

Article

# Assessment of Measurement Accuracy of a Micro-PIV Technique for Quantitative Visualization of Al<sub>2</sub>O<sub>3</sub> and MWCNT Nanofluid Flows

## Hanwook Park<sup>1</sup>, Jeonggyun Ham<sup>2</sup>, Honghyun Cho<sup>2</sup> and Sung Yong Jung<sup>2,\*</sup>

- <sup>1</sup> Department of Medical and Mechatronics Engineering, Soonchunhyang University, 22 Soonchunhyang-Ro, Asan, Chungnam 31538, Korea
- <sup>2</sup> Department of Mechanical Engineering, Chosun University, 309 Pilmun-Daero, Dong-gu, Gwangju 61452, Korea
- \* Correspondence: syjung@chosun.ac.kr; Tel.: +82-62-230-7051

Received: 22 May 2019; Accepted: 17 July 2019; Published: 19 July 2019



Abstract: Nanofluids, which are liquids containing nanoparticles, are used to modify heat transfer performance in various systems. To explain the mechanism of heat transfer modification with nanofluids, many theories have been suggested based on numerical simulations without experimental validation because there is no suitable experimental method for measuring the velocity fields of nanofluid flows. In this study, the measurement accuracy of micro-particle image velocimetry ( $\mu$ -PIV) is systemically quantified with Al<sub>2</sub>O<sub>3</sub> and multi-walled carbon nanotube (MWCNT) nanofluids. Image quality, cross-correlation signal-to-noise ratio, displacement difference, and spurious vector ratio are investigated with static images obtained at various focal plane positions along the beam pathway. Applicable depth is enough to investigate micro-scale flows when the concentrations of Al<sub>2</sub>O<sub>3</sub> and MWCNT nanofluids are lower than 0.01% and 0.005%, respectively. The velocity fields of Hagen–Poiseuille flow are measured and compared with theoretical velocity profiles. The measured velocity profiles present good agreement with the theoretical profiles throughout. This study provides the criteria for  $\mu$ -PIV application and demonstrates that  $\mu$ -PIV is a promising technique for measuring the velocity field information of nanofluids.

**Keywords:** nanofluids; velocity field measurement; particle image velocimetry; correlation signal-to-noise ratio

## 1. Introduction

Over the past century, energy consumption reduction has received much attention in various research fields. In heat transfer systems such as heat exchangers and electronic components, many researchers have focused on the reduction of energy consumption called heat transfer enhancement [1,2]. As recent systems are becoming compact in size, shape, and weight, traditional methods of heat transfer are inadequate. To improve heat transfer performance in miniaturized systems, nanofluids, which are liquids containing nanometer-sized particles called nanoparticles, were introduced in 1995 by Choi and Eastman [3]. Nanofluids showed better thermal characteristics than base fluids. Since then, various studies have been widely conducted in the research fields of heat transfer using nanofluids, and it is found that the addition of nanoparticles affects thermo-physical properties such as thermal conductivity, viscosity, and surface tension [4–13].

In addition to conductive heat transfer related to thermo-physical properties, convective heat transfer using nanofluids has also been studied [13–17]. The Nusselt number for nanofluids is different to that for base fluids. This means that the addition of nanoparticles alters the convective heat transfer mechanism. To design an efficient heat exchanger with nanofluid convection, a prerequisite is precise understanding



of the mechanism. Therefore, many researchers have proposed several mechanisms including the effect of Brownian motion, thermophoresis, and aggregation to explain the alteration of convective heat transfer due to the suspension of nanoparticles in a simple fluid [13,17,18]. These theories were derived based on the investigation of flow phenomena using numerical simulation because convective heat transfer is closely related to mass transfer by flows. However, these theories have not been experimentally validated because there is no detailed experimental flow information yet.

