A Study of the Effect of Nanoparticle Concentration on the Characteristics of Nanofluid Sprays

B. Kang[1†], M. Marengo[2] and S. Begg[2]

[1] *Department of Mechanical Engineering, Chonnam National Univ., 77 Yongbong-ro, Buk-gu, Gwangju, 61186, Korea*
[2] *School of Computing, Engineering and Mathematics, Univ. of Brighton, Lewes Road, BN2 4GJ, Brighton, United Kingdom*

†*Corresponding Author Email: bskang@jnu.ac.kr*

ABSTRACT

Nanofluids are metallic or nonmetallic, nanometer-sized particles dispersed in liquid. They can be used in various fields to increase heat transfer rates, as the thermal conductivity of nanofluids can be increased significantly. Nanofluids may be used as a good alternative coolant in spray cooling applications. This study conducted experiments to compare spray characteristics, such as droplet diameters and velocities, between water and alumina nanofluid sprays. The mass ratio of alumina nanoparticles was varied from 0.2 to 0.5 weight percentages (wt.%) and the spray injection pressure was varied between 0.2 and 0.3 MPa. The local distributions of droplet sizes and velocities along the spray axial and radial directions were measured by a laser doppler instrument. Generally, the spray characteristics of nanofluid sprays is significantly different from that of water sprays. The average droplet diameters of the fluids tested increased in an approximately linear manner with the increase in the mass ratio of nanoparticles up to 0.4 wt.%, whereas the average droplet velocities decreased. In the case of the nanofluid spray of 0.5 wt.%, the increase in droplet diameters and the decrease in droplet velocities were much more marked, departing from the linear relationship. This unusual behavior could also be observed in the local distributions of droplet diameters and velocities along the axial and radial directions. Further research studies are required to reveal how the addition of nanoparticles affects the atomization mechanism of nanofluids. The difference in the spray characteristics of nanofluid sprays from that of water sprays should be taken into consideration when the cooling effectiveness of nanofluids and water in spray cooling is compared.

Keywords: Nanofluid; Nano particles; Nanofluid Spray; Spray cooling.

1. INTRODUCTION

For the enhancement of heat transfer performance in the convective heat transfer field, nanofluids are considered to be one of promising candidates as coolants in thermal management for the ultra-high cooling requirements of the present day and near future (Kakac and Pramuanjaroenkij 2009). Nanofluids are liquid suspensions that contain small amounts of metallic or nonmetallic, nanometer-sized particles. The addition of metal or metal oxide nanoparticles having high thermal conductivity to traditional coolants (water, oil, ethylene glycol, and refrigerants) increases the thermal conductivities of those fluids. The increased effective thermal conductivity of nanofluids is expected to increase the rate at which heat can be transferred away from a hot surface.

The use of nanofluids as coolants for spray cooling is an extension of their application to the enhancement of heat transfer performance. Spray cooling uses atomized liquid droplets injected from spray nozzles to cool hot surfaces. It has several advantages compared with other cooling methods, including relatively high cooling capacity, convenience of use, low operating cost, uniform cooling of hot surfaces, and easy control of cooling performance by adjusting the spray characteristics. Spray cooling has been widely used for a long time in various industrial applications where there are materials with relatively high surface temperatures, such as heat treatment in the continuous casting process of steel plates, fire extinguishing, and emergency cooling of molten cores of light-water reactors in nuclear power plants. In recent years, spray cooling has also been utilized in the cooling of high-density electronic devices and high-power solid-state lasers which require that the surface temperature be maintained at a safe low level.

Spray cooling in itself is a complex phenomenon encompasses flow and heat transfer with phase change (Kim 2007). Various factors affect heat
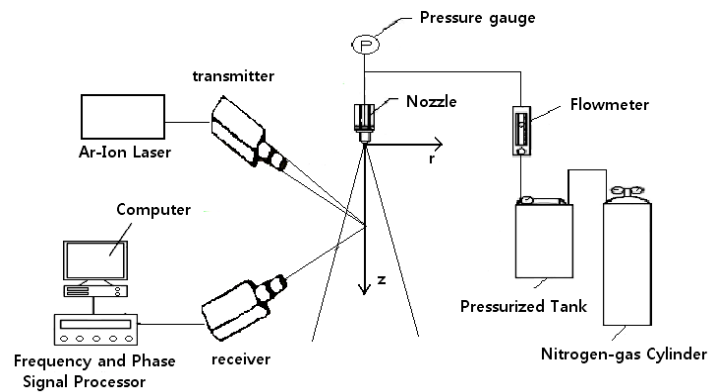
Fig. 1. Schematic of experimental apparatus.

