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HEAT TRANSFER COEFFICIENT AND VISCOSITY OF ALUMINA-WATER NANOFLUIDS

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ABSTRACT

Boiling heat Transfer Coefficient of 0.1 vol.% water-alumina nanofluids and the effect of pH value of the solution was studied. It was observed that as the pH value changed from neutral (6.5) to acidic (5), the particle cluster size and solution heat transfer coefficient were affected. The cluster size of the nano-alumina fluid decreased with increasing sonicating time. The flow behavior of the nanofluid for 1 to 4 vol.% concentrations was studied and it was observed that these nanofluids behaved as Newtonian and their viscosity decreased with increasing sonicating time. The decrease in viscosity could be attributed to the fragmentation of the nano-particles and clusters as observed from their microstructure.

INTRODUCTION

Research in nanotechnology promises breakthroughs in areas such as materials and manufacturing, nanoelectronics, medicine and healthcare, energy, biotechnology and information technology [1]. Commonly, particle size less than 100 nm and Zero-Dimensional (regardless of size and morphology) are called nano-particles [2]. A dispersion of nano-particles in a base fluid is called nanofluid and most of the ceramic nano-particles suspensions are used in the production of ultra-thin dielectrics, solid-oxide fuel cells and oxygen separation systems for medical and aerospace application [3-6]. Alumina-water nanofluids is one of the more commonly used system and finds applications in heat exchangers in refrigerators, automobiles and power plants [7-10].

In the study of the nanofluid it is important to understand the interaction between the particles and their flow behaviour with the base fluid. Therefore, sample preparation is one of the important parameters in the nanofluid research. Unfortunately, until now there is no standard procedure for dispersing the nano-particles in the base fluid. Nano-particles have a high tendency to form agglomerates by Van der Waals force interactions between the particles [11,12]. Ultrasonic vibrator is commonly used in the alumina nanofluid preparation to break down the particle agglomerates and typical sonicating times are from 5h to a few days. The residence time in the ultrasonic vibrator would be referred to as the sonication time hereafter in this publication. The other method used to disperse the nano-particles is by changing the pH value of the nanofluid and referred to as Electrostatic Stabilisation [11,13,14].

Yu et al [15] reported in a review article on thermal conductivity of alumina nanofluid that sample preparation varied from one researcher to another and experimental parameters such as temperature, size of the particle also varied. It may be one of the reasons that results published so far show a large scatter in the measured thermal conductivity of these fluids. In the present study, the Heat Transfer Coefficient (HTC) and viscosity of alumina-water nanofluid suspension was studied as a function of the sonicating time and pH value.

MATERIALS, APPARATUS AND PROCEDURE

Dry alumina nano-powder (40 to 50 nm) was weighed and mixed with deionized water in a glass bottle. Branson Ultrasonic Cleaner 3510† was used to mix the solution at a sound frequency of 42 KHz ± 6%. Two types of experiments were carried out: the boiling vessel used to study the heat transfer coefficient and the rotational rheometer used to study the flow behaviour and viscosity.

The boiling vessel

The boiling vessel used in this study is shown in Figure 1. The main body of the vessel was a 20 cm diameter stainless steel pipe (13). A stainless steel skirt was fixed (16) to support the liquid within the pipe. A 2.54 mm diameter and 71 mm length copper block (18) was installed at the centre of the skirt to serve as the boiling surface. Three ¼ inch diameter and 1 ½ inch length cartridge heaters were fixed inside the bottom of the copper block to provide the heat flux to the liquid, referred to as

† Branson Ultrasonic Corporation, Danbury, CT, USA http://www.bransonic.com.

the main heater (8). Three 1.0 mm diameter type-E thermocouples (17) were installed in the copper block at different axial distances from the top of the block to determine the axial temperature profile of the copper block. These blocks were wrapped in insulation (9) to reduce radial heat loss. A linear best fit was carried out on the temperatures recorded, assuming that radial heat losses are negligible and the temperature profile is linear. The equations used to apply the linear best fit and obtain heat flux, q″ and surface temperature, T_s are shown in equations (1) and (2) respectively.