To measure the quantitative velocities of fluid flows, various techniques including hot wire, pitot tube, laser Doppler velocimetry (LDV), and particle image velocimetry (PIV) have been commonly employed [19]. The hot-wire and pitot-tube methods use a probe, which can disturb flows. LDV is a non-intrusive measurement method. However, it is not suitable for measuring information about the entire velocity field of fluid flows because it is a point-wise measurement technique. PIV is a non-intrusive optical technique measuring two-dimensional velocity fields with a high spatial resolution. Recently, PIV using tracing particles seeded in a working fluid has come to be utilized as a powerful and reasonable velocity field information measurement technique [20]. In a conventional PIV technique, a thin light sheet generated by laser and optics illuminates a plane in the flow and scattered light from a seeded particle is recorded using a camera with a macro lens. The incident laser light sheet is not retained owing to light absorption, diffraction, and refraction caused by the suspended nanoparticles in the nanofluids. Therefore, the conventional PIV technique using a laser sheet is inapplicable to measure the velocity field information of nanofluids.

Santiago et al. [21] introduced a micro-PIV ( $\mu$ -PIV) system in which a microscope was implemented as a key element. In the  $\mu$ -PIV technique, light is illuminated on the volume instead of a thin light sheet. The location and thickness of the measurement plane are determined by the focal plane and numerical aperture of an objective lens, respectively. To our knowledge, only Walsh et al. [22] attempted to measure nanofluid flows using the  $\mu$ -PIV technique. Although the study suggested the measurement feasibility with a qualitative observation, no research has been reported on the velocity field measurement of nanofluid flows using the  $\mu$ -PIV technique since then because of the lack of systematic quantitative analysis of the measurement accuracy, which is essential for practical use.

In this study, we systematically analyze the measurement accuracy of the  $\mu$ -PIV technique for measuring nanofluid flows. Al<sub>2</sub>O<sub>3</sub> and multi-walled carbon nanotube (MWCNT) nanofluids at various concentrations are used as test samples. To quantify the effect of focal depth on the measurement accuracy, a cross-correlation signal-to-noise ratio (SNR) is calculated using static images acquired at various depths. Velocity fields of simple tube flows are measured to investigate the effects of particle motion and velocity gradient on the measurement accuracy.

#### 2. Materials and Methods

#### 2.1. Nanofluid Preparation

In this study,  $Al_2O_3$  and MWCNT nanofluids with deionized (DI) water as the base fluid were prepared to analyze the measurement accuracy of  $\mu$ -PIV.  $Al_2O_3$  nanoparticles are most widely used owing to their easy availability and low cost. MWCNT nanofluids represent high enhancement in Nusselt number in most of the previous studies [13]. A two-step method was employed to prepare nanofluid solutions [5]. To prepare the nanofluids,  $Al_2O_3$  nanoparticles and MWCNT were purchased from KoreaRND.  $\alpha$ -Al\_2O\_3 nanoparticles with a mean size of 80 nm and purity of 99.9% were selected. MWCNT with the carboxyl group was employed for dispersion stability. MWCNTs have a mean diameter of 5–10 nm, length of 10–30  $\mu$ m, and purity of more than 95%. Al\_2O\_3 (0.005, 0.01, 0.1, 1, and 2.5 vol%) and MWCNT (0.005 and 0.01 vol%) nanofluids with different concentrations were prepared.

Various surfactants such as sodium dodecyl sulfate, gum arabic, and cetyltrimethylammonium bromide (CTAB) were employed to enhance the dispersion stability of Al<sub>2</sub>O<sub>3</sub> nanoparticles in the base fluid, and the cationic dispersant CTAB among various surfactants represents the best stability [23,24].