transfer by spray cooling, including the spray characteristics (flow rate, droplet sizes, droplet velocities), the conditions of the high temperature surface to be cooled (its properties, temperature, surface roughness, wettability, inclination), fluid properties (material properties, supercooling temperature), and environment conditions (temperature, pressure, distance from nozzle to surface). Despite the number of research studies into spray cooling to date, there are still a lack of understanding of the spray cooling mechanism, and several efforts have been made to enhance spray cooling performance.

However, there have been not many research studies on the spray cooling characteristics performed with nanofluids. Bansal (2007) used an alumina nanofluid for the spray cooling of a heated copper surface, and an increase in the heat transfer capability of nanofluids was observed at lower temperatures and heat fluxes. But at high surface temperatures and heat fluxes, the performance of nanofluids deteriorated compared to that of water due to the deposition of nanoparticles on the surface. Martinez (2009) showed that a single-phase heat transfer using alumina nanofluids was increased by approximately 42%, compared with water. The study also observed an increase in the critical heat flux and a delay of two-phase heat transfer. Zhu *et al.* (2009) investigated spray cooling of a heated surface by a TiO$_2$-water nanofluid spray under a non-boiling regime. The results showed that the heat transfer coefficient was 35% higher than that of the water spray. The study reported that this was possibly due to the fact that nanoparticles destroy the spray boundary layer and intensify the turbulence.

On the other hand, Bellerova *et al.* (2010) observed an adverse effect of nanoparticles on heat transfer performance. The heat transfer coefficient of an alumina-water spray was 45% lower than that of a pure water spray. Chang *et al.* (2012) found that high volume fraction nanofluids are unsuitable for spray cooling applications because the deposition of nanoparticles on a heated surface reduced the number of nucleation sites and hindered the convection heat transfer. To the contrary, low volume fraction nanofluids provided a significant

enhancement in cooling performance, since most of the nanoparticles rebounded from the heated surface or were washed away.

The main focus of all the previous studies on spray cooling with nanofluids was a comparison of the spray cooling characteristics of water and nanofluids. Conflicting results have been reported about the role of nanoparticles in spray cooling. As mentioned above, the spray characteristics such as droplet sizes and velocities plays an important role in heat transfer performance. Nevertheless, to the best of the present authors' knowledge, there have been no research to date that has investigated the spray characteristics of nanofluid sprays. The addition of nanoparticles to the base fluid changes the thermophysical properties of the fluid. Atomization of the bulk liquid is certainly affected by this change in such fluid properties as density, viscosity, and surface tension. In addition, the atomization mechanism of the bulk liquid may be influenced by the presence of solid nanoparticles within it. Depending on the concentration of nanoparticles in a nanofluid, the spray characteristics of that nanofluid may differ from that of the base fluid, resulting in different spray cooling characteristics.

In this study, the spray characteristics of nanofluid sprays (droplet diameters and velocities) with a change of nanoparticle mass concentration was investigated using a laser measurement instrument, Particle Dynamics Analyzer (PDA). The results were compared with those of water sprays. The mass concentration of alumina nanoparticles was in the range from 0 (water) to 0.5 wt.% and the spray injection pressures set at 0.2 and 0.3 MPa. The local distributions of droplet sizes and velocities along the spray axis and the radial direction were measured.

