small and } \sigma_g \text{ is small} \quad (11a) \]

\[ i_{dp} \approx \frac{d_p^2}{a} \quad \text{rest of the situations} \quad (11b) \]

The calibration factor (\( K_{eq,12} \)) can be expressed as Eq. (12) after plugging in Eqs. (6, 8–11).

\[ K_{eq,12} = \frac{1}{\eta} \cdot \frac{m_{total}}{I} = \frac{1}{\eta} \cdot \frac{\rho_p \pi}{6} \cdot M_3 = \frac{1}{\eta} \cdot \frac{1}{6} \cdot \frac{\rho_p \pi}{M_0} \cdot e^{\frac{3}{2}d_{pg}^2} \cdot e^{\frac{3}{2}d_{pg}^2} \quad (12a) \]

\[ K_{eq,12} = \frac{1}{\eta} \cdot \frac{m_{total}}{I} = \frac{1}{\eta} \cdot \frac{1}{6} \cdot \frac{\rho_p \pi}{M_0} \cdot e^{\frac{3}{2}d_{pg}^2} \quad (12b) \]

The errors of the calibration factor predicted by the proposed model (\( K_{eq,6} \) and \( K_{eq,12} \)) can be calculated by Eq. (13), regarding to the experimental results (\( K_{exp} \))

\[ \text{error} = \frac{K_{exp} - K_{eq,6} \text{ or } K_{eq,12}}{K_{exp}} \quad (13) \]

**Estimation of the Number Concentration with Known Parameters**

A method of estimating number concentration with given parameters is presented as follows. Mass concentration and number concentration are relevant to the third and the zeroth moment of size distributions respectively. In addition, the mass concentration can be derived from Eq. (3). Therefore, the number concentration estimated from Eq. (15) were compared with the number concentration measured by the SMPS. The errors between the two values were calculated with Eq. (16). \( N_{SMPS} \) and \( N_{exp} \) represent the number concentrations measured by the SMPS and evaluated from Eq. (15) respectively.

\[ m_{total} = \frac{\rho_p \pi}{6} M_3 = \frac{\rho_p \pi}{6} M_0 \cdot e^{\frac{3}{2}d_{pg}^2} \cdot e^{\frac{3}{2}d_{pg}^2} \quad (14) \]

\[ N = M_0 = \frac{6m_{total}}{\rho_p \pi \cdot e^{\frac{3}{2}d_{pg}^2} \cdot e^{\frac{3}{2}d_{pg}^2}} = \frac{K(S - S_0)}{\rho_p \pi \cdot e^{\frac{3}{2}d_{pg}^2} \cdot e^{\frac{3}{2}d_{pg}^2}} \quad (15) \]

The number concentration estimated from Eq. (15) were compared with the number concentration measured by the SMPS. The errors between the two values were calculated with Eq. (16). \( N_{SMPS} \) and \( N_{exp} \) represent the number concentrations measured by the SMPS and evaluated from Eq. (15) respectively.

\[ \text{error} = \frac{N_{SMPS} - N_{exp}}{N_{SMPS}} \quad (16) \]
RESULTS AND DISCUSSION

Relationship between the Scattered Light Intensity of a Single Particle (idp) and the Particle Size (dp)

The scattered light intensity of a single particle (idp) is plotted in Fig. 5 as a function of particle size (dp). Fig. 5(a, c, and e) show the calculated scattered light intensity of a single particle (idp) as a function of particle diameter (dp). According to the plots, the slopes of the curve change from 6 to 2 with increasing particle diameter on logarithm scale, which demonstrated that idp is proportional to dp6 and dp2 for small and large particles respectively. This linearity is consistent with the different light scattering characteristics in the Rayleigh, Mie, and geometric scattering regimes. In the Rayleigh regime, the scattered light intensity is proportional to dp6, while in the geometric scattering regime, the scattered light intensity is proportional to dp2. The transition regime between the above two regimes is the Mie regime.

