Measurement of Optical Properties of Nanofluids and its Effects in Near-wall Flow Evaluation

Kanjirakat Anoop and Reza Sadr
Micro Scale Thermo Fluids (MSTF) Laboratory
Texas A&M University at Qatar
e-mail: anoop.baby@qatar.tamu.edu
email: reza.sadr@qatar.tamu.edu

Abstract—**There have been several ongoing researches in nanofluids (suspensions of nanoparticles in a basefluid) due to the anomalous heat transfer enhancement that were reported earlier. Exploration of the near-wall flow region using Particle Image Velocimetry (PIV) technique could bring more insights for reasons behind such enhancements. However, such measurement techniques are extremely depended on the optical properties of the fluid under study. Hence prior measurements of the optical properties are necessary for estimating velocity values while implementing these fluids. In present study, optical properties of SiO_2 – water nanofluids at various particle concentrations are investigated. Measurements of refractive indices and the optical transmittance of nanofluids, which are directly related to the depth of penetration and visible depth in nPIV (nano PIV) measurements, are carried out. Further, near-wall velocities of water and nanofluids are measured using nPIV technique as a case study.**

Keywords-Refractive index, transmittivity, nPIV

I. Introduction

Cooling of components still remains as one of the major challenges faced by electronic industries. Many modes of cooling techniques were tried in the past. Improving the heat transfer capacity of the cooling liquid by suspending solid particles was one among them. Suspending micron-sized particles however resulted in effects such as particle sedimentation, higher pumping power requirement, and erosion of heat exchanger surfaces. Suspending nano-sized particles seemed to be a better option, hence introducing of new class of cooling fluid known as nanofluids. Nanofluids**,** are engineered colloidal suspensions of nano-sized particles in a heat transfer fluid, and have received considerable attention; due to the anomalous thermal properties reported earlier [1,2]. However, in recent times, many contradicting results with respect to thermal performance of nanofluids are being reported. Main reason for such contradicting observation is due to the unclear understanding of the phenomenon behind the thermal enhancements. Non-intrusive near-wall velocity measurements are expected to bring insights explaining reasons for the anomalous thermal enhancements. However, any non-intrusive optical flow measurement techniques would be highly dependent on the optical properties of the medium. As nanofluids are fluids with suspended nan-sized particles, estimation of optical properties based on classical theories may be unreliable. Hence, detailed investigations of its optical properties are required before implementing them in measurements. In present work optical properties of nanofluids are measured, and a case study analysis is carried out on its effects in near-wall flow measurements.

Initial attempt to measure near-wall flow fields of nanofluids was made by Walsh et al. [3] by using a Micro Particle Image Velocimetry (μPIV) technique. They obtained velocity profiles of nanofluids flowing inside a microchannel. However, the spatial resolution of their work was limited to several microns and could not capture details of velocity field very close to the walls. To surpass this limitation and to achieve a detailed flow field evaluation at near-wall region, efforts were made by Anoop and Sadr [4] to conduct nPIV (nano Particle Image Velocimetry) measurements while using nanofluids. nPIV is an extension of *μ*PIV working on evanescent-wave illumination generated by total internal reflection (TIR) of a laser beam at the fluid-solid interface between the flow and the wall [5]. The effects of errors in measured velocity values in nPIV measurements as a result of particle mismatch of tracers was investigated by Sadr et al. [6]. This was further expanded by including the effects of Brownian motion, light penetration profiles, surface forces such as van der Waals, and electrostatic forces, and the velocity gradient on the near-wall measurements using a traditional PIV cross-correlation method [7].

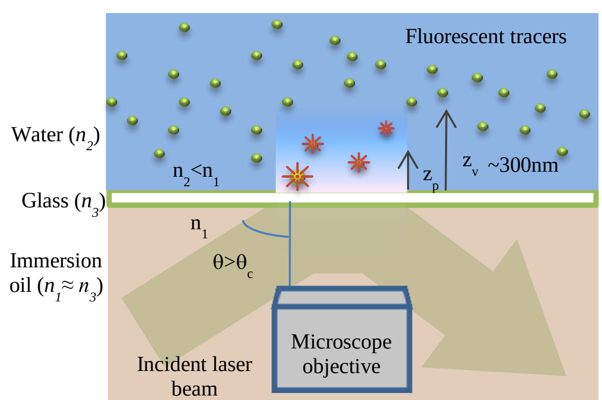

Figure 1. Schematic showing nPIV measurement principle.