2. EXPERIMENTAL APPARATUS

As shown schematically in Fig. 1, the experimental apparatus was mainly composed of a liquid supply system to a spray nozzle and a laser measurement system for measuring the spray characteristics. A high-pressure N$_2$ gas cylinder with a pressure regulator was used to pressurize a liquid reservoir to direct a non-fluctuating, stable liquid to flow to the

full cone spray nozzle (Spraying Systems Inc., TG-SS1, *D*= 0.51 mm, flow rate=0.54~1.3 *l*/min). The liquid from the reservoir passed through a flowmeter and was directed to the spray nozzle. The spray injection pressure was monitored by a pressure gauge placed immediately upstream of the inlet of the spray nozzle. The sprays of all the tested fluids were injected at pressures of 0.2 and 0.3 MPa. The average temperature of liquids was 18°C and the spray can be assumed as axisymmetrical.
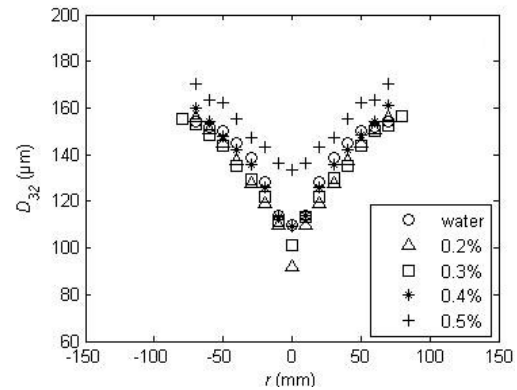
Measurements of droplet diameters and velocities of the nanofluid and water sprays were made using the PDA (Particle Dynamics Analyzer, Dantec Dynamics) system. The two component beams from a 5 W Argon ion laser were divided into two wavelengths of 514.5 nm and 488 nm. To prevent directional ambiguity, one component was shifted by a Brag Cell with a shift frequency of 40 MHz. The scattered light from the droplets was collected by a receiver, amplified by photomultipliers, and then processed by a signal processor. Both the transmitting and receiving probes could be moved using a three-dimensional traverse system with a resolution of 0.5 mm. Measurements were performed at three axial locations measured from the injector tip, *z*= 100, 150, and 200 mm. In the radial direction at each axial measurements were repeated at a 10 mm interval from the spray center to the spray edge. The number of samples measured at each measuring point was approximately 3 to 5 million to ensure statistical accuracy.
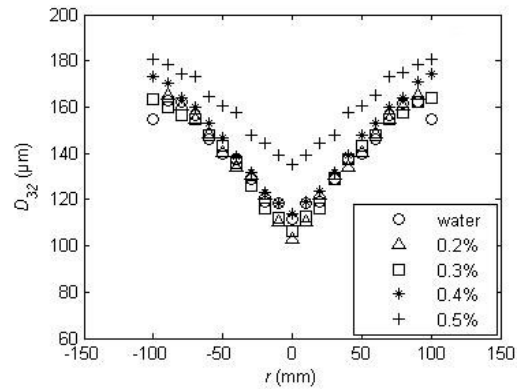
Table 1 Properties of water and nanofluids

Fluid		Density (kg/m³)	Viscosity (kg/m ·s)
Water		998.2	0.940 x 10⁻³
Nanofluid Weight Percent (%)	0.2	1004.4	0.953 x 10⁻³
	0.3	1009.6	0.958 x 10⁻³
	0.4	1010.8	0.961 x 10⁻³
	0.5	1014.8	0.965 x 10⁻³

The nanoparticles in the nanofluids were of alumina (Al_2O_3) and their average diameter was approximately 30 nm. The tested fluids were water and four alumina-water nanofluids with varying mass concentrations (weight %) of alumina nanoparticles. The nanofluids were prepared by mixing alumina nanoparticles of fixed mass concentration with water, as a base fluid. Uniform dispersion of nanofluids was achieved by sonicating them for a minimum of 12 hours with an ultrasonic cleaner sonicator, to prevent agglomeration of nanoparticles. The mass concentrations of nanoparticles used in the experiments ranged from 0 (water) to 0.5 wt.%. The physical properties such as the density and the viscosity of water and nanofluids were measured directly. The densities were measured by measuring the mass of known volume of nanofluids using a 25 ml flask. An ultra rheometer (Model DV-Ⅲ, Brookfield Eng. Co.) was used to measure the viscosities. Regardless of the change in the mass concentration of
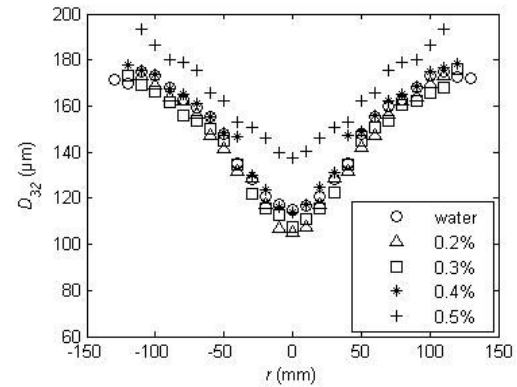
nanoparticles, the transparency and the refractive index of nanofluids didn't change. The measured properties of all the fluids are shown in Table 1.

a) *z* = 100 mm

b) *z* = 150 mm

c) *z* = 200 mm

Fig. 2. Distribution of droplet diameters in the radial direction at *P*= 0.2 MPa; a) *z*= 100 mm, b) *z*= 150 mm, c) *z*= 200 mm.