$$q'' = k\frac{\sum x_i T_i - \sum x_i \sum T_i}{N\sum\left(x_i^2\right) - \left(\sum x_i\right)^2} \quad (1)$$

$$T_s = \frac{N\sum x_i^2 \sum T_i - \sum x_i \sum x_i T_i}{N\sum\left(x_i^2\right) - \left(\sum x_i\right)^2} \quad (2)$$

In equations (1) and (2) N is the number of temperature reading and i is the i^{th} reading. Bulk fluid heater (4) and air heater (7) were used to heat the air surrounding the copper block and reduce the heat loss. A support disc (10) was used to trap the air around the copper block to minimize mixing with the air in the room. A condensing coil (2) was used to minimize the loss of fluid during the experiments. This important feature helped maintain a constant concentration throughout the experiment time when boiling the nanofluids. The water flow rate through the condensing coil was regulated through a needle valve. Two opposing glass side windows (6) allowed visual observation of the boiling phenomenon on the surface from the side. A top window (5) also allowed visual observation on the boiling surface from above.

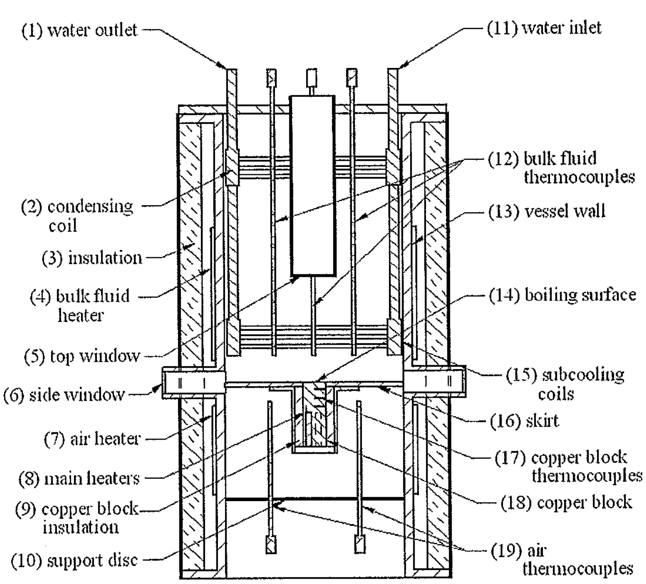
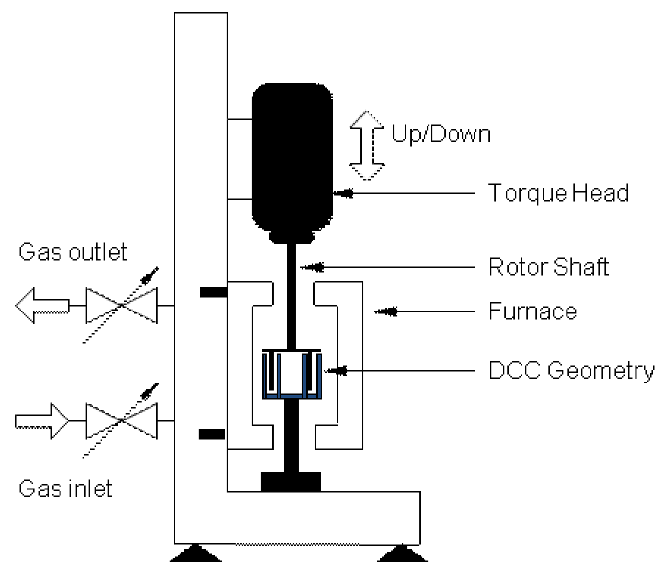


Figure 1 Schematic of the boiling vessel

The boiling surface 3D profile was examined using a Zygo White Light Interferometer. The surface was positioned under the interferometer to scan an area of 1.09 X 1.45 mm. The resolution used was 640 X 480 pixels for the scanned area. The interferometer was used with MetroPro 8.1.5 software to capture the image on a personal computer. The software generated a 3D image of the surface, and determined the average surface roughness of the scanned area. The software evaluated the average surface roughness of the scanned area in both the x and y directions. Measurements were carried out at five different spots on the boiling surface before and after each experiment to represent the average surface-roughness of the surface. The initial average surface roughness was kept constant at 50 nm. Concentrated HCl was added to the nanofluid to change the pH value and Dynamic Light Scattering (DLS) technique was used to measure the cluster size of the alumina nanofluid.