In this study, CTAB was added to the nanofluids to keep the particles properly spread in the base fluid. The added CTAB was 0.25 times of  $Al_2O_3$  in mass. After dispersing the nanoparticles and CTAB in DI water, the nanofluids were stirred by a magnetic stirrer for 30 min. Thereafter, for better stability, the pH level was also controlled to avoid reaching the iso-electrical point (IEP) at which stability deteriorates. The IEP of  $Al_2O_3$  nanofluids is 8 and the pH of nanofluids was reduced to 3 by adding a buffer solution of NaOH and HCl at 0.1 mM. Finally,  $Al_2O_3$  nanofluids were prepared by an ultrasonification process (STH-750S, Sonictopia) for 1 h. MWCNT nanofluids were prepared by the same procedure except for the surfactant addition and pH control. The viscosity of  $Al_2O_3$  is 1.01, 1.01, 1.02, 1.09 and 1.17 mPa·s when the concentration of  $Al_2O_3$  is 0.005%, 0.01%, 0.1%, 1% and 2.5%, respectively. The density of  $Al_2O_3$  is 998.2, 998.3, 998.9, 1005.5 and 1016.8 kg/m<sup>3</sup> when the concentration of  $Al_2O_3$  is 0.005% and 0.01%, respectively. The both densities of MWCNT are 998.2 kg/m<sup>3</sup> when the concentration of MWCNT is 0.005% and 0.01%.

#### 2.2. Microscopic Imaging

Figure 1 shows the schematic representation of the experimental setup of microscopic imaging system. A 2.8 W continuous laser (Shanghai Dream Laser Technology, Ltd., Shanghai, China) was employed in the present study to excite polymer fluorescence particles with 0.5  $\mu$ m average diameter (Duke Scientific Corporation, CA, USA). Two plano-convex lenses were used to expand the beam and the corresponding focal lengths are 250 and 50 mm, respectively. A narrow focal plane was formed using a 20× water immersion objective lens with a NA of 0.5. The depth of correlation ( $\delta z_{corr}$ ), which is highly related to the particle images, was influenced by the focal plane thickness [25].  $\delta z_{corr}$  is calculated as follows [26]:

$$\delta z_{corr} = 2 \left[ \frac{1 - \sqrt{\epsilon}}{\sqrt{\epsilon}} \left( f^{\#2} d_p^2 + \frac{5.95(M+1)^2 \lambda^2 f^{\#4}}{M^2} \right) \right]^{\frac{1}{2}},\tag{1}$$

where  $f^{\#}$  is the focal number of the lens,  $d_p$  is the particle diameter, M is the lens magnification,  $\lambda$  is the fluorescent wavelength, and  $\varepsilon$  is the signal threshold parameter. The corresponding  $\delta z_{corr}$  was 12 µm. A 532 nm notch filter was employed to obstruct the backscattering of green light. Images were acquired by a high-speed camera (SA 1.1, Photron, Japan) at 2000 fps for a static fluid and 500 (Reynolds number (Re) = 1) and 5000 (Re = 10) fps for tube flows. The field of view was 1000 × 1000 µm (1024 × 1024 pixels).



Figure 1. Schematic diagram of the experimental apparatus.

For quantifying the measurement accuracy, a simple rectangular chamber with a slide glass cover was made. Mixtures of nanofluid and fluorescent microparticles were filled in the chamber and static fluid images at various depths were acquired. The depth (positive *z* in Figure 1) was described from the upper cover. To validate the measurement feasibility under actual flow conditions, the nanofluid with fluorescent microparticles was pumped into fluorinated ethylene propylene microtube with a diameter of 500  $\mu$ m using a syringe pump. The volume flow rate was 0.025 and 0.25 mL/min with Re of about 1 and 10, respectively.

## 3. Results and Discussion

Images of the fluids with fluorescent particles were acquired at *z* ranging from 100 to 1500  $\mu$ m and the images are compared in Figure 2. Images of DI water were also recorded for comparison standards. Bright spots are caused by light from the fluorescent particles and no obvious change in the image quality in water is observed with increasing depth. In contrast, image qualities of nanofluids are strongly influenced by the depth of the imaging plane regardless of the concentration and material of nanoparticles. All images of the nanofluids become blurred and no bright spots are observed when *z* is higher than a specific depth value. Light intensity gradually decreases when light travels through nanofluids because they are semi-transparent. Therefore, nanofluids have a critical depth at which sufficient light for the PIV measurement is introduced into the camera. The depth depends on the concentration and type of nanofluid. For high concentrations (higher than 1%), bright spots are diminished even if the depth of focal plane is less than 100  $\mu$ m.