3. RESULTS AND DISCUSSION

3.1 Sauter Mean Diameters of Spray Droplets

The distribution of the diameters of the spray droplets in the radial direction at three axial locations (*z*= 100, 150, 200 mm) is shown in Figs. 2 and 3 at the injection pressures, *P*= 0.2 and 0.3

MPa, respectively. The typical distribution of diameters in the radial direction for the cone-shaped spray is observed regardless of fluid type, injection pressure, and axial location. The bulk fluids are well atomized in the center of spray, resulting in the smallest droplet diameters, whereas the droplet diameters increase gradually away from the center of spray and moving toward the spray edge. The water spray and the nanofluid sprays (except for the nanofluid spray of 0.5 wt.%) do not show any noticeable differences in droplet diameters at the measuring points and at the tested injection pressures. But the diameters of the nanofluid spray of 0.5 wt.% are markedly different from those of all the other tested fluids. The diameters of the nanofluid spray of 0.5 wt.% are the highest among all the tested fluids, which suggests that the bulk liquid is poorly atomized. These differences are much more marked in the spray center axis, and reduce gradually moving away from the center of spray and toward the spray edge. At the injection pressure, $P= 0.3$ MPa (Fig. 3), these differences are greater at the spray center and lower at the spray edge, compared with those at $P= 0.2$ MPa.

Figure 4 shows the effect of injection pressure on the distribution of droplet diameters in the radial direction at $z= 200$ mm, for the water spray and the nanofluid spray of 0.5 wt.%. The distribution of droplet diameters shows that the droplet diameters of the nanofluid spray of 0.5 wt.% are always higher than those of the water spray, regardless of the injection pressure. The water spray shows the typical characteristics, with the resulting droplet diameters generally decreasing with the increase in the injection pressure. This behavior is especially obvious around the spray center and at the spray edge. On the other hand, unusual results are observed around the spray center in the case of the nanofluid spray of 0.5 wt.%. In spite of the increase of the injection pressure from 0.2 to 0.3 MPa, the droplet diameters around the spray center do not decrease as expected. Around the spray edge, the droplet diameters decrease in a normal way with the increase of the injection pressure.

Figure 5 shows the distribution of droplet diameters in the radial direction at $P= 0.2$ MPa with the change of axial location for the water spray and the nanofluid spray of 0.5 wt.%. The distribution of droplet diameters shows that the droplet diameters of the nanofluid spray of 0.5 wt.% are always higher than those of the water spray, regardless of the axial location. In the case of the nanofluid spray of 0.5 wt.%, there is little difference in droplet diameters at three axial locations, which stronglyimplies that the bulk liquid of the nanofluid is completely atomized after the axial distance, $z= 100$ mm from the nozzle exit. On the other hand, for the water spray, noticeable differences in the droplet diameters at the three axial locations are observed, depending on the radial position.

The average droplet diameters at the varying nanoparticle concentrations of nanofluids are compared in Fig. 6. From water (0 wt.%) to the nanofluid spray of 0.4 wt.%, the average droplet diameters increase slightly in an almost linear manner, with the increase of nanoparticle concentrations of nanofluids. However, for the nanofluid spray of 0.5 wt.%, the average droplet diameters increase more significantly, which suggests that the atomization of this nanofluid is the poorest among the tested fluids. With the increase of the injection pressure from 0.2 to 0.3 MPa, the average droplet diameters decrease by almost the same amount except in the case of the nanofluid spray of 0.5 wt.%. Even with the increase of the injection pressure, the improvement of atomization is the smallest for this nanofluid among all the tested fluids. Based on the above results, it seems that the existence of nanoparticles has a small effect upon the atomization of nanofluids, up to a certain level of nanoparticle concentration. However, above that level, the existence of nanoparticles may strongly suppress the atomization of nanofluids. The degree of atomization of nanofluids may be affected by the physical properties of nanofluids. The spray characteristics is strongly influenced by the liquid properties such as density, viscosity, and surface tension (Lefebvre 1989). Surface tension represents the force that resists the formation of new surface area so fluids with higher surface tension tend to produce a larger average droplet size. A fluid's viscosity has a similar effect on droplet size as surface tension. Viscosity causes the fluid to resist agitation, tending to prevent its breakup and leading to a larger average droplet size. Density causes a fluid to resist acceleration but the effect of liquid density on mean droplet size is quite small.