The working principle behind the nPIV measurement technique is described next. When a light beam travels through a medium with a refractive index n_1, into another transparent medium with a lower refractive index of n_2 at an angle exceeding the critical angle, $\theta_c = sin^{-1}(n_2/n_1)$, it gets totally reflected at the interface (Fig.1). However, the electromagnetic field penetrates into the lower refractive index region and propagates for a small distance parallel to the interface, creating what is known an evanescent wave. This evanescent wave is capable of exciting fluorescent particles in this region while the large numbers of particles farther away in the bulk liquid remain unexcited. Evanescent wave intensity, I, in the direction normal to the interface decays exponentially with distance, z:

$$I = I_0 \exp(-z/z_p) \qquad (1)$$

where I_0 is the maximum intensity at the wall and z_p is the penetration depth.

$$z_p = \frac{\lambda_0}{4\pi n_1}\left(sin^2\theta - (n_2/n_1)\right)^{-1/2} \qquad (2)$$

λ_0 is the wavelength of the light and θ is the incident angle. For visible light at a glass water interface, z_p is on the order of O (100nm). Figure 1 shows the schematic of a general TIRF setup used in an nPIV experiment where only the near-wall fluorescent particles in the fluid are excited and viewed from the bottom of the microscope plate [6]. The emission intensity of the tracer particles in this region is an exponential function of the distance from the wall with a decaying trend as stated by (1) [7]. It can be noted that the penetration depth is depended on refractive index of the medium (2). When nanofluids are used as the medium their refractive index values of the medium will change with respect to particle loading. Hence, prior knowledge of refractive index values of nanofluid would be crucial while implementing them in nPIV measurements.

For an evanescent wave, z_p is the penetration depth, however, the actual depth that could be imaged would be larger than it and is defined as visible depth (z_v). Depending on the optical characteristics of the imaging system, this depth of visible region, z_v, changes with the intensity of the incident laser beam, transmission of light through the medium, fluorescent particle characteristics, camera and the background noise of the imaging system. In short, z_v represents actual visible depth in the captured image. Another point to be noted is the opaque nature of nanofluids. From visual observation of nanofluids, it can be noted that the opacity of medium is increased with particle addition. This in-turn could reduce the visible depth. Hence, it would be important to see the effect of light transmittivity in nanofluids also while implementing them in nPIV measurements. It is assumed that any reduction in transmittivity due to use of nanofluids would reduce visible depth.

Even though nPIV measurements were made earlier for nanofluids [4], the optical characterisation of nanofluids were not carried out and were estimated on theoretical studies alone. No experimental efforts were made to investigate the optical properties of them. Thus, in present study, the optical properties of nanofluids are measured and their influence on nPIV measurements are analysed. Refractive index value and transmittivity values are measured to obtain their influence on penetration depth (z_p) and visible depth (z_v). Nanoparticle concentrations are varied from 0 to 6% by mass. Further, nPIV measurements are conducted with nanofluids to see the effect of nanoparticles in the near-wall flow region.

II. MEASURMENT OF OPTICAL PROPERTIES

Before detailing the measurements of nanofluids optical properties, a brief description on preparation of nanofluids is given. SiO_2-water nanofluids are used in the present study. Nanofluids are prepared by a top down approach in which commercially bought nanoparticles are mechanically dispersed in a basefluid (in present case water). Appropriate amounts of SiO_2 nanoparticles (~ 20nm average diameter, Sigma Aldrich, #637238) are dispersed in de-ionized water using an ultrasonic bath (VWR ultrasonic cleaner, 35 kHz) for 30 minutes. Further, the colloidal suspension is subjected to intensified ultrasonication by immersing a probe type sonicator (QSonica S-4000, 20 kHz). Cyclic ultrasonic pulses for about 45 minutes are given to the suspension so as to achieve maximum possible de-agglomeration of particles. Particle concentrations varying from 0 to 6% by mass (henceforth represented as %wt) are considered for present investigation.