Figure 2. Images of nanofluids with fluorescent microspheres obtained at various z positions.

At low concentrations, as the depth increases, bright spots initially become sharp and disappear thereafter. In  $\mu$ -PIV, fluorescent light from the entire volume enters into the microscope because volume illumination is employed. Background noise occurs owing to fluorescence light from the other planes except for the focal plane. As aforementioned, light intensity decreases in nanofluids, which means that the semi-transparent property acts like an optical filter. Therefore, fluorescence light from the out-of-focus plane is filtered out and this effect makes the bright spots sharp. However, the brightness

smears and no bright spot is observed as *z* becomes large because light intensity from the focal plane is reduced.

In PIV measurements, various sources such as number of particles, mean particle diameter, focal plane thickness, and in-plane and out-of-plane motion of particles generally influence the measurement uncertainty. The resultant effect of these factors is represented in the cross-correlation plane, which is used for seeking the displacement of particles. Various error sources, which govern the estimation of a particle pattern displacement, contribute to the loss of correlation. In other words, the coupled effects of the various error sources are expressed in the correlation plane. Therefore, a method was established to directly quantify PIV measurement accuracy from the information included in the cross-correlation plane [27]. The accuracy and uncertainty of PIV measurements are calculated by the SNR strength of the PIV cross-correlation plane. The models for the uncertainty estimation are developed using three kinds of SNR metrics including peak to root mean square ratio, primary peak ratio, and peak to correlation energy (PCE). In this study, PCE is used for investigating the SNR variations with changes in the focal plane depth. PCE is calculated as

$$PCE = \frac{|C_{max}|^2}{E_c},$$
(2)

where  $C_{max}$  is the height of the primary peak.  $E_c$  is the correlation energy calculated as follows:

$$E_c = \frac{1}{S} \left( \sum_{S} \left| C(x) \right|^2 \right), \tag{3}$$

where *S* is the size of the correlation plane.

To quantify the effect of focal plane depth on the measurement accuracy, artificial image pairs were generated by shifting the images obtained at various depths (*z*) as shown in Figure 1. The distance between artificial image pairs was 8 pixels in both the horizontal and vertical directions. PCE and displacement difference were obtained by applying interrogation windows of size  $32 \times 32$  pixels. Figure 3 shows the variation of SNR with increasing *z*. SNR is normalized with SNR<sub>0</sub>, which is the PCE value at the smallest *z* for each case represented in Table 1. The lower and upper limits of the standard uncertainty corresponding to SNR<sub>0</sub> are calculated based on the model developed by Xue, Charonko, and Vlachos [27]. Compared to water, SNRs of nanofluids near the top surface are higher except for the 2.5% of Al<sub>2</sub>O<sub>3</sub> nanofluid. Higher SNR values are caused by the filtering effect of nanofluids as aforementioned.



**Figure 3.** Variation of correlation signal-to-noise ratio (SNR) with changes in the focal plane depth. SNR is normalized with  $SNR_0$  (peak to correlation energy at the smallest *z* for each case).