According to the change in the physical properties of the tested nanofluids, the increase of the average droplet diameters is expected with the increase of nanoparticle concentrations of the nanofluids, because the viscosity of the nanofluids increased with the addition of nanoparticles. In addition to the effects of physical properties of nanofluids, the presence of nanoparticles may affect the resulting flow in the disintegrating liquid elements and eventually the atomization mechanism of the bulk liquid. Investigation of the effect of nanoparticles on the atomization mechanism of nanofluids has never been reported so far. It deviates from the focus of the present research, so further research is required on this subject.

3.2 Mean Velocities of Spray Droplets

Figures 7 and 8 show the distributions of the velocities of spray droplets in the radial direction at three axial locations ($z= 100, 150, 200$ mm) at the injection pressures, $P= 0.2$ and 0.3 MPa, respectively. In a typical distribution of the velocities of spray droplets produced by a cone spray nozzle, the droplet velocities are the highest in the center of the spray and decrease gradually away from the center of the spray toward the spray edge. These results can be expected from the results of droplet size measurements. That is to say, in the center of the spray, the droplet diameters are small, resulting in high velocities. The droplet diameters increase toward the spray edge, causing a decrease in droplet velocities. Overall, the droplet velocities are slowly reduced toward the downstream of the spray due to the drag force acting on them.
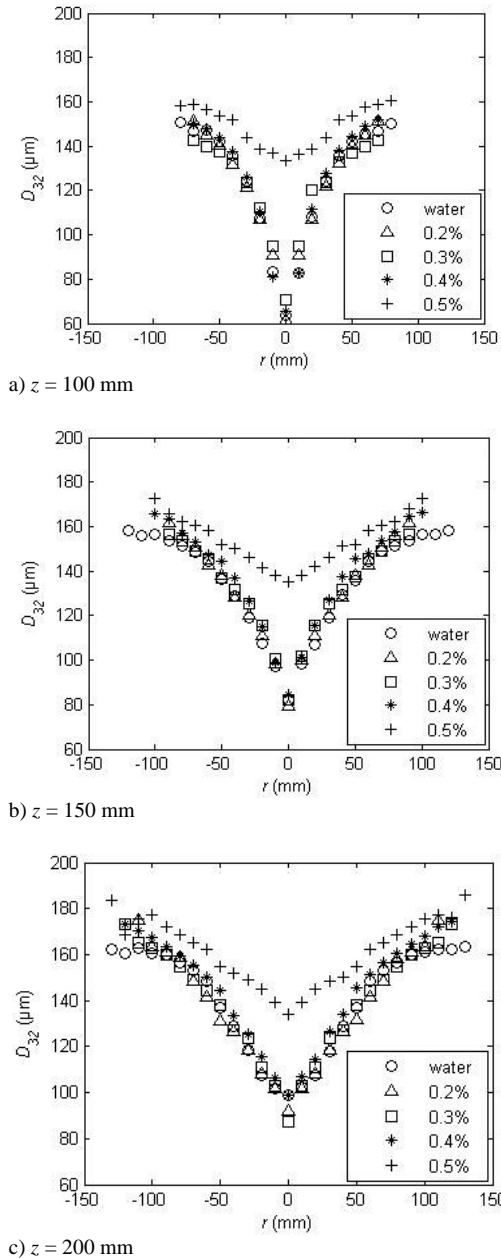
a) z = 100 mm