Since the final aim is to estimate the mass concentration with the sensor signal output, we also plot the scattered light intensity of unit volume against particle diameter in Fig. 5(b, d, and f). The scattered light intensity of unit volume is calculated by dividing the calculated scattered light intensity of a single particle (idp) by the volume of the particle (πdp3/6). After assuming the density of the particle (shown in Table 1) is a constant, the curves can be interpreted as the scattered light intensity of unit mass. For NaCl, sucrose, and SiO2 particles, the peaks of responsive curve occur around 600 nm to 1000 nm, which illustrates that Sharp GP2Y is more sensitive to above range for mass concentration prediction.

Relationship among the Mass Concentration (m_total), the Calculated Total Scattered Light Intensity (I), and the Sensor Signal Output (S)

With idp from Fig. 5 and ndp(dp) from SMPS, calculated total scattered light intensity (I) and total mass concentration (m_total) can be determined by Eqs. (1–2). Fig. 6 shows the plots of the calculated total scattered light intensity (I) and the total mass concentration (m_total) versus the signal output (S) over the range of measurements. The parameters: slope, intercept, and R² for the various cases are shown in the column 3–6 of Table 2. Column 3 and column 4 report the fitting equations and the R² values of the calculated total scattered light intensity (I) versus the sensor signal output (S), while column 5 and column 6 report the fitting equations and the R² values of the total mass concentration (m_total) versus the sensor signal output (S). The R² values are larger than 0.951 in all separate tests, which demonstrates that the sensor signal outputs are proportional to both the mass concentration and the calculated scattered light intensity. However, while plotting experiments of a same component with different concentrations on one graph, the calculated total scattered light intensities are easier to line up on a single straight line against sensor output, as shown in Fig. 6.

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Fig. 5. Scattered light intensity of a single particle as a function of particle diameter for (a) NaCl particles, (c) sucrose particles, and (e) SiO2 particles. Scattered light intensity of unit volume as a function of particle diameter for (b) NaCl particles, (d) sucrose particles, and (f) SiO2 particles.
Fig. 6. Relationship of the calculated total scattered light intensity and the mass concentration as a function of the sensor outputs. Hollow symbols represent calculated scattered light intensity for (a) NaCl particles, (c) sucrose particles, and (e) SiO₂ particles. Solid symbols represent mass concentration for (b) NaCl particles, (d) sucrose particles, and (f) SiO₂ particles. (g) and (h) are combinations of (a, c, and e) and (b, d, and f) respectively.

In Figs. 6(a)–6(f), the fitting equations and the $R^2$ values are obtained by combining all tests of the same composition, while Figs. 6(g, h) showed the fitting results of all tests from all compositions. In detail, the $R^2$ values of calculated scattered light intensity (Figs. 6(a, c)) are larger than the $R^2$ values of mass concentration (Figs. 6(b, d)) for NaCl and sucrose tests. The $R^2$ values are comparable for the SiO₂ tests (Figs. 6(e, f)). In Figs. 6(g, h), the $R^2$ value for scattered light intensity (Fig. 6(g)) is significantly larger than the $R^2$ value for mass concentration (Fig. 6(h)) after plotting all measurement data together. This indicates that the correlation between the signal output and the total calculated scattered light intensity is better. On the contrary, when estimating the total mass concentration from the signal output, although high linearity was preserved in the separate tests (selected size distributions), the intercept and the calibration factor ($K_{exp}$) changed with the particle size distributions and the particle composition.