Fluids (vol%)		SNR <sub>0</sub>	Uncertainty Lower Limit	Uncertainty Upper Limit
Water		77.3	0.039	0.298
Al <sub>2</sub> O <sub>3</sub>	0.005	209.1	0.018	0.203
	0.01	100.2	0.032	0.269
	0.1	92.4	0.033	0.275
	1	253.7	0.017	0.192
	2.5	63.0	0.050	0.335
MWCNT	0.005	94.8	0.033	0.273
	0.01	102.5	0.035	0.322

**Table 1.**  $SNR_0$  and the corresponding lower and upper limits of standard uncertainty.

SNR for water almost remains constant even though the focal depth changes. SNR of the lowest concentration of  $Al_2O_3$  nanofluid has a tendency similar to that of water. SNRs of other nanofluids are significantly changed with the increase of *z*. For higher concentrations (1% and 2.5% for  $Al_2O_3$  and 0.01% for MWCNT) SNR gradually decreases even if *z* increments slightly. In contrast, for lower concentrations, SNR gradually increases with an initial increase in *z* and attains the maximum value at a specific depth. Thereafter, SNR sharply decreases with further increase in *z*. The starting depth of the SNR drop is strongly influenced by the concentration and the depth is lower when the nanoparticle concentration is higher. These variations of SNR agree well with the image quality changes as shown in Figure 2.

Displacements were calculated using artificial image pairs by employing the same algorithm including image pre-processing, cross-correlation, and vector validation used in practical PIV measurements. The MATLAB based open-source software was utilized in this study for PIV analysis [28]. The  $32 \times 32$  pixels with a 50% overlap was determined as an interrogation window size. The difference between the calculated displacement and shifted distance is represented in Figure 4. The red dotted line indicates a 1% difference. The difference for water is slightly increased with increase in the focal depth; however, the largest difference is less than 1%. This lower difference is resulted from the fact that no error factor caused by particle motion such as in-plane and out-of-plane is affected because an artificial image pair from a static image was used in this validation. Except for higher concentration nanofluids, the difference for nanofluids is lower than that for water when the focal plane is near the top surface. This reduction is due to the effect of the SNR increase as shown in Table 1. The semi-transparent property of nanofluids induces the increase of both correlation SNR and measurement accuracy when *z* is small. When *z* is greater than 1000 µm, the difference for nanofluids is obviously increased owing to the negative influence of the semi-transparent property.



**Figure 4.** (a) Displacement difference at different focal plane depths. (b) The magnified graph of the displacement difference of less than 3% and the red dotted line represents a 1% difference.

Poor image quality and low correlation SNR lead to wrong displacement findings. In PIV measurements, error vectors are decided and removed in the vector validation process. Spurious vectors were determined by using global and local threshold filters with the same criteria as in practical PIV measurements. The ratio of spurious to total vectors is represented in Figure 5, and the number of total vectors is 2025. The ratio for water and the lowest concentration of  $Al_2O_3$  is lower than 3% at all the depths. In other cases, the number of spurious vectors increases as the focal plane depth increases. The number rapidly increases from a specific *z* where correlation SNR starts to decrease as shown in Figure 3. This means that the reduction in image quality and correlation SNR strongly affect the number of error vectors although the reduction also influences the accuracy of the calculated displacements as shown in Figure 4. These results show that velocity fields can be successfully measured up to a *z* of 1000 µm when the concentrations of  $Al_2O_3$  and MWCNT nanofluids are lower than 0.01% and 0.005%, respectively. The measurable depth decreases with increase in the concentration and µ-PIV is inapplicable to measure velocity information when the concentrations of  $Al_2O_3$  and MWCNT



**Figure 5.** Variations of spurious vector ratios obtained by particle images at different focal plane depths. The total number of vectors is 2025 and the red dotted line indicates a 5% ratio.

In addition to the effect on image quality, particle motion including velocity gradient, in-plane, and out-of-plane strongly influences the correlation SNR leading to measurement errors in PIV measurements. Therefore, the effect of particle motion is also investigated. To validate the measurement feasibility by considering the effect of image quality and particle motion together, the velocity fields of Hagen–Poiseuille flow with a well-known velocity profile were measured using  $\mu$ -PIV. Water, 0.005% and 0.01% Al<sub>2</sub>O<sub>3</sub> nanofluids, and 0.005% MWCNT nanofluid were used for measuring the velocity fields of tube flows.