b) z = 150 mm

c) z = 200 mm

Fig. 3. Distribution of droplet diameters in the radial direction at *P*= 0.3 MPa; a) *z*= 100 mm, b) *z*= 150 mm, c) *z*= 200 mm.
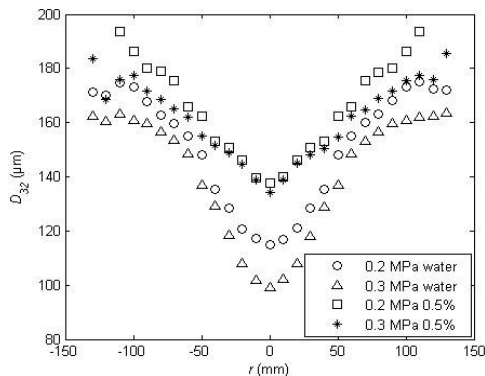

Fig. 4. Effect of injection pressure on the distribution of droplet diameters in the radial direction at *z*= 200 mm.
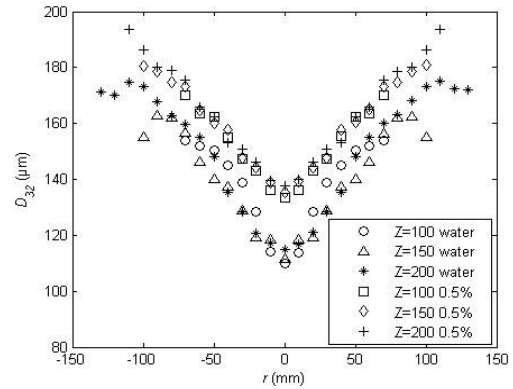

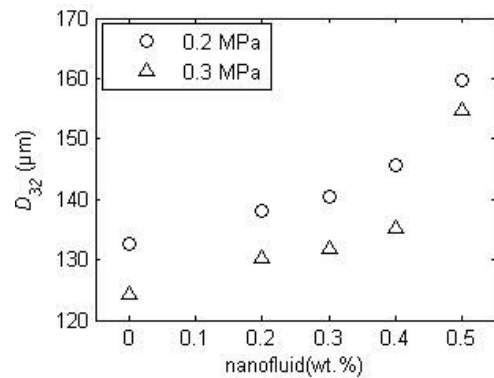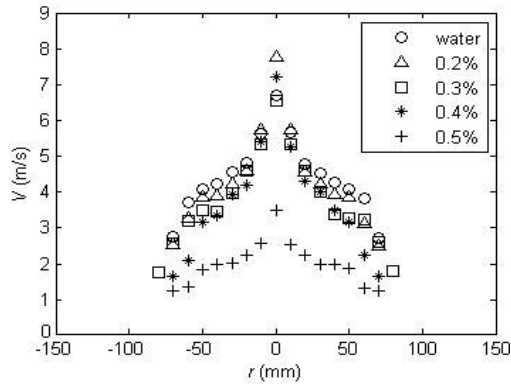**Fig. 5. Distribution of droplet diameters in the radial direction at *P*= 0.2 MPa with the change of axial location.**