In present work, refractive indices of nanofluids are measured using a laboratory refractometer (RE40D, Mettler Teldo), which measure reflective index values based on total internal reflection principle. Light from a LED light source gets partially reflected to an optical CCD sensor at the surface of sapphire prism and sample interface. Measurement from the sensor is used in evaluation of refractive index values. The equipment had a measurement range of refractive index values from 1.32 to 1.7, which matches with the measurement requirements of the nanofluids. Prior to actual measurements, the refractometer was calibrated with standard distilled water at ambient conditions.

To acquire information of transmission of visible light through the nanofluid sample, experiments are conducted to determine the transmittance using a spectrometer. Percentage transmittance of the nanofluid samples are measured using a Perkin Elmer Lamda 950 spectrometer in the visible region. The spectrometer consists of a light source, a mono-chromator, a wave length selector, a sample holder having a specified path length, and a detector. Light at a desired wavelength is passed through the sample and the transmitted light through the medium is measured by the detector. The sample path lengths can be varied using different sizes of cuvettes. During experimentation, initial baseline readings are obtained by placing the basefluid (water) in the spectrometer and are later compared with the nanofluid samples. Percentage transmittance is measured for the sample at wavelengths in the visible region. In present work, experiments were conducted with two path lengths, 10mm and 1mm (Starna Cells Inc.).

III. NANO-PIV MEASUREMENTS

After measuring the optical properties of nanofluids, near-wall velocity measurements of nanofluids are performed using nPIV technique. An objective based TIR method is used in present study. The microchannel flow cell (Translume Inc) used in the experiment is fabricated in quartz and has a rectangular cross section (300μm width and 100μm Height). The bottom quartz plate is customized to have a thickness of 0.12mm in order to have a clear TIR falling on the objective of the microscope. During the experiment, different flow rates ranging from 0.005ml/min (±0.1%) to 0.06ml/min is maintained in the micro channel using a syringe pump (KDS200, KD Scientific) along with a 2.5 ml gas-tight glass syringe (Hamilton). The excitation light in the near-wall region was provided by an Argon-Ion CW laser beam with a wave length of 488 nm (Spectra Physics BeamLok 2060). Images were obtained using an EMCCD camera (ProEM 512, Princeton Instruments) attached to an inverted epi-fluorescence microscope (Leica DMI6000B) via a 63x 1.47NA oil immersion objective. The pixel resolution for the images obtained from this imaging set up was 4×10^6 (pixel/meter). The nPIV seeding particles used were 100nm (±5%) diameter polystyrene fluorescent particles (F8803, Invitrogen) having peak excitation and emission wavelengths of 505nm and 515nm, respectively.

In all the experimental runs, the fluorescent particle concentration was maintained at a constant volume concentration of 0.017%. When nanofluid samples were prepared, the fluorescent particles were added to the nanofluids suspension and sonicated thoroughly, keeping the same fluorescent particle concentration. Thus, the nanofluids sample contained both SiO_2 nanoparticles as well as the fluorescent particles suspended in it. However, when visualizing the flow it was observed that fluorescent particles were alone getting excited. The SiO_2 nanoparticles were seen not self-illuminating or creating a background illumination. The angle of incidence of light in the water-quartz interface was evaluated to be 65^o, based on the numerical aperture value of the objective lens and refractive indices at the interface. This yielded a penetration depth of $z_p \cong 90$nm (2). The depth of visible region (z_v) is then estimated to be 350±20nm for the basefluid, based on the penetration depth and the intensity value of the background noise in captured images.

IV. RESULTS AND DISCUSSION

Initially, the optical properties of nanofluids are discussed. Figure 2 shows the effective refractive index values of nanofluids measured for various concentrations. Measurements show a rapid increase in refractive index values at lower particle loadings (from 0 to 1wt%) and a gradual increase after that up to 6wt%. A careful observation, however, would reveal that the total percentage increase in refractive index values were below 1% even while particle loading were increased by 6wt%. Similar orders of refractive index values were reported in earlier studies for other nanofluids [8, 9].