Apart from reporting the fitting results, Table 2 also includes the estimated calibration factor calculated from Eq. (6) in column 8. Test 2 (NaCl 1.087 g cc⁻¹) was chosen as calibration to calculate the response coefficient ($\eta$) due to its highest $R^2$ value for both mass fitting and intensity fitting. After substituting the density ($\rho_p = 2.16$ g cc⁻¹), the
Table 2: Detail properties of the generated particles and the fitting results for mass concentration and calculated total scattered light intensity against sensor signal output.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Mass conc. ((y, \mu g \text{ m}^{-3}))</th>
<th>Keq,(_g) from fitting</th>
<th>Error from Eq. (13)</th>
<th>Keq,(_g) from fitting</th>
<th>Error from Eq. (6)</th>
<th>Scattered light int. ((y, \text{UA}))</th>
<th>Fit equation</th>
<th>R(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. NaCl 1</td>
<td>(y = 3.20 \times 10^{-16} x - 5.35 \times 10^{-14})</td>
<td>0.978</td>
<td>0.948</td>
<td>(y = 11.26(x - 146.98))</td>
<td>0.951</td>
<td>11.26</td>
<td>Eq. (13)</td>
<td>0.996</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.03</td>
<td>Eq. (6)</td>
<td>NA</td>
</tr>
<tr>
<td>I. NaCl 2</td>
<td>(y = 2.58 \times 10^{-16} x - 4.24 \times 10^{-14})</td>
<td>0.977</td>
<td>0.940</td>
<td>(y = 12.74(x - 146.98))</td>
<td>0.961</td>
<td>12.74</td>
<td>Eq. (13)</td>
<td>0.996</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.89</td>
<td>Eq. (6)</td>
<td>NA</td>
</tr>
<tr>
<td>I. NaCl 3</td>
<td>(y = 3.26 \times 10^{-16} x - 3.08 \times 10^{-14})</td>
<td>0.990</td>
<td>0.977</td>
<td>(y = 3.75(x - 146.98))</td>
<td>0.989</td>
<td>3.75</td>
<td>Eq. (13)</td>
<td>0.990</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.66</td>
<td>Eq. (6)</td>
<td>NA</td>
</tr>
<tr>
<td>II. Sucrose 4</td>
<td>(y = 2.16 \times 10^{-16} x - 2.42 \times 10^{-14})</td>
<td>0.979</td>
<td>0.966</td>
<td>(y = 2.44(x - 146.98))</td>
<td>0.977</td>
<td>2.44</td>
<td>Eq. (13)</td>
<td>0.994</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.43</td>
<td>Eq. (6)</td>
<td>NA</td>
</tr>
<tr>
<td>II. Sucrose 5</td>
<td>(y = 1.81 \times 10^{-16} x - 3.43 \times 10^{-14})</td>
<td>0.990</td>
<td>0.977</td>
<td>(y = 3.04(x - 146.98))</td>
<td>0.977</td>
<td>3.04</td>
<td>Eq. (13)</td>
<td>0.994</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.28</td>
<td>Eq. (6)</td>
<td>NA</td>
</tr>
<tr>
<td>II. Sucrose 6</td>
<td>(y = 2.39 \times 10^{-16} x - 3.80 \times 10^{-14})</td>
<td>0.984</td>
<td>0.984</td>
<td>(y = 4.84(x - 146.98))</td>
<td>0.977</td>
<td>4.84</td>
<td>Eq. (13)</td>
<td>0.994</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.56</td>
<td>Eq. (6)</td>
<td>NA</td>
</tr>
<tr>
<td>III. SiO(_2) 7</td>
<td>(y = 2.56 \times 10^{-16} x - 3.69 \times 10^{-14})</td>
<td>0.995</td>
<td>0.995</td>
<td>(y = 5.30(x - 146.98))</td>
<td>0.977</td>
<td>5.30</td>
<td>Eq. (13)</td>
<td>0.994</td>
</tr>
</tbody>
</table>

The K values of low-cost particle sensors varying with regards of aerosol composition and size distributions have been reported by several groups (Wang et al., 2015; Sousan et al., 2016). Wang et al. (2015) compared the response of three sensors and an instrument (the Shinyei PPD42NS, the Samyoung DSM501A, the Sharp GP2Y, and the SidePak™) to three types of particles (NaCl particles, Sucrose particles, and NH\(_4\)NO\(_3\) particles) and recommended repeated calibration for different types of particles to obtain higher accuracy. Sousan et al. (2016) also demonstrated the same conclusion that the sensors require repeated calibration, since the size distribution, the refractive index, and the shape of the particles would influence sensors’ performance. However, there is no systematic study on how K changes and how to improve the sensors’ performance without repeated calibration.