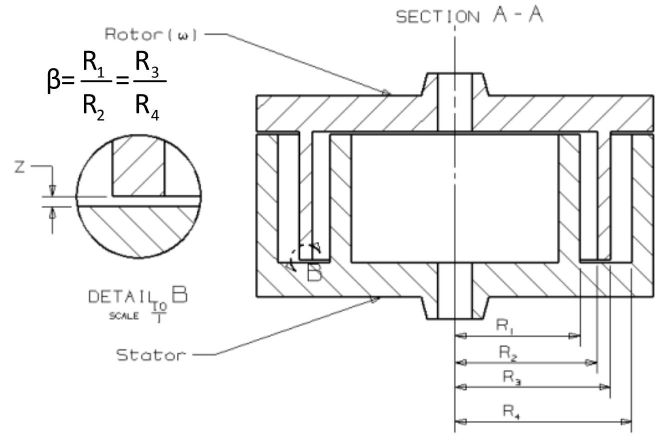
Rotational rheometer

An AR-2000‡ rheometer was used to evaluate the nanofluid rheological properties and the schematic of the experimental arrangement and the geometry are shown in Figure 2. The details of the rheometer and the geometry were explained in a recent publication [16]. In the present study, the shear rate was increased from 0 to 120 s^{-1} and back to 0 each in 2 minutes for the entire cycle, each experiment was repeated six times. The first experiment was carried out after 5 h of sonicating time. The experiments were individually carried out for 1, 2, 3 and 4 vol. % alumina concentrations in water at room temperature after subjecting the nanofluid to various sonicating times ranging from 5 to 140 h.



(a)

‡ Advanced Rheometer, TA Instruments, New Castle, DE, USA http://www.tainstruments.com.



(b)

Figure 2 Schematic of (a) rotational rheometer, and (b) Cross-section of Double Concentric Cylinder (DCC) measurement geometry

The evaluation of the shear stress equation (3) and shear rate equation (4) from the torque and angular velocity, respectively was carried out using the analytical solutions derived for the measuring geometry [16].

$$\tau = \frac{\left(1+\beta^2\right)T}{4\,\pi\,H\left(R_1^2+R_3^2\right)} \qquad (3)$$

$$\dot{\gamma} = \frac{2\,\omega\,\beta}{1-\beta^2} \qquad (4)$$

In equations (3) and (4), τ is the shear stress, $\dot{\gamma}$ is the shear rate, T is the measured torque, ω is the angular velocity, and β, H, R1 and R3 are dimensions of the measurement geometry as shown in Figure 2(b). The viscosity, η of the fluid was measured as the ratio of τ over $\dot{\gamma}$.

The surface morphology of the alumina particle was analysed by using Scanning Electron Microscope (SEM) JEOL JSM-7000F. The sample for SEM was taken from 0.1 vol% alumina nanofluid after two different sonicating times of 5 and 95 h. A small amount of solution was taken out of the glass bottle and poured on top of a metal stub and allowed to dry in atmospheric temperature.

RESULTS AND DISCUSSION

The effect of pH value on deionized water on HTC is shown in Figure 3. In Figure 3, the (T_s-T_{sat}) is called as nanofluid surface superheat temperature and T_{sat} is the boiling temperature of the nanofluid. Figure 3 shows that the pH value reduced from normal (pH=6.5) to acidic (pH=5) as the HTC reduced to 20% and could be attributed to the change in surface tension and thermal conductivity [13]. Hydrocholoric acid has a higher surface tension and lower thermal conductivity than water.