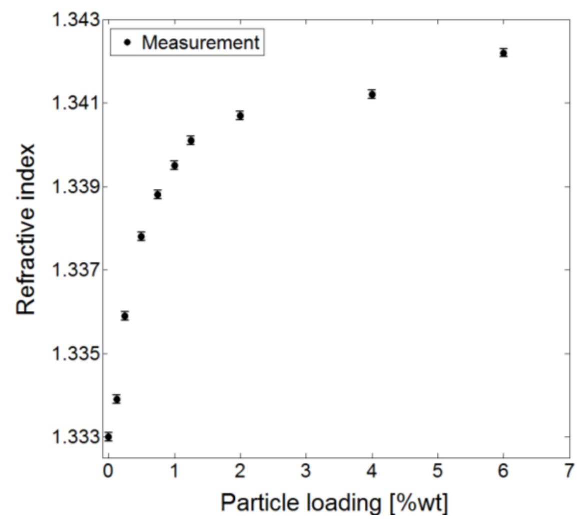

Figure 2: Refractive index values of nanofluids.

Even though the increases in refractive index values were low, their effect in increasing penetration depth (z_p) needs to be considered. The penetration depth is evaluated using (2) and is plotted in Fig. 3.

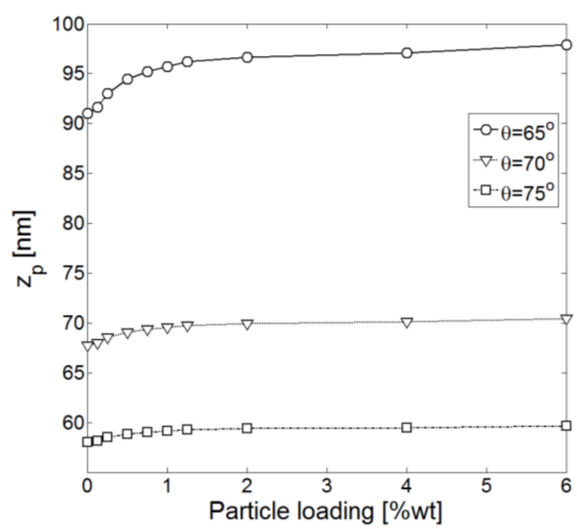

Figure 3: Effect refractive index of nanofluids on penetration depth

Effects of three incident angles which are above critical angles are plotted. Only a minimal increase in penetration depth is observed while using nanofluids. It is observed that penetration depth has increased by about

7nm for 6wt% nanofluid when compared with that of water.

Effect of opacity of nanofluids and its influence on transmission of visible light is examined next. Figures 4 and 5 show the percentage transmittance of nanofluid samples measured using 10mm and 1 mm path length respectively. Percentage transmission at a wavelength of 488nm (wavelength of incident light in nPIV measurements) is chosen for estimation. Inset figure shows the transmittance spectrum of all the samples in the entire visible region wavelengths. Photograph of the cuvette used in the measurement is also given in the figure.

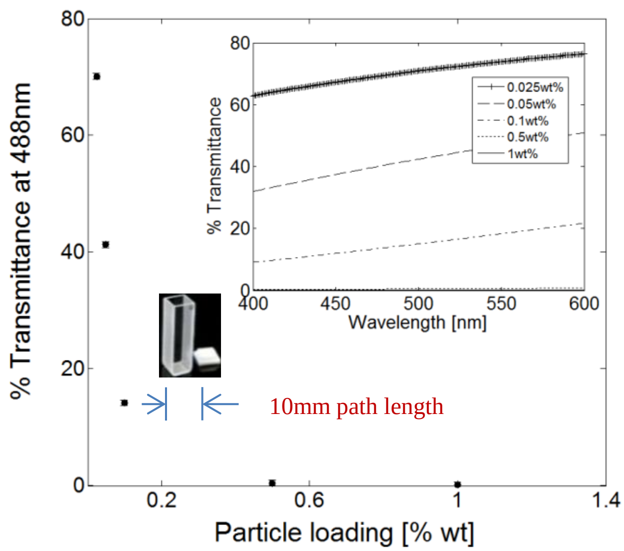

Figure 4: Percentage transmittance for nanofluids measured with 10mm path length.

