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RHEOLOGY OF CuO NANOPARTICLE SUSPENSION PREPARED BY ASNSS

H. Chang[1], C. S. Jwo[2], C. H. Lo[1], T. T. Tsung[1], M. J. Kao[1] and H. M. Lin[3]

[1] Department of Mechanical Engineering, National Taipei University of Technology, Taipei, 10608, Taiwan, R.O. C.
[2] Department of Air-Conditioning and Refrigeration Engineering, National Taipei University of Technology, Taipei, 10608, Taiwan, R.O. C.
[3]Department of Materials Engineering, Tatung University, Taipei, 10452, Taiwan, R.O. C.

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Abstract. In this study, a low-pressure control method for an arc-submerged nanoparticle synthesis system (ASNSS) was proposed and developed for CuO nanoparticle fabrication. This study investigates into the rheology of CuO nanofluid having different mean particle sizes. Experimental results indicate that the pH value of the CuO nanofluid fabricated in this study is 6.5, which is far smaller than isoelectric point (i.e.p) of pH 10. The CuO nanofluid with larger mean particle sizes has a larger shear stress when the shear rate of different mean particle sizes are the same. Moreover, the smaller the mean particle size of the CuO nanofluid, the higher its viscosity is because of the larger the specific surface area, and the electrostatic force between particles would also be increased.

1. INTRODUCTION

Nanoscale science and technology has attracted global attention particularly in the last three years and is becoming a frontier area of research. The advancement of nanoscience and technology has not only been stimulating the exploration of new phenomenon and new theory in science, but it also has been leading to industrial revolutions and consequently, becoming a new driving force for the economic growth in the 21st century. The thermal conductive efficiency of the nanofluid is inversely proportional to the size of the particles [1]. A maximum increase in thermal conductivity of approximately 20% was observed in the study for 4 vol.% of CuO nanoparticles with average diameter of 35 nm dispersed in ethylene glycol [2].

Furthermore, the effective thermal conductivity has shown to increase up to 40% for the nanofluid consisting of ethylene glycol with approximately 0.3 vol.% Cu nanoparticles of mean diameter less than 10 nm [3]. In addition, when the nanofluids are in high electric potential, their thermal conductivity would be increased [4]. Carrying an excellent thermal conductivity, CuO nanofluid can be used in machine tools as a highly effective circulation fluid. When the machine tool is in motion, the rheology of nanofluid would affect the performances of the circulation fluid. Thus, it is very important to investigate the rheology of the nanoparticle suspension.

According to the basic principles of the gas condensation method, this study has developed a vacuum Arc-Submerged Nanoparticle Synthesis System (ASNSS) for preparing nanoparticle suspension. The experiment device mainly comprises a heating system, an ultrasonic system, a pressure control system, and a temperature control system.

Corresponding author: Ho Chang, e-mial: f10381@ntut.edu.tw

The nanoparticles thus produced are dispersed in deionized water, which helps reduce the aggregation phenomenon upon particle collection and avoids particle powder spray.

The nature of rheology refers to the flowing or transforming behavior of substances in light of external forces. Affecting by the action of shear stress, the internal of fluid would create a velocity gradient, and the relationship between the two is indicated as the following equation:

$$\tau = A\gamma^{n}, \quad (1)$$

where τ is the shear stress, and γ is the velocity gradient or shear rate. If A is a constant and n=1, then such kind of fluid can also be known as Newtonian Fluid. Besides, the proportional constant A is called the viscosity of fluid, which can be viewed as a resistance against the fluid owing to the friction occurred between the inner particles. Suppose the relationship between τ and γ is a non-linear one, such kind of the fluid is a non-Newtonian Fluid, which can be subdivided into the pseudoplastic fluid (n<1) and dilatant fluid (n>1). The A value of pseudoplastic fluid would decrease along with the increase of shear rate, whereas that of the dilatant fluid would increase along with the increase of shear rate [5,6]. If the fluid can begin to flow only when the exerting shear stress has exceeded a certain value, such shear stress value is called the yield stress of fluid. The relationship between the shear stress and shear rate of fluid can also be further sub-divided into linear (Bingham fluid) and non-linear (pseudoplastic and dilatant) ones.

