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Single Image Corrections to Facilitate Planar Imaging of Particle Concentration in Particle-laden Fluids

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Abstract

Planar Nephelometry is a laser-based technique capable of providing instantaneous planar local number density measurements of particles in fluid systems. This technique records laser light scattered from particles to obtain information regarding particle concentration. Planar Nephelometry does not need to resolve particles individually, thus enabling large image viewing areas. However, when particle loadings are sufficiently high, attenuation of the incident laser beam becomes significant. As Planar Nephelometry infers particle concentration from incident laser intensity, attenuation can result in erroneous concentration measurements. Planar Nephelometry measurements under these conditions must thus be corrected for laser attenuation to ensure accurate concentration measurements. Experiments were conducted on suspensions of neutral density spherical particles in water at various homogeneous concentrations. The attenuation correction method implemented is a ray-based extinction model which incorporates the use of scattered light from a polymer strip at a down-beam location. This method is suitable for highly turbulent flows requiring instantaneous planar information since single shot images are used in the post-processing work. The derived correction method provides an alternative to Beer-Lambert's law for attenuation corrections in laser diagnostics techniques. The proposed method is validated experimentally using non-homogenous particle distributions in fluid suspensions.

Introduction

Particle-laden flows, where solid particulates or liquid droplets are dispersed within a fluid, are commonly encountered in industrial applications such as engines, gas turbines and power plants. Studies concerned with particle-laden flows are frequently motivated by environmental considerations to reduce toxic emissions while simultaneously improving system efficiency. Studies of this nature utilize visualization and quantitative measurements of important particulate parameters, such as particle concentration and velocity, temperature, and pollutant emission. These measurements are generally made using laser diagnostic techniques due to their non-intrusive characteristics as well as their high spatial and temporal resolution.

Laser diagnostic techniques generally rely on the interaction between the laser light and particles present within the investigated medium. As a light sheet propagates through a medium, it interacts with particles through absorption and scattering [2]. Depending on which interaction is exploited by the laser diagnostic technique, various properties of the medium may be measured and investigated. When investigating particle-laden fluids in industrial processes, flow conditions tend to be turbulent and particle distributions are highly non-uniform. Planar imaging of such systems is often preferable to single-point measurements as there is no need to resolve individual particles and instantaneous information regarding particle concentrations, and measurement volumes are possible. Planar Nephelometry is a planar imaging technique whereby particle concentration is inferred from the Lorenz-Mie scattering.

When imaging fluids with high particle loading, the interaction between the light and particles causes the intensity of the unperturbed light to decrease as a function of light path as well as particle concentration for a given study. The diminishing intensity of light as it propagates through a medium (predominantly due to the effects of absorption and Mie scattering by particles) causes a phenomenon known as laser attenuation [2]. When laser attenuation is severe (especially in optically dense media), data obtained are susceptible to errors introduced by the occurrence of laser attenuation.

Laser attenuation has been previously investigated in axisymmetrical flows. Axisymmetry enables the determination of laser attenuation (out-of-plane information) based on in-plane data [1, 7, 8, 9]. However, correction techniques that require flow symmetry are inapplicable in complex cases which do not have flow regularity. In contrast, [5] spatially resolved measured signals and determined the absolute attenuation across the medium before correcting for laser attenuation through an iterative process. Limitations associated with this method are that particles used in the media must absorb a significant amount of light and require very sensitive equipment. Alternatively, the use of counter propagating light sheets has also been employed to address the effects of laser attenuation [7, 8, 9, 11]. Data from both the forward- and backward scattering are recorded simultaneously to obtain different histories of attenuation for the same medium. Local extinction coefficients are then reconstructed from the intensity profiles recorded and the true intensity distribution profiles are obtained from the processing of image pairs [9, 11]. The major limitation with this method is that for high laser extinction values and high noise levels, low signal-to-noise ratios are generated due to the increased non-linearity of the sensitivity of this technique to noise [10].

Laser attenuation is conventionally described using Beer-Lambert's Law which uses a logarithmic dependence to relate light transmissivity through a medium to its absorbance [6, 4]. In contrast, the current study proposes attenuation corrections for Planar Nephelometry using scattered light from a polymer strip placed down-beam from the flow region of interest. The proposed correction technique uses this scattered light to obtain corrections which accounts for variations in laser light intensity. This method uses single image shots for corrections thus enabling instantaneous particle concentrations to be obtained without needing prior knowledge of the fluid flow field or particle distribution. This method is particularly suitable for the Planar Nephelometry technique and as a consequence, Planar Nephelometry measurements are used to validate the accuracy of the proposed correction method.