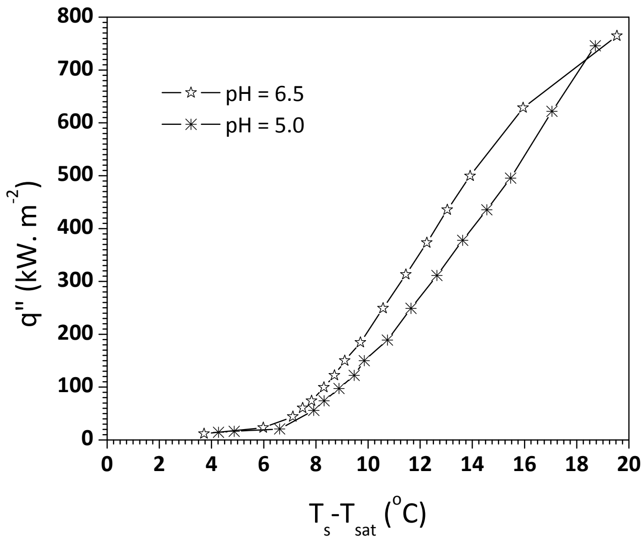


Figure 3 Heat transfer coefficient in the effect of superheat temperature for different pH value of deionized water

Figure 4 shows that the cluster size of the nanofluid with 0.1 vol % alumina decreased with increasing sonicating time. In this study the particle size used was 40 – 50 nm, the cluster size was approximately 4 to 5 times higher than the initial particle size. The cluster size was reduced to around 85 nm after 5h of sonicating time.

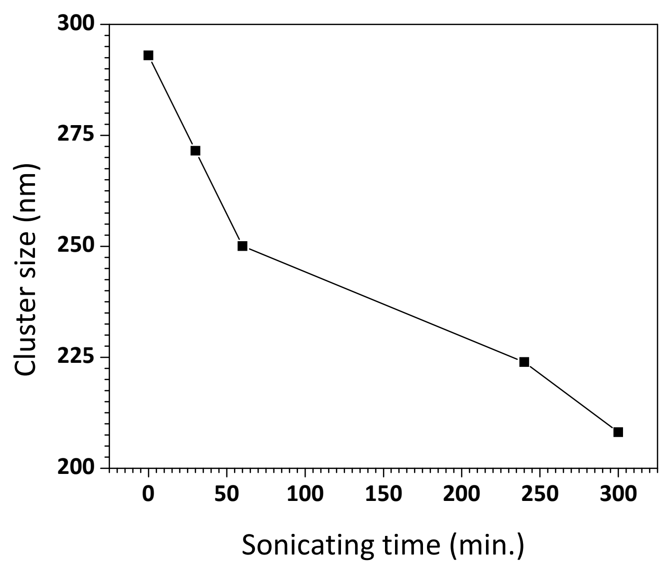


Figure 4 Variation of cluster size of nanofluid with 0.1 vol% alumina for various sonicating times.

The cluster size reduced when the pH value of the nanofluid changed from 6.5 to 5 as shown in Table 1. The mobility of small particle will be higher than the large particle in the fluid which may bring about micro-convection of the fluid and hence increase the heat transfer [17]. Therefore, the solution with pH=5 resulted in a higher HTC compared to that with pH=6.5 as shown in Table 1. The copper surface roughness at the end of the experiment was observed to be lesser for the nanofluid with pH=5 than for that with pH=6.5.

Table 1 Heat transfer coefficient, average post boiling surface-roughness, and effective particle size in the effect of pH value

pH value	HTC % of water @ 15°C	Average post-boiling surface roughness (nm)	Cluster size (nm)
Neutral (6.5)	55	6970	215
Acidic (5)	70	430	180

In this study it was observed that the cluster size reduced when pH value reduced from 6.5 to 5 which is in agreement with the past findings of electrostatic stabilization [18]. This reduction in the cluster size affected the deposition rate of the nano-clusters on the copper plate which in turn changed the surface roughness as shown in the Table 1. It is clear that large clusters were deposited faster on the copper surface and gave high surface roughness compared with the small clusters. The small clusters increased the HTC significantly at 15°C superheat temperature as shown in Table 1. Though the pH value was changed from 6.5 to 5 the HTC reduced in the deionized water as shown in Figure 3. However, when nano alumina was added to deionized water, nanofluid of pH value 5 resulted in high HTC than neutral (pH=6.5) nanofluid. It was confirmed that the reduction in the cluster size significantly increased the HTC of the solution. It was also observed that cluster size reduced with increasing sonicating time as shown in Figure 4. Therefore, sonication time is one of important parameters in the nanofluid preparation.