Estimation of K for Lognormally Distributed Particles

As presented in Table 2 and Fig. 6, calibration factor is not universal for all aerosols, but depends on the size distribution parameters and particle composition (refractive index). To further analyze how these parameters would influence the calibration factor, we assumed lognormal distribution as shown in Eq. (7). The size distribution generated by Eq. (7) was plugged into Eq. (6) to evaluate the influence of each parameter.

By assuming lognormal parameters, \(ln\sigma\) ranging from 0.1 to 0.7 and \(d_{pg}\) ranging from 0.2 to 2 \(\mu m\) respectively, we simulated the calibration factor of various size distributions for NaCl particles, sucrose particles, and SiO\(_2\) particles as shown in Fig. 7. The values of calibration factors significantly differ from various combinations of \(ln\sigma\) and \(d_{pg}\). Fig. 7 could be an important tool for estimating how much error will be created by a one-time calibration. For example, if the sensor is calibrated with SiO\(_2\) particles (\(ln\sigma = 0.7, d_{pg} = 1.0 \mu m\)), then, the error can be controlled within ± 60% while using this calibration factor to measure particles ranges from 0.1–2.0 \(\mu m\) whose \(ln\sigma\) is 0.7. However, if the sensor is calibrated with NaCl particles (\(ln\sigma = 0.1, d_{pg} = 0.6 \mu m\)), then, the error would be enlarged to ± 700% while using this calibration factor to measure particles ranges from 0.1–2.0 \(\mu m\) whose \(ln\sigma\) is 0.1. Furthermore, two rules can be summarized to describe the variation. First, with a small \(ln\sigma\) value, the calibration factor is nonmonotonically related to \(d_{pg}\) value. Generally, the calibration factor initially decreases.
with the increasing \( d_{pg} \) value. However, after the turning point, the calibration factor increases with the increasing \( d_{pg} \) value in the successive stage. Second, for a larger \( \ln\sigma_g \) value, the calibration factor is a monotonic function of \( d_{pg} \), and it increases with increasing \( d_{pg} \) value. Above two rules are common for NaCl, sucrose, and SiO\(_2\) particles.

To further investigate the above phenomena, \( i_{dp} \) was simplified as a function of particle diameter (\( d_p \)). The details of fitting \( i_{dp} \) with \( d_p \) for values of \( a \) and \( b \) with six types of substances – NaCl, sucrose, SiO\(_2\), elemental carbon, Al\(_2\)O\(_3\), and Fe\(_2\)O\(_3\) are shown in Fig. 8. We included elemental carbon, Al\(_2\)O\(_3\), and Fe\(_2\)O\(_3\) to demonstrate that Eq. (10) should be universal for different species. \( i_{dp} \) for element carbon whose refractive index has an imaginary part is slightly different from others. The parameters, \( a \), \( b \), and \( R^2 \) varying with the refractive indices of the different materials for each set are listed in Table 3. The \( R^2 \) values vary from 0.7313 to 0.983. Element carbon demonstrated the highest \( R^2 \) value, since the imaginary part reduced the wrinkle of the \( i_{dp} \) curve, which improved the accuracy of fitting. For other species, lower \( R^2 \) values were resulted from the fluctuation of the \( i_{dp} \) curve.

Regarding the fitting results as shown in Fig. 8 and Table 3, Eq. (10) is capable of depicting the correlation between \( i_{dp} \) and \( d_p \). For small particles and large particles respectively, which leads to the phenomena we summarized from Fig. 7. For small \( \ln\sigma_g \), the feature of the aerosol whose geometric mean diameter is \( d_{pg} \) is similar to the feature of monodisperse particles with only size \( d_{pg} \), so Eq. (6) can be simplified as Eq. (17).