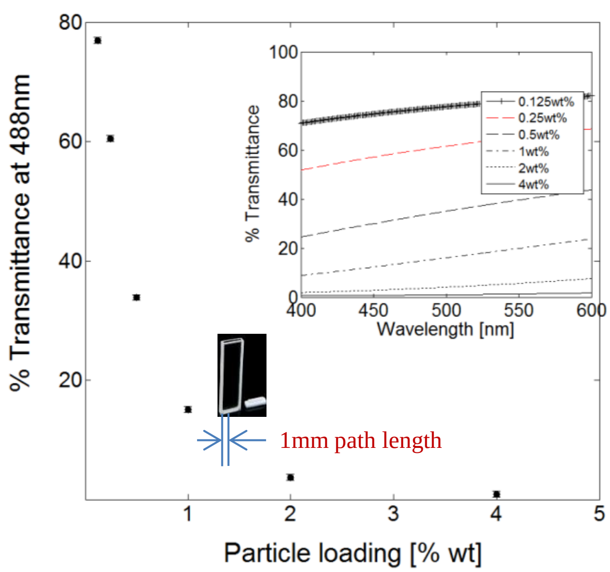

Figure 5: Percentage transmittance for nanofluids measured with 1mm path length.

It is observed that adding nanoparticle in the basefluid has increased the opacity of the solution. With 10mm path length, percentage transmittance became almost zero when the particle loading has reached 1wt%. Further measurements were not possible with this path length. However, percentage transmittance measurements were possible at higher particle loadings while using 1mm path length cuvette. Measurements up to 4 wt% were possible with 1mm path length as shown in Fig. 5. A maximum of ±2% uncertainty is observed in all the measurements.

Following Beer-Lambert law, transmittance (T) is related to path length (l) and absorption coefficient (α) of the liquid as given below [10].

$$T = 10^{-\alpha l} \quad (3)$$

In order to combine the results of 1mm path length and 10mm path length, variation of absorption coefficient with that of particle loading is plotted in Fig. 6.

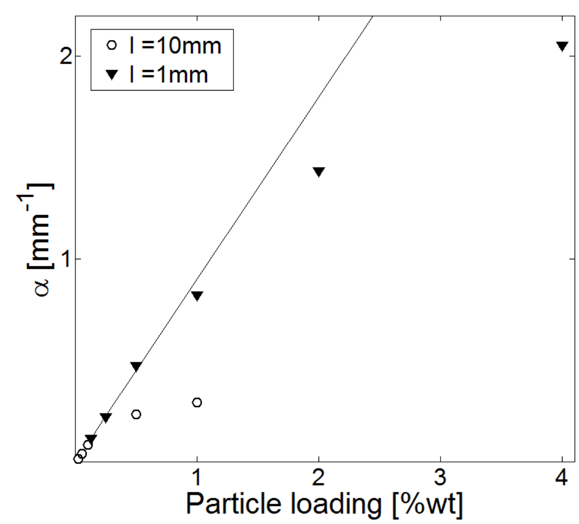

Figure 6: Variation of absorption coefficient with particle concentration

Ideally, absorption coefficient for a suspension needs to be constant for a particular loading even while measuring with varying path lengths. However, present measurements did not show considerable matching beyond 0.5 wt% particle loading. One reason for this could be the fact that the sensor in the spectrometer was not getting sufficient signals to evaluate transmittivity beyond particle loading of 0.5wt% (Note from Figure 4 that the percentage transmission was below 1% above 0.5% particle loading for 10 mm path length measurements). At 1wt% the percentage transmittance measurement was 0.122%, which would be highly unreliable. Similarly for 1mm path length experiments beyond 2 wt% seems unreliable. Further examination of Fig. 6 shows that, the linear trend of absorption coefficient with respect to concentration for nanofluids was true only below 2 wt% particle loading. Thus, it would be judicious to consider only measurements with

1mm path length below 2wt% concentration in our further analysis. A linear fit in this region is made and is estimated to be,

$$\alpha = 89.\phi \tag{4}$$

where, ϕ, is the particle loading by mass. Using equations 3 and 4, transmittivity at any given path length could be evaluated. The maximum focal depth in nPIV measurements is of magnitude 500nm. For a path length of 500nm and particle loading of 6wt%, the percentage reduction in transmittivity could be evaluated to be less than 1%. In other words, percentage reduction in transmittivity in a depth of 500nm for nanofluids would be very minimal.