Figure 6a shows the raw image of a 0.005% MWCNT nanofluid flow for Re = 10, ensemble averaged velocity vectors, and velocity magnitude contour. The flow images were captured at the tube center plane and 500 instanton velocities were averaged. Bright particles in the tube flows were clearly observed. The SNR is smaller than that in Figure 3 owing to the particle motion effect and PCE of 71.11. The corresponding upper and lower limits of the standard uncertainty are 0.494 and 0.051, respectively. The mean velocity forms a typical profile observed in the Hagen–Poiseuille flow, where the velocities are low near the tube wall and maximum at the center. The measured maximum velocity is 41.2 mm/s and the difference with the theoretical value is 2.94%. The velocity is normalized by the maximum velocity and compared to the theoretical profile of the Hagen–Poiseuille flow. The velocity

profile matches well with the theoretical one although the difference slightly increases as the wall region is approached.



**Figure 6.** (a) Typical particle image of a 0.005% multi-walled carbon nanotube (MWCNT) nanofluid flow (upper). Ensemble averaged velocity vectors and contour (lower). (b) Measured stream-wise velocity magnitude is compared with the theoretical profile of the Hagen–Poiseuille flow. The flow rate is 0.25 mL/min and the corresponding Re is 10.

The measured velocity profiles of all the samples are compared in Figure 7. Each profile is normalized by its maximum velocity. The difference is slightly increased in high Re flows and the highest difference of the maximum velocity is 4.47% in water with the Re of 10. PCE values are 56.58, 116.22, 88.86 for water, and 0.005% and 0.01% of Al<sub>2</sub>O<sub>3</sub> nanofluids, respectively. Compared to the SNR of water, the SNRs of nanofluids are better owing to their semi-transparent optical property. SNR improvement in nanofluids leads to good agreement in the velocity profiles as shown in Figure 7. Good agreement with the theoretical profile is observed throughout in all the cases although small discrepancies exist. The nPIV technique called evanescent wave-based PIV has been used to investigate the fluid motion near the wall region such as the effect of the near-wall force and Brownian diffusion [29]. Therefore, the combination of both nPIV and µPIV has strong potential to investigate the multi-scale heat transfer phenomena of the nanofluid in the micro-scale channel.



**Figure 7.** Normalized velocity profiles obtained by micro-particle image velocimetry (PIV) techniques. The measured profiles are compared to the theoretical profile of the Hagen–Poiseuille flow.

### 4. Conclusions

In this study, the measurement accuracy of the  $\mu$ -PIV technique is systemically quantified for measuring nanofluid flows with static images captured at various depths. Al<sub>2</sub>O<sub>3</sub> and MWCNT nanofluids with different concentrations were prepared. Image quality is strongly affected by the depth of the imaging plane owing to the semi-transparent optical property of nanofluids. The cross-correlation SNR, displacement difference, and spurious vector ratio were analyzed with artificial image pairs. The applicable depth is up to a *z* of 1000  $\mu$ m, which is enough in the investigation of micro-scale flows when the concentrations of Al<sub>2</sub>O<sub>3</sub> and MWCNT nanofluids are lower than 0.01% and 0.005%, respectively. The combined effects of image quality and particle motion on the measurement accuracy were also investigated by measuring simple tube flows. The measured velocity profiles well agreed with the theoretical profile throughout for all the samples. Systematic observation of the measurement uncertainty gives the criteria for the use of  $\mu$ -PIV and demonstrates that  $\mu$ -PIV is a promising technique for measuring the velocity field information of nanofluids. This study would be helpful to validate theories and understand mechanisms about nanofluid heat transfers.