Theoretical Considerations

The attenuation correction method implemented in this study relates the decrease in laser intensity through a medium to the probability of particles being in the laser path (i.e. how much light is blocked). Consider a system of spherical particles in fluid suspension being illuminated by a collimated sheet of monochromatic light (i.e. laser light). The light scattered off particles and recorded on a device located perpendicular to the flow represents a fraction of the total scattered light. Assuming an axisymmetric scattering pattern, the fraction of scattered light recorded can be used as an approximation of the total light scattered. This scattered light is a function of particle property and size. Therefore, for a given type and size of particle, the scattered signal recorded, Φ is a function of particle number density. This relation may be expressed mathematically as [6, 8]:

$$\Phi_i = N_i I_i \sigma K_1 \tag{1}$$

where i is the location corresponding to pixel i, I refers to the local laser intensity, N refers particle number density, σ denotes the particle scattering cross section and K_1 includes information about the experimental setup and equipment efficiency. Since these signals are recorded as a 2-D array of pixels, the medium can be considered to be a series of pixel volumes (each of which contains a certain number of particles) in which light passes through. Signals from a pixel volume would therefore be dependent on the number of particles present in that pixel volume (as expressed by Equation (1)). However, the relation between laser intensity and particle concentration is only accurate across the entire beam path if the overall laser transmittance is high (laser intensities entering and exiting media are approximately equal).

When investigating an optically dense media, large numbers of particles are present in each pixel volume. The laser intensity therefore diminishes significantly as it passes through each pixel volume investigated. When this happens, the signals from each subsequent pixel volume no longer reflect the true distribution of the local particle concentration thus leading to the occurrence of errors associated with laser attenuation. Therefore, measured signals from the pixel volumes must be compensated for laser attenuation before any interpretation regarding the local particle concentration in the media may be applied. Using the probability of unobstructed light propagating through the pixel volumes derived in [3], the intensity of light transmitted through a single pixel volume is:

$$I_{out} = I_{in}\left(1 - \frac{\pi d^2}{4xy}\right)^{N_{p,i}} \tag{2}$$

where I_{in} and I_{out} is the intensity of light entering and exiting the pixel volume (with a cross-sectional area of $x \cdot y$) which contains N_p number of particles with diameter d. Considering the intensity of light transmitted through a row of M pixel volumes within a region of interest, Equation (2) becomes:

$$I_{end} = \sum_{i=1}^{M} I_o\left(1 - \frac{\pi d^2}{4xy}\right)^{N_{p,i}} \tag{3}$$

I_{end} and I_o now refers to the intensity of light exiting and entering the region of interest respectively. Combining Equation (1) and Equation (3), the local laser intensity at any pixel volume, m, is:

$$I_m = \sum_{i=1}^{m} I_o\left(1 - \frac{\pi d^2}{4xy}\right)^{E_i}, \quad E_i = \frac{\Phi_i}{K_1 \sigma I_i} \tag{4}$$

Signals from the polymer strip (attenuation strip) placed down-beam of the laser provides information regarding the laser intensity exiting the region of interest (i.e. I_{end}). Using I_{end}, corrected local laser intensity values, I_m (expressed in terms of Φ) is therefore determine iteratively through Equation (4). The corrected distribution of I_m propagating through the media is subsequently computed into Equation (1) to determine the local particle number densities. Through the relation:

$$C_i = \frac{N_{p,i}}{xyz} \tag{5}$$

where $x \cdot y \cdot z$ is the pixel volume, the local particle concentration, C, may be determined once local particle number densities N_p are obtained. Consequently, it is common in Planar Nephelometry to assume that particle concentration, $C \propto I$ through the consideration of Equation (1) and Equation (5) (since $I \propto N$ and $C \propto N$ respectively). Therefore, subsequent calibration of the light intensity field against a known concentration will enable accurate particle concentrations (within the region of interest) to be determined.

Experimental Setup

Particles used for the experiments were mono-dispersed neutrally buoyant Polyamid Seeding Particles (PSP-20) with mean particle diameter of 20μm. Particles were suspended in two adjacent chambers, each with dimensions of 125mm $\times$ 200mm $\times$ 200mm. These chambers were placed in the middle of a transparent acrylic tank to ensure that any reflected or refracted light (from the attenuation strip and the tank wall respectively) did not affect signal measurements (Figure 1).