Figure 5 shows that the flow curve for various volume fraction of alumina in water and it was observed that increasing the volume of the alumina nano-particle increased the viscosity of the nanofluid due to the increased inter-particle friction forces. Also, nanofluid (1 to 4 vol % alumina) behaved as a Newtonian fluid.

Figure 6 (a) to (d) shows flow curve as an effect of the sonicating time, where it was observed that the slope of the curve decreased with increasing sonicating time which implies the viscosity decreased with increased time.

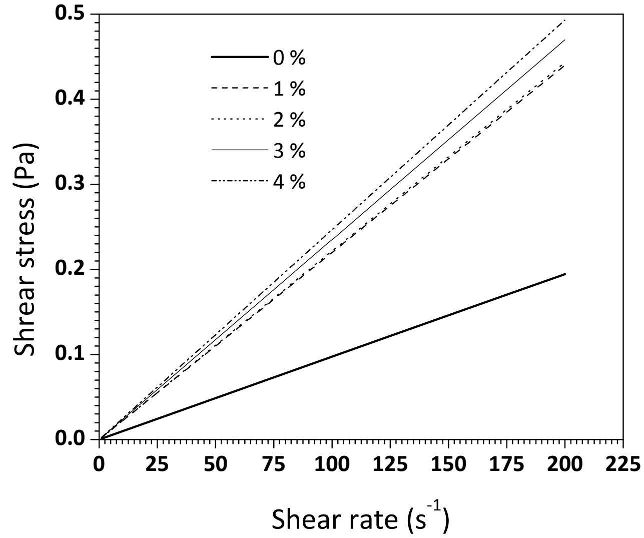
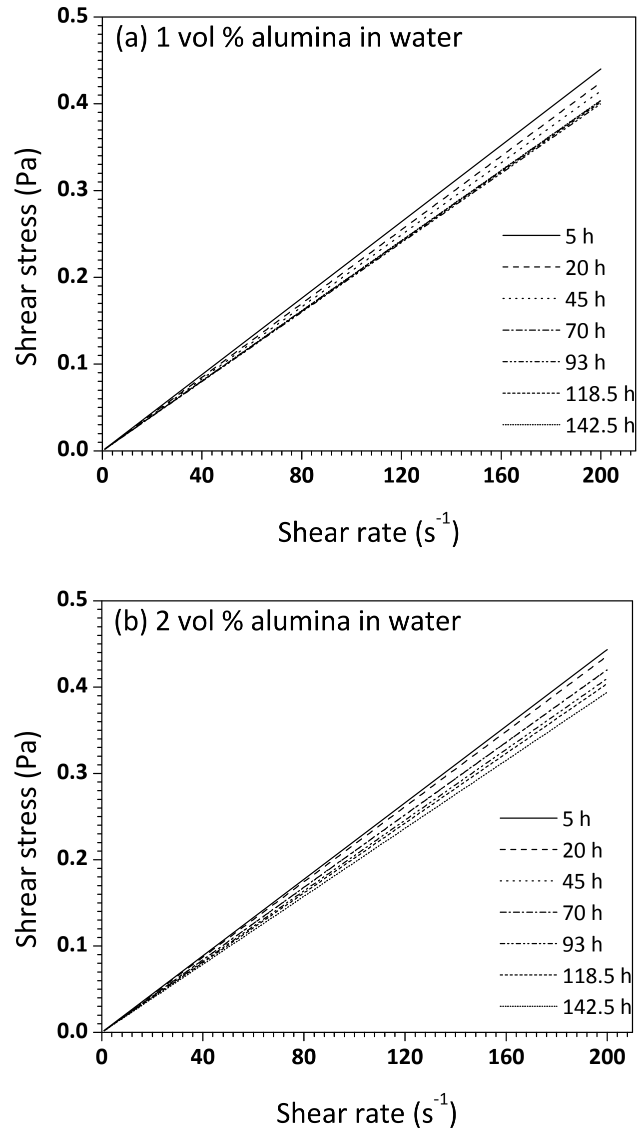


Figure 5 Flow curve of nanofluid of 0 to 4 vol% alumina in water.