\[
K = \frac{1}{\eta} \int \rho_p \frac{\pi d^3}{6} \eta(d_p) d(d_p) \approx \frac{1}{\eta} \int \rho_p \frac{\pi d^3}{6} \eta(d_p) d(d_p) = \frac{1}{\eta} \frac{\pi d_{pg}^3}{6} \]

\[
(17)
\]

where \( i_{dp} \) is the scattered light intensity of particles whose size equals to \( d_{pg} \). When \( d_{pg} \) is small, \( K \) is proportional to \( d_{pg}^{-2} \), where \( K \) decreases with increasing \( d_{pg} \). After some turning point, \( d_{pg} \) is large enough to fall in the range where \( i_{dp} \) is proportional to the \( d_p^g \), so \( K \) is proportional to \( d_{pg} \) and increases with increasing \( d_{pg} \). However, when \( \ln\sigma_g \) is larger, the characteristics mentioned above will disappear since the particles tend to be distributed evenly through the size range rather than monodisperse. Under this situation, the larger particles under the size distribution are more influential, so \( i_{dp} \) is approximately proportional to the \( d_p^g \), so \( K \) is proportional to \( d_{pg} \) and increases with increasing \( d_{pg} \). Apart from qualitatively explaining the trends in Fig. 7, the method of moments and further simplification of \( i_{dp} \) were applied to overcome the disadvantage of repeated calibration.

### Estimate K with Simplified Equation for Practical Use

As shown in Eq. (11), Eq. (10) can be simplified for small and large particles separately. With Eq. (11), Eq. (6) is further simplified as Eq. (12). An expression for \( K \) as a function of geometric mean diameter, geometric standard deviation, and refractive index is established by assuming lognormal distribution, as shown in Eq. (12). While some information (\( \sigma_g \), \( d_{pg} \), and \( m \)) will need to be known for determining the value of \( K \); estimates can be inferred for a specific type of aerosol in a region. Eq. (12a) can be applied when most of particles are smaller than 0.5–0.8 µm. On the contrary, Eq. (12b) can be applied when most of particles are larger than 0.5–0.8 µm. Generally, whether to chose Eq. (12a) or Eq. (12b) needs to be considered regarding particle size distribution parameters.

To validate the equations, Eq. (12) was applied to the experimental results with parameters we calculated before. \( \eta \) is still equal to 3.85 × 10\(^{-3}\). The values of \( a \) and \( b \) for each composition are from Table 3. The density and size distribution parameters for each experiment is from Table 1. Since NaCl solutions produced particles with smaller \( \sigma_g \)
Fig. 8. The scattered light intensity of a single particle simulated by MiePlot (black solid line) and fitted by Eq. (9) (red solid line) for NaCl, sucrose, SiO$_2$, Fe$_2$O$_3$, Al$_2$O$_3$, and elemental carbon particles.

Table 3. Details of fitting $i_{dp}$ as a function of $d_p$ in Eq. (10) for NaCl, sucrose, SiO$_2$, Fe$_2$O$_3$, Al$_2$O$_3$, and elemental carbon particles.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Refractive index</th>
<th>$a \times 10^{-15}$</th>
<th>$b \times 10^{-15}$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>1.536</td>
<td>29.44</td>
<td>1.394</td>
<td>0.7508</td>
</tr>
<tr>
<td>Sucrose</td>
<td>1.5376</td>
<td>29.58</td>
<td>1.012</td>
<td>0.7344</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>1.486</td>
<td>33.64</td>
<td>0.932</td>
<td>0.7313</td>
</tr>
<tr>
<td>Element carbon</td>
<td>1.96–0.66i</td>
<td>172.8</td>
<td>0.258</td>
<td>0.983</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>3.011</td>
<td>32.19</td>
<td>0.1582</td>
<td>0.7849</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>1.765</td>
<td>25.27</td>
<td>0.447</td>
<td>0.8567</td>
</tr>
</tbody>
</table>

and $d_{pg}$, Eq. (12a) was applied to Test 1–3. Compared to NaCl particles, sucrose and SiO$_2$ solutions generated particles with larger $\sigma_g$ and $d_{pg}$, so Eq. (12b) was applied to Test 4–8.