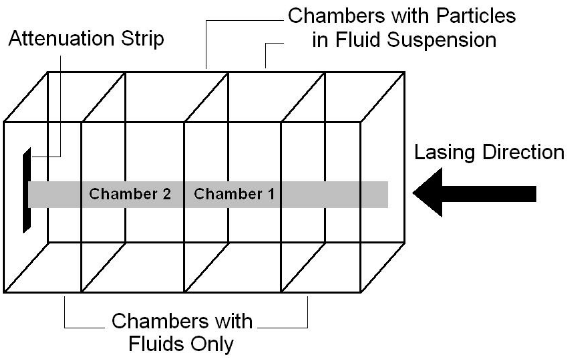

Figure 1: Schematic diagram of experimental setup: chambers

Chambers 1 and 2 each contained different known concentrations of particles in water. The suspensions were stirred intermittently during experiments to ensure a homogenous particle distribution was maintained in each chamber. The use of known total particle concentrations for each chamber allowed the attenuation correction method to be validated against experimental data. Particle concentrations investigated were 10, 20, 30, 40, 50 ppm under the following combinations (Table 1):

Case	Chamber 1	Chamber 2
Case 1	20 ppm	10 ppm
Case 2	30 ppm	20 ppm
Case 3	40 ppm	30 ppm
Case 4	50 ppm	40 ppm

Table 1: Particle concentration in each chamber for investigated cases

A collimated laser sheet with a thickness of 2mm and a width of 25mm was generated using a pulsed Nd:YAG laser, emitting 532nm (second-harmonic output) at 10Hz. This laser sheet was used to illuminate the particles in the chambers. Light scattered by the particle surfaces were recorded using a Redlake Megaplus II (10-bit resolution) Charged-Coupled Device (CCD) camera (2048 pixels $\times$ 2048 pixels) with a Nikon 24mm - 120mm lens. The CCD camera was located perpendicularly to the tank and laser sheet (Figure 2). This setup provided an imaging region of 500mm $\times$ 500mm, a field-of-view sufficient to record the entire tank on each image.

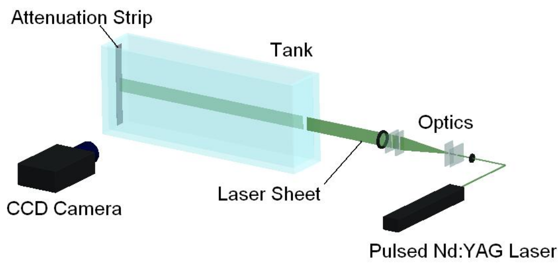

Figure 2: Schematics of experimental setup

The attenuation strip is placed at a down-beam location inside the tank. Since the chamber with the attenuation strip is devoid of particles, signal attenuation is constant but negligible thus ensuring that accurate information on the exit intensity, I_{end}, is obtained. This information is then used to implement corrections using the ray-based formulation which uses the relative intensity values of each pixel volume recorded.

Results and Discussion

Signals are obtained from an ensemble of 429 images, with the average data for each case determined from ensemble and space averages. Space averages are obtained by averaging signals within the laser sheet region over the number of pixels corresponding to the height of the laser sheet (i.e. 25mm). This procedure generates a single row of pixel values which represents particle loading case investigated. An identical treatment is used to process the background noise (data which is recorded with the laser turned on but without particles within the chambers). Signals used to represent each case are obtained by removing background noise (e.g. Figure 3, with the laser sheet propagating from left to right). Signals recorded were restricted to the dynamic range of the CCD camera used in order to avoid signal saturation and to ensure the validity of the intensity values recorded.

Figure 3 demonstrates a typical trend of average signal intensities to laser propagation path within the two chambers with particles. A sudden decrease in signal intensity corresponds to the location where the chambers were divided by an acrylic sheet. Observing the signals from each chamber, a decrease in signal intensity is observed over the laser path. Comparison between the cases investigated validates that the rate of decrease in signal intensity (with laser path) increases with particle concentration. This observation indicates that laser attenuation is more significant when particle concentration is increased. Particle concentration is inferred from the averaged signal intensities through Equation (1). However, when laser attenuation is significant, the error in concentration measurements increases. As such, attenuation corrections are crucial when working with high particle concentrations (i.e.

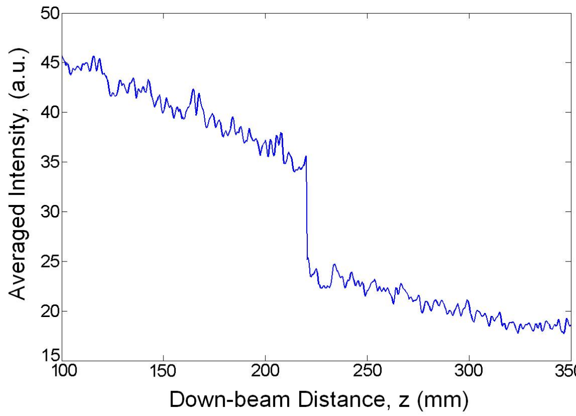

Figure 3: Example of uncorrected signal intensities as a function of laser path (background noise removed) for case 4 (50ppm, 40ppm)

when laser attenuation is significant).