Author Contributions: Conceptualization, S.Y.J.; Methodology, H.P., J.H., H.C. and S.Y.J.; Validation, H.P. and S.Y.J.; Formal analysis, H.P. and S.Y.J.; Investigation, H.P., J.H., and S.Y.J.; Resources, J.H. and H.C.; Data Curation, H.P. and S.Y.J.; Writing—Original Draft Preparation, S.Y.J.; Writing—Review and Editing, H.P., J.H., and H.C.; Visualization, H.P. and S.Y.J.; Supervision, S.Y.J.; Project Administration, S.Y.J.; Funding Acquisition, H.P., H.C., and S.Y.J.

**Funding:** This work was supported by the Soonchunhyang University Research Fund and the Human Resources Program in Energy Technology of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), which was granted financial resources from the Ministry of Trade, Industry & Energy, Republic of Korea [grant number 20194030202410].

Conflicts of Interest: The authors declare no conflict of interest.

#### References

- 1. Bergles, A.E. Recent developments in enhanced heat transfer. *Heat Mass Transf.* 2011, 47, 1001. [CrossRef]
- 2. Sheikholeslami, M.; Gorji-Bandpy, M.; Ganji, D.D. Review of heat transfer enhancement methods: Focus on passive methods using swirl flow devices. *Renew. Sustain. Energy Rev.* **2015**, *49*, 444–469. [CrossRef]
- 3. Choi, S.U.; Eastman, J.A. *Enhancing Thermal Conductivity of Fluids with Nanoparticles*; Argonne National Lab.: Lemont, IL, USA, 1995.
- 4. Hwang, Y.; Lee, J.; Lee, C.; Jung, Y.; Cheong, S.; Lee, C.; Ku, B.; Jang, S. Stability and thermal conductivity characteristics of nanofluids. *Thermochim. Acta* **2007**, *455*, 70–74. [CrossRef]
- Lee, J.H.; Hwang, K.S.; Jang, S.P.; Lee, B.H.; Kim, J.H.; Choi, S.U.; Choi, C.J. Effective viscosities and thermal conductivities of aqueous nanofluids containing low volume concentrations of Al<sub>2</sub>O<sub>3</sub> nanoparticles. *Int. J. Heat Mass Transf.* 2008, *51*, 2651–2656. [CrossRef]
- Eastman, J.A.; Choi, S.; Li, S.; Yu, W.; Thompson, L. Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles. *Appl. Phys. Lett.* 2001, *78*, 718–720. [CrossRef]
- 7. Murshed, S.; Leong, K.; Yang, C. Investigations of thermal conductivity and viscosity of nanofluids. *Int. J. Therm. Sci.* **2008**, 47, 560–568. [CrossRef]
- 8. Buongiorno, J.; Venerus, D.C.; Prabhat, N.; McKrell, T.; Townsend, J.; Christianson, R.; Tolmachev, Y.V.; Keblinski, P.; Hu, L.; Alvarado, J.L. A benchmark study on the thermal conductivity of nanofluids. *J. Appl. Phys.* **2009**, *106*, 094312. [CrossRef]
- 9. Vafaei, S.; Wen, D. Convective heat transfer of aqueous alumina nanosuspensions in a horizontal mini-channel. *Heat Mass Transf.* **2012**, *48*, 349–357. [CrossRef]
- 10. Vafaei, S.; Purkayastha, A.; Jain, A.; Ramanath, G.; Borca-Tasciuc, T. The effect of nanoparticles on the liquid-gas surface tension of Bi2Te3nanofluids. *Nanotechnology* **2009**, *20*, 185702. [CrossRef]
- 11. Park, H.; Lee, S.J.; Jung, S.Y. X-ray imaging analysis on behaviors of boiling bubbles in nanofluids. *Int. J. Heat Mass Transf.* **2019**, *128*, 443–449. [CrossRef]