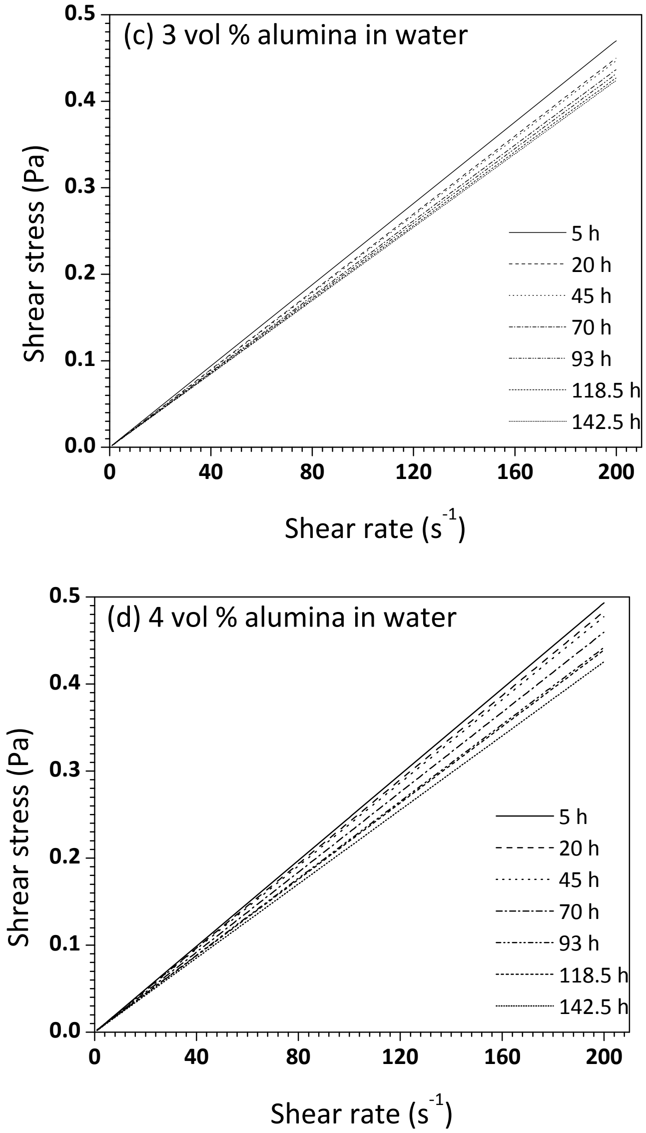


Figure 6 Flow curves for (a) 1, (b) 2, (c) 3 and (d) 4 vol % alumina in water nanofluid as a function of the residence time in the ultrasonic vibrator.

It is clear from Figure 6 (a) to (d), that all the flow curves follow the simple Newtonian fluid behaviour relationship shown in equation (5).

$$\tau = \eta\dot{\gamma} \qquad (5)$$

The viscosity, η increased with increasing volume fraction of alumina in the nanofluid and decreased with increasing sonicating time of the nanofluid as shown in Figure 7.

Figure 8 (a) and (b) shows the microstructure of the nanoparticle with 5 and 95h sonicating times of the 1 vol % alumina in water solution, respectively. In Figure 8 (a) and (c), after 5 h of sonicating time, several nanoparticle clusters of alumina was observed in the nanofluid. These clusters were about four to five times the size of the nano-particle. After 95 h of sonicating time, as shown in Figure 8 (b) and (d), the clusters disintegrated and the nano-particles were predominantly individual in the solution. Therefore, in Figure 6 (a), the flow curves and viscosity of the nanofluid was measured to be a constant after 93 hours of sonicating time. However, after 95 h of sonicating time, as shown in Figure 8 (b) and (d), the individual nano-particles began to fragment as shown by the cracks in them and the distortion of their spherical morphology which could be attributed to the inter-particulate collisions during ultrasonic vibrations.