Thus, from the measurement and analysis of optical properties of nanofluids it is clear that the changes due to refractive index values and opacity would not influence nPIV measurements in the measurement depth. To evaluate the effect of nanofluids on nPIV measurements, preliminary near-wall velocity measurements using water and nanofluids at various particle concentrations are made. The flow rates are varied from 0.005ml/min to 0.06ml/min and near-wall images are captured. For each experiment, 1500 nPIV image pairs of 256x80 pixels were acquired with a inter frame time delay of 0.6 ms. The images were then post–processed using a standard FFT-based cross correlation program that uses a 3D Gaussian peak finding algorithm based on a Gaussian surface fit to determine the tracer particles' displacements and velocities[4]. In nPIV measurements, the focal depth of the objective lens is larger than the penetration depth of the evanescence wave, therefore, all the particles in the image are in focus and there would be no back-ground light. Figure 7 shows the near-wall velocities measured for nanofluid and water at a visible depth of 350nm.

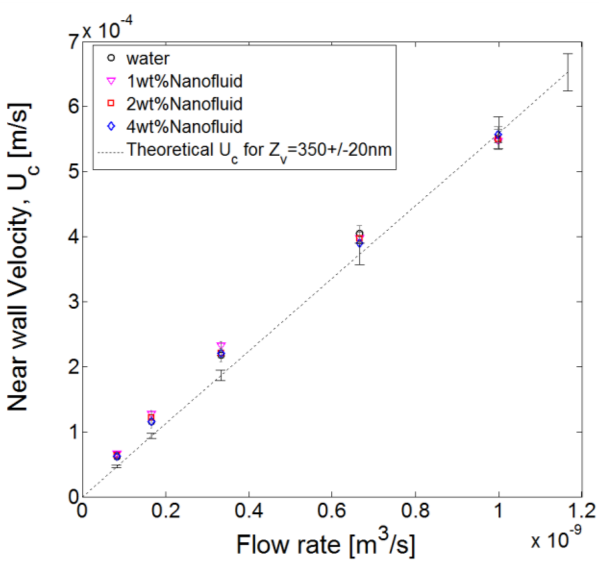

Figure 7. Near-wall velocity of nanofluids measured using nPIV technique.

It is observed from the figure that there is not much noticeable variation in near-wall velocity values measured for nanofluids even after considerable amount nanoparticles loading. The velocity variations measured for each flow rates are all falling within the experimental uncertainty values [11].The plot shows that even after increasing the particle loading by one order of magnitude, the near-wall velocity behaves the same. This indicates that nanofluids behaves as a homogeneous mixture and have Newtonian flow characteristics. Similar observation was made in earlier studies with nanofluids also [3, 4].

It should be kept in mind that, in present study, visible depth (z_v) variation while using nanofluids were estimated qualitatively from the transmittivity values. Their actual effect in nPIV measurements may be different owing to their effect on background and increasing noise levels. More efforts to measure z_v quantitatively and to include them in the near-wall velocities are being currently undertaken at our laboratory.

V. CONCLUSIONS

The present work investigates the effect of optical properties of SiO_2-water nanofluids on near-wall flow measurements. Particle concentrations were varied from 0 to 6wt%. Refractive index values of nanofluids, which affect penetration depth of the evanescent wave (z_p) were measured. Less than one percent increase in refractive index values were observed for nanofluids. Transmittivity, which would indirectly influence visible depth (z_v) were measured using a spectrometer. Analysis showed that transmittivity of light or opacity, in a depth of 500nm was not much affected by the use of nanofluids. No significant variation in near-wall velocities were recorded for nanofluids in comparison with that of water. nPIV measurements vindicated the homogeneous and Newtonian nature of the nanofluids.

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