- 12. Park, H.; Lee, S.J.; Jung, S.Y. Effect of nanofluid formation methods on behaviors of boiling bubbles. *Int. J. Heat Mass Transf.* **2019**, *135*, 1312–1318. [CrossRef]
- 13. Sajid, M.U.; Ali, H.M. Recent advances in application of nanofluids in heat transfer devices: A critical review. *Renew. Sustain. Energy Rev.* **2019**, *103*, 556–592. [CrossRef]
- 14. Ebrahimi, M.; Farhadi, M.; Sedighi, K.; Akbarzade, S. Experimental investigation of force convection heat transfer in a car radiator filled with SiO2-water nanofluid. *Int. J. Eng.* **2014**, *27*, 333–340. [CrossRef]
- 15. Ghozatloo, A.; Rashidi, A.; Shariaty-Niassar, M. Convective heat transfer enhancement of graphene nanofluids in shell and tube heat exchanger. *Exp. Therm. Fluid Sci.* **2013**, *53*, 136–141. [CrossRef]
- 16. Selvakumar, P.; Suresh, S. Convective performance of CuO/water nanofluid in an electronic heat sink. *Exp. Therm. Fluid Sci.* **2012**, *40*, 57–63. [CrossRef]
- Xuan, Y.; Li, Q. Investigation on Convective Heat Transfer and Flow Features of Nanofluids. *J. Heat Transf.* 2003, 125, 151–155. [CrossRef]
- Khaled, A.R.A.; Vafai, K. Heat transfer enhancement through control of thermal dispersion effects. *Int. J. Heat Mass Transf.* 2005, 48, 2172–2185. [CrossRef]
- Nabavi, M.; Siddiqui, K. A critical review on advanced velocity measurement techniques in pulsating flows. *Meas. Sci. Technol.* 2010, 21, 042002. [CrossRef]
- Adrian, R.J. Particle-Imaging Techniques for Experimental Fluid Mechanics. Annu. Rev. Fluid Mech. 1991, 23, 261–304. [CrossRef]
- 21. Santiago, J.G.; Wereley, S.T.; Meinhart, C.D.; Beebe, D.J.; Adrian, R.J. A particle image velocimetry system for microfluidics. *Exp. Fluid.* **1998**, *25*, 316–319. [CrossRef]
- 22. Walsh, P.; Egan, V.; Walsh, E.J. Novel micro-PIV study enables a greater understanding of nanoparticle suspension flows. *Microfluid. Nanofluid.* **2009**, *8*, 837–842. [CrossRef]
- 23. Kwek, D.; Crivoi, A.; Duan, F. Effects of Temperature and Particle Size on the Thermal Property Measurements of Al2O3–Water Nanofluids. *J. Chem. Eng. Data* **2010**, *55*, 5690–5695. [CrossRef]
- 24. Sakamoto, M.; Kanda, Y.; Miyahara, M.; Higashitani, K. Origin of Long-Range Attractive Force between Surfaces Hydrophobized by Surfactant Adsorption. *Langmuir* **2002**, *18*, 5713–5719. [CrossRef]
- 25. Nguyen, C.V.; Fouras, A.; Carberry, J. Improvement of measurement accuracy in micro PIV by image overlapping. *Exp. Fluids* **2010**, *49*, 701–712. [CrossRef]
- 26. Olsen, M.; Adrian, R. Out-of-focus effects on particle image visibility and correlation in microscopic particle image velocimetry. *Exp. Fluids* **2000**, *29*, S166–S174. [CrossRef]
- 27. Xue, Z.; Charonko, J.J.; Vlachos, P.P. Particle image velocimetry correlation signal-to-noise ratio metrics and measurement uncertainty quantification. *Meas. Sci. Technol.* **2014**, *25*, 115301. [CrossRef]
- 28. Thielicke, W.; Stamhuis, E. PIVlab-towards user-friendly, affordable and accurate digital particle image velocimetry in MATLAB. *J. Open Res. Softw.* **2014**, *2*, e30. [CrossRef]
- 29. Anoop, K.; Sadr, R. nPIV velocity measurement of nanofluids in the near-wall region of a microchannel. *Nanoscale Res. Lett.* **2012**, *31*, 284. [CrossRef]



© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).