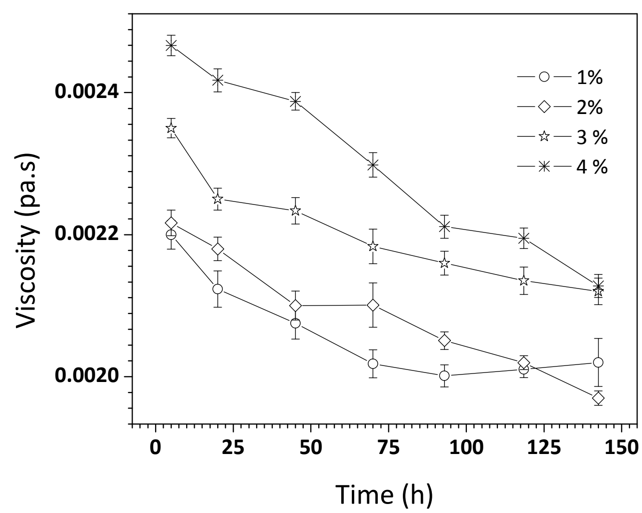
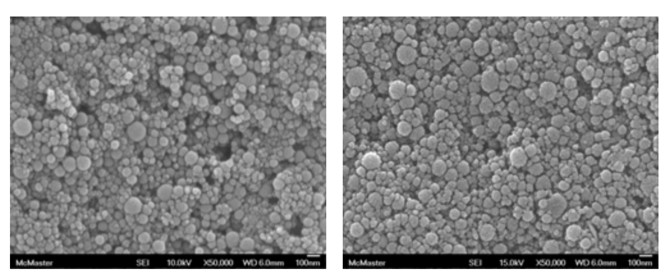
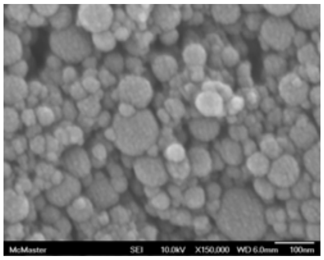


Figure 7 Viscosity, η of the alumina water nanofluid as a function of the residence time in the ultrasonic vibrator.

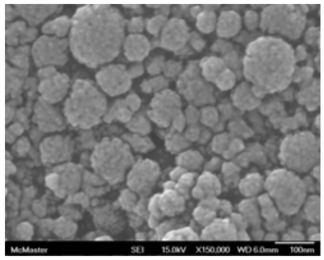
Due to fragmentation, the average size of the nano-particles continuously decreased and produced low friction between the nano-particles in the fluid and the viscosity reduced as shown in Figure 7. The particle size affects the Brownian motion which is one of the important parameters in the nanofluid that will affect the thermal conductivity [19]. Small particles have high Brownian motion compared to large particles in the bulk fluid. From Figure 8 it was apparent that the cluster and particle size decreased with increasing sonicating time, thus increasing the Brownian motion of the particle and hence, increasing the thermal conductivity of the nanofluid.



(a) (b)



(c)



(d)

Figure 8 Morphology of the alumina nano particles obtained from 0.1 vol% nanofluid with different sonicating time (a) 5 h and (b) 95 h. Figure (c) and (d) are the higher magnification images of (a) and (b), respectively

Most research in the alumina nanofluid is focusing in the area of cooling nuclear reactors, transportation, and electronics. The present study shows that the property of the alumina nanofluid is affected by the sample preparation such as modifying the pH and residence time in the ultrasonic vibrator during preparation of the nanofluid.

CONCLUSION

It was observed that the cluster size of the alumina in the nanofluid decreased with increasing sonicating time and decreasing pH value of the fluid. The heat transfer coefficient increased with decreasing number and size of alumina particle clusters in the nanofluid. Nanofluids with alumina between 1 and 4 vol% in water behave as Newtonian fluids and the viscosity increased with increasing particle concentration and decreased with increasing sonicating time.

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