The calibration factor estimated from Eqs. (12) ($K_{eq,12}$) are listed in Table 4. The errors between $K_{exp}$ and $K_{eq,12}$ were calculated with Eq. (13) and listed in the last column of Table 4. The errors can be controlled within ± 40%, thus proving that the accuracy of Eq. (12) is reasonable.

One thing worth noting is that one-time calibration probably would introduce serious errors for mass concentration estimation. For example, if we just calibrate the sensor once and use the calibration factor of Test 5 ($K_{exp} = 2.44$) for other measurements, the errors will be enlarged to –422.13% for the aerosol from Test 3 ($K_{exp} = 12.74$). And compared to this, the errors of the proposed model are reasonable and acceptable.

In general, the calibration factor can be adjusted according to former calibration results and three parameters ($m$, $\sigma_g$, and $d_{pg}$) for mass concentration estimation. It will be more accurate than singly using a fixed calibration factor for all types of aerosols. More field comparison studies are to be conducted to further verify and validate this approach.

**Estimate Number Concentration with Known Parameters**

As mentioned above, with an estimation of size distribution parameters, the calibration factor can be predicted with moderate accuracy. Furthermore, with known parameters, number concentrations can be derived from Eq. (15).

With Eq. (15) and the calibration factor from Eq. (12), the number concentrations for each experiment were calculated. Table 5 summarizes the number concentrations both estimated from proposed model and reported by the SMPS. The errors between SMPS reported number concentration and model predicted number concentration can be controlled within ± 50% for most of tests, except for Test 1.

The calibration method presented here for estimating mass concentration and number concentration requires particle properties and size distributions. However, the adjusted calibration factor increases the data accuracy for mass concentration. Furthermore, the number concentration is
Table 4. Parameters and results of estimating calibration factor from Eq. (12).

<table>
<thead>
<tr>
<th>Refractive index</th>
<th>Test number</th>
<th>$d_{pg}$</th>
<th>$\sigma_g$</th>
<th>$\mu_p$</th>
<th>Equation</th>
<th>$K_{exp}$ from experiments</th>
<th>$K_{eq,12}$ from Eq. (12)</th>
<th>Error from Eq. (13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>1</td>
<td>92.02</td>
<td>1.77</td>
<td>2.16</td>
<td>12a</td>
<td>11.26</td>
<td>8.04</td>
<td>28.6%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>119.55</td>
<td>1.69</td>
<td></td>
<td></td>
<td>7.03</td>
<td>7.27</td>
<td>-3.4%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>156.95</td>
<td>1.48</td>
<td></td>
<td></td>
<td>12.74</td>
<td>16.60</td>
<td>-30.3%</td>
</tr>
<tr>
<td>Sucrose</td>
<td>4</td>
<td>115.78</td>
<td>1.91</td>
<td>1.59</td>
<td>12b</td>
<td>3.75</td>
<td>2.57</td>
<td>31.5%</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>126.99</td>
<td>1.99</td>
<td></td>
<td></td>
<td>2.44</td>
<td>3.25</td>
<td>-33.2%</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>155.57</td>
<td>1.87</td>
<td></td>
<td></td>
<td>3.04</td>
<td>3.24</td>
<td>-6.6%</td>
</tr>
<tr>
<td>SiO₂</td>
<td>7</td>
<td>150.93</td>
<td>2.07</td>
<td>2.32</td>
<td>12b</td>
<td>4.84</td>
<td>7.51</td>
<td>-41.7%</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>176.06</td>
<td>1.91</td>
<td></td>
<td></td>
<td>5.30</td>
<td>6.64</td>
<td>-40.7%</td>
</tr>
</tbody>
</table>

Table 5. Examples of estimating number concentrations from the proposed model. Each test has several data points, and the statistics reports the maximum and minimum errors of all data points.