Profiles of corrected particle concentrations are presented in Figure 4. Results of the corrected particle concentrations are in agreement with the actual particle concentration used in experiments, therefore establishing the validity of the attenuation correction method presented. Noise level associated with each case is observed to worsen with increasing particle concentration. Statistical analysis of the variance for each case was also determined to increase with particle loading. Collectively, these results suggest that the source of noise is not entirely due to electrical noise. Although the noise is determined to have negligible influences on the corrections implemented, it is proposed that the occurrence of out-of-plane scattering (multiple scattering) is another source of noise to the experimental data. Investigations on the effects of multiple-scattering are beyond the scope of the current study.

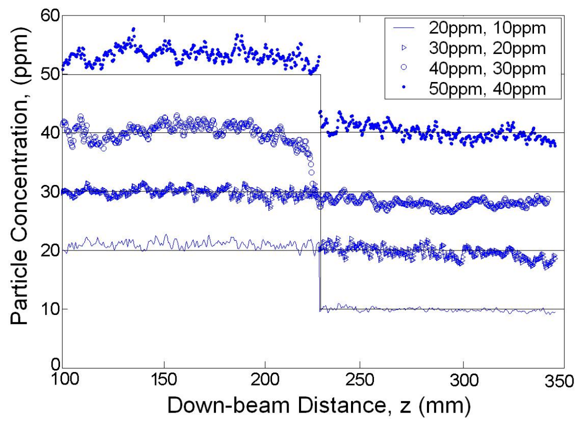

Figure 4: Particle concentration as a function of laser path (corrected for attenuation) for investigated cases

The suitability of the attenuation corrections used in the current study was evaluated using the averaged overall transmittance I_{end}/I_o for each particle distribution investigated. The I_{end}/I_o values were obtained by averaging the overall transmittance sustained in Chambers 1 and 2 achieved in each case. These values were obtained for both corrected and uncorrected laser intensities to compare the effectiveness of the correction algorithm used (Figure 5).

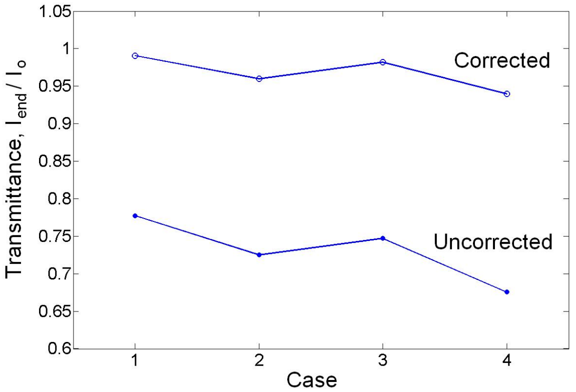

Figure 5: Average overall transmittance for investigated cases

An overall transmittance of unity is obtained when the initial and final laser intensities are equal indicating that laser attenuation is non-existent. As such, when the effects of laser attenuation is significant, the overall transmittance would deviate from unity (becoming increasingly <1). Uncorrected laser intensities recorded overall transmittance between 0.65-0.8 for all the cases investigated (Figure 5). Conversely, when laser intensities were corrected for attenuation, the overall transmittance recorded for all the cases investigated was improved significantly to lie between 0.95-1. Such results indicate that the corrections applied are capable of correcting for the effects of laser attenuation effectively. The accuracy of particle concentration measurements inferred from the corrected laser intensity measurements is thus improved. This correction method is therefore applicable to non-homogenous particle distributions which in turn extend the capabilities of the Planar Nephelometry technique.

Conclusion

The current study proposes an attenuation correction method to facilitate Planar Nephelometry measurements using an attenuation strip placed down-beam from the flow region of interest. Experimental validation involved imaging two adjacent chambers with different homogenous particle concentrations using a collimated light sheet simultaneously. Lorenz-Mie scattering recorded were calibrated against known particle concentrations to determine the suitability of the correction method used. Overall transmittance of the corrected laser intensities were improved from a range of 0.65-0.8 up to a range of 0.95-1 for corrected intensities. Such results indicate that corrections applied are capable of generating accurate particle concentration measurements from the measured Lorenz-Mie signals. Results confirm the validity of the new method proposed and establishes the applicability of the proposed method on non-homogenous particle distributions in order to facilitate the development of the Planar Nephelometry technique.

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