Fig. 6. Comparison of average droplet diameters with different nanoparticle concentration of nanofluids.
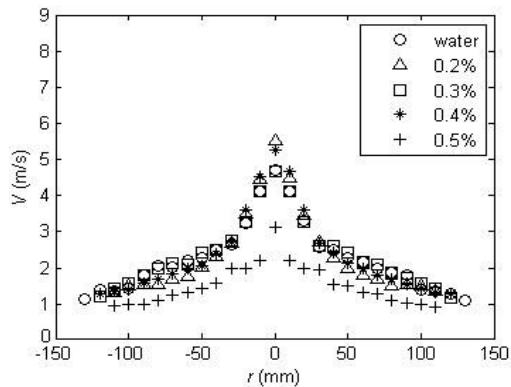
In Fig. 7 for *P*= 0.2 MPa, the droplet velocities of the water spray and the nanofluid sprays (except the nanofluid spray of 0.5 wt.%) do not show any noticeable differences especially toward the spray downstream. However, the velocities of the nanofluid spray of 0.5 wt.% are the lowest among the tested fluids, and totally different from those of all other tested fluids. This difference is very severe around the center of the spray and reduces gradually moving away from the center of the spray toward the spray edge. This result can also be deduced from the results of the droplet size measurements shown in Fig. 2. The nanofluid spray of 0.5 wt.% produced the largest droplets among the tested fluids, resulting in the slowest droplet velocities. In Fig. 8 for *P*= 0.3 MPa, the droplet velocities of all the fluids increase with the increase of the injection pressure. In the measured region of the furthest downstream of the spray, *z*= 200 mm, shown in Fig. 8(c), the same trend which appeared at *P*= 0.2 MPa in Fig. 7(c) is observed. However, in the measured region nearer to the injector exit, namely, *z*= 100 and 150 mm, the droplet velocities except the center of the spray are the highest for the water spray and the lowest for the nanofluid spray of 0.5 wt.%. The droplet velocities of the other mass concentrations of the nanofluids are in-between, and no big differences are observed between them.
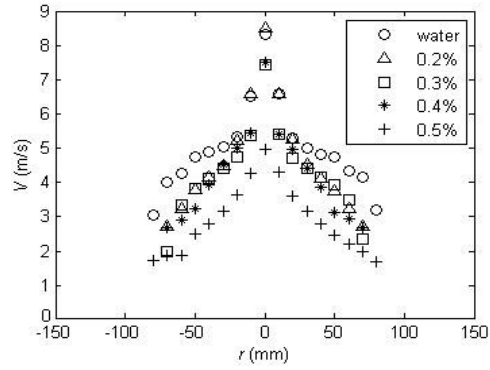
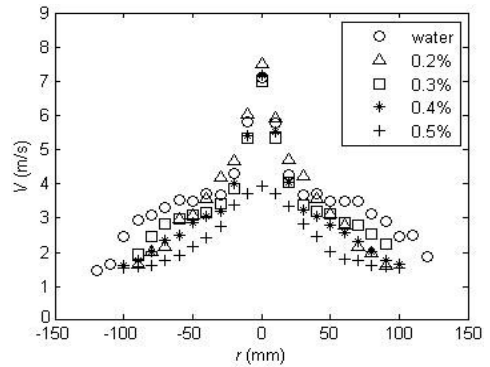a) *z* = 100 mm

b) *z* = 150 mm

c) *z* = 200 mm

Fig. 7. Distribution of droplet velocities in the radial direction at *P*= 0.2 MPa; a) *z*= 100 mm, b) *z*= 150 mm, c) *z*= 200 mm.
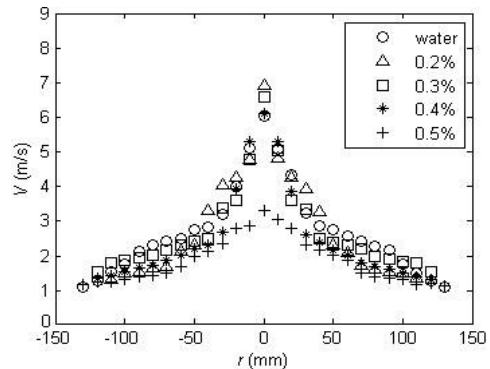
Figure 9 shows the effect of the injection pressure on the distributions of droplet velocities in the radial direction at *z*= 200 mm for the water spray and the nanofluid spray of 0.5 wt.%. As expected for the typical characteristics of spray droplet velocities, the resulting droplet velocities generally increase with the increase of the injection pressure. Especially, in the center region of the water spray, this trend appears strongly. The droplet velocities of the water spray are always higher than those of the nanofluid spray of 0.5 wt.%, regardless of the injection pressure.

a) *z* = 100 mm

b) *z* = 150 mm

c) *z* = 200 mm

Fig. 8. Distribution of droplet velocities in the radial direction at *P*= 0.3 MPa; a) *z*= 100 mm, b) *z*= 150 mm, c) *z*= 200 mm.
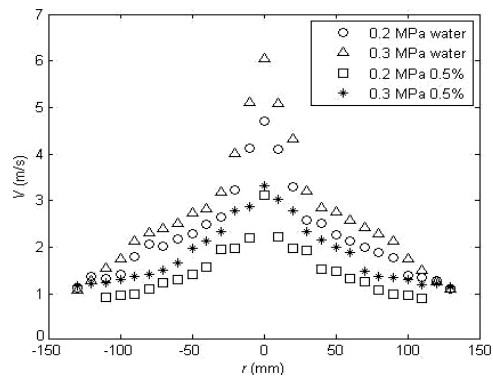

Fig. 9. Effect of injection pressure on the distribution of droplet velocities in the radial direction at *z*= 200 mm.