| Solution conc. mg cc⁻¹ | Test number | Distribution characterization $d_{pg}$ $\sigma_g$ | Statistics No. of points max min | Examples Signal SMPS From Eq. (16) Error |
|-------------------------|-------------|---------------------------------|-------------------------------|-------------------------------------|-----------------------------|
| I. NaCl                 | 0.507       | 1 92.02 1.77                   | 12 75.52% –57.50% | 554.0 7.70 × 10⁵ 8.57 × 10⁵ | –11.29%                    |
|                         | 1.087       | 2 119.55 1.69                 | 9 17.91% –26.68% | 373.8 2.53 × 10⁵ 2.47 × 10⁵ | –23.90%                    |
|                         | 1.892       | 3 156.95 1.48                 | 16 37.10% –41.84% | 396.4 4.65 × 10⁵ 4.74 × 10⁵ | –1.99%                     |
| II. Sucrose 1.150       | 4           | 115.78 1.91                   | 9 61.23% 45.52%   | 332.9 1.09 × 10⁵ 5.62 × 10⁵ | 48.52%                     |
|                         | 3.325       | 5 126.99 1.99                 | 8 38.63% 8.59%    | 418.2 6.71 × 10⁴ 6.13 × 10⁴ | 8.59%                      |
|                         | 4.315       | 6 155.57 1.87                 | 8 31.60% 24.28%   | 350.3 4.76 × 10⁴ 3.60 × 10⁴ | 24.28%                     |
| III. SiO₂ 1%            | 7           | 150.93 2.07                   | 10 55.92% 14.76%  | 526.4 7.42 × 10⁴ 6.30 × 10⁴ | 15.05%                     |
|                         | 8           | 176.06 1.91                   | 12 35.97% 14.72%  | 508.8 7.05 × 10⁴ 5.51 × 10⁴ | 21.93%                     |

critical for practical use too. Both the improved data quality and additional number concentration will benefit the field measurements. Based on the structure of low-cost particle sensors, these are limited improvements that could be achieved.

CONCLUSIONS

The calculated total scattered light intensity based on scattering theories were well correlated to the experimentally measured signals from the low-cost particle sensor. The experimental results also indicated the important dependency on the size distribution and the composition of the particles. The sensor signal outputs were not well correlated to the mass concentration. A model was proposed to determine the calibration factor ($K$) which would provide a more accurate estimate of the mass concentrations from the signal outputs. Based on the proposed model, an equation for $K$ as a function of the refractive index and the size distribution parameters (geometric standard deviation and geometric mean diameter) was derived. The use of this value of $K$ resulted in a better accuracy in the estimation of the mass concentration; and additionally, could provide an estimate of the number concentration. From experimental and simulation results, the low-cost sensor’s ability of evaluating mass concentration has been confirmed with particles of a single composition. However, the ability to extend the application to more complex aerosol systems encountered in the ambient environment would need to be carefully examined.

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NOMENCLATURE

Symbol

$a$  Fitting parameter for geometric scattering regime
in Eq. (10)

$b$  Fitting parameter for Rayleigh regime in Eq. (10)

d$_p$  Particle diameter

d$_{mg}$  Geometric mean diameter of the size distribution

$i_{gp}$  Scattered light intensity of a single particle

$I$  Calculate total scattered light intensity

$I_0$  Incident light intensity

$K$  Calibration factor

$K_{eq.6}$  Calibration factor calculated from Eq. (6)

$K_{eq.12}$  Calibration factor calculated from Eq. (12)

$K_{exp}$  Calibration factor fitted from experiments

$m$  Refractive index

$m_{img}$  Imaginary part of refractive index

$m_{real}$  Real part of refractive index

$m_{total}$  Mass concentration

$M_0$  Total number concentration represented by the method of moments

$M_g$  General moment of the particle size distribution

$N_{c0}$  Total number concentration of the size distribution

$n_x(d_p)$  Size distribution function

$R$  The distance between the illuminated particles and the phototransistor

$S$  Sensor signal output

$S_0$  Signal output obtained from sensor at a particle concentration of zero

$\gamma$  The order of the moment

$\eta$  Response coefficient of the sensor

$\lambda$  Wavelength of light source

$\sigma_g$  Geometric standard deviation of the size distribution

$\theta$  Scattering angle

$\rho_p$  Particle density

REFERENCES