Figure 10 shows the distribution of droplet velocities in the radial direction at $P= 0.2$ MPa with the change of axial location for the water spray and the nanofluid spray of 0.5 wt.%. The distribution shows that the droplet velocities of the water spray are always higher than those of the nanofluid spray of 0.5 wt.%, regardless of the axial location. For the water spray, the droplet velocities are highest near to the nozzle exit, at $z= 100$ mm, and then the droplet velocities decrease moving toward the spray downstream. On the other hand, for the nanofluid spray of 0.5 wt.%, there is little difference in droplet velocities along the axial location.

Figure 11 shows the average droplet velocities with different nanoparticle concentrations of the nanofluids. Similar to the trend of the average droplet diameters shown in Fig. 6, the average droplet velocities decrease almost linearly between water (0 wt.%) and the nanofluid spray of 0.4 wt.% with the increase of nanoparticle concentrations of nanofluids. However, the average droplet velocities for the nanofluid spray of 0.5 wt.% decrease much more abruptly than the other nanoparticle concentrations of nanofluids. With the increase of the injection pressure from 0.2 to 0.3 MPa, the average droplet velocities increase by approximately the same amount except in the case of the nanofluid spray of 0.5 wt.%. The increase of the average droplet velocities for the nanofluid spray of 0.5 wt.% is the highest among the tested fluids.
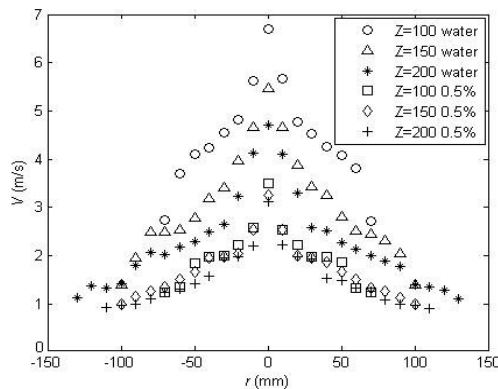

Fig. 10. Distribution of droplet velocities in the radial direction at $P= 0.2$ MPa with the change of axial location.
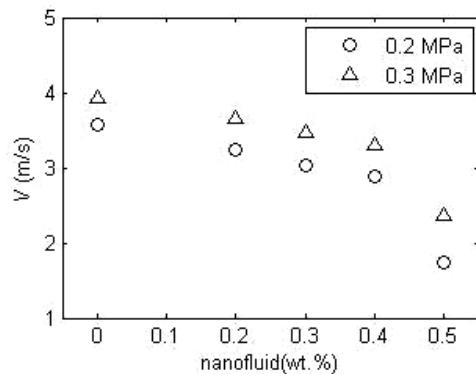

Fig. 11. Comparison of average droplet velocities with different nanoparticle concentration of nanofluids.

4. CONCLUSION

This study investigated the spray characteristics of alumina-water nanofluid sprays with varying nanoparticle mass concentrations using a laser measurement instrument. The results were compared to those of a water spray. While changing the mass concentrations of alumina nanoparticles ranging from 0 (water) to 0.5 wt.%, and setting the spray injection pressures at 0.2 and 0.3 MPa, the local distributions of the droplet diameters and velocities at three spray axial locations and across the radial direction were measured.

Generally, the droplet diameters and velocities of the alumina-water nanofluid sprays were markedly different from those of the water spray. The average droplet diameters or velocities of the tested fluids increased and decreased, respectively, in an almost linear manner with the increase of the mass concentrations of nanoparticles from 0 (water) to 0.4 wt.%. For the nanofluid spray of 0.5 wt.%, this increase in the droplet diameters and decrease in the droplet velocities was more significant, departing from the linear relationship. This special trend for the nanofluid spray of 0.5 wt.% was also observed in the local distributions of droplet diameters and velocities in the radial direction at each of three axial locations.

The difference in the spray characteristics of nanofluid sprays from that of water sprays should be considered when making comparison of cooling effectiveness between nanofluid sprays and water sprays. Further research is required to reveal how added nanoparticles affect the atomization mechanism of nanofluids.

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