The prepared nanoparticles were characterized for microstructural properties by the Transmission Electron Microscope (TEM, JEOL JSM-1200EX2). The dry nanoparticle powders could be obtained by heating the particle suspension with an appropriate temperature. The zeta potential of the nanoparticle suspension was measured using zeta potential analyzer (Zeta Plus,Brookhaven Instruments Co.). The Particle Size Distribution (PSD) of the nanoparticles was acquired by dynamic light-scattering measurement (Horiba-LB500). The rheology of CuO nanofluid was measured using the rheometrics dynamic analyzer.

2. EXPERIMENTAL

This study has developed a combined vacuum Arc-Submerged Nanoparticle Synthesis System (ASNSS) for preparing nanoparticle suspension and has investigated into the properties of nanoparticle [7-9]. In the process, a bulk metal applied as the electrode is submerged in dielectric liquid in a vacuum chamber. Applied electrical energy then produces heating source for generating an adequate arc with a high temperature ranging from 6000 to 12000 °C. In the development process, a copper bar is melted and vaporized in deionized water, which is used as an insulating liquid. In addition, the dielectric liquid is vaporized by part of the submerged arc rapidly while the metal electrodes are heated. Water vapor with high pressure is generated by the inertia force of the surrounding dielectric liquid (deionized water). The vapor promotes effectively a rapid removal of the vaporized aerosol from the electrodes. Then, the vaporized aerosol present in the dielectric liquid changes its current phase state through the nucleating, growing and solidifying stages, and eventually becomes metal nanoparticles dispersed in the dielectric liquid. This study integrates the ultrasonic vibration system in ASNSS. The main function of ultrasonic vibration is to increase the stability of the electric arc. In addition, the energy released by the ultrasonic vibration can generate minute disturbance and impact on the discharge fusion zone, which makes the gasified metal easier to be removed from the fusion zone and be quickly cooled down by the low-temperature dielectric fluid surrounding it, thereby obtaining smaller nanoparticles. The CuO nanoparticles synthesized using the proposed method are of a suspension type, meaning they are dispersed in the fluid (deionized water). The nanoparticle suspension synthesized by the proposed method using better process variables already demonstrate good dispersion and even without dispersant, they can still remain in stable suspension for a fairly long time. In other words, the nanoparticle suspension prepared by this study is readily usable for subsequent research or application purposes.

This study investigates into the rheology of CuO nanofluid having different mean particle sizes [10]. Besides, Eq. (1) is applied to formulate the relationship between the shear stress and shear rate, so as to fit the experimental data of rheology of the nanoparticle suspension acquired by different process parameters. Subsequently, we acquire the values of A and n in Eq. (1) which demonstrates the rheological curves.

3. RESULTS AND DISCUSSION

Because oxygen exists in deionized water, the nanoparticles are easily oxidized. The suspension nanoparticle may be oxidized continuously in deionized water. Table 1 shows the experimental parameters deployed in the study. The morphology of the

Table 1. Process variables of CuO nanofluid preparation by means of ASNSS.

Working condition	Description
Current (A)	9
Voltage (V)	220
Tool polarity	positive
Pressure of chamber (Torr)	30
Ultrasonic frequency (kHz)	19.8
Amplitude of Ultrasonic vibration (μm)	4
pulse-duration time (μs)	12
pulse-off time (μs)	12
Diameter of electrode (mm)	12.7
Capacity of cooling media (L)	0.3
Temperature of cooling mediums (°C)	0
Working time (hr)	0.5

Fig. 1. TEM image of CuO nanoparticles produced in deionized water.

CuO nanoparticles prepared in deionized water reveals a needle-like structure, with an average width of 20 nm and length of 80 nm (shown as in Fig.1). It is clear that its particle size distribution is uniform and well dispersed in deionized water.

Fig. 2a shows the rheology of CuO nanofluid with different mean particle sizes. As can be seen, the CuO nanofluid with larger average particle sizes has a larger shear stress when the shear rate of different mean particle sizes are the same. In Fig. 2a, the shear stress of CuO nanofluid with mean particles size of 30 nm and 75 nm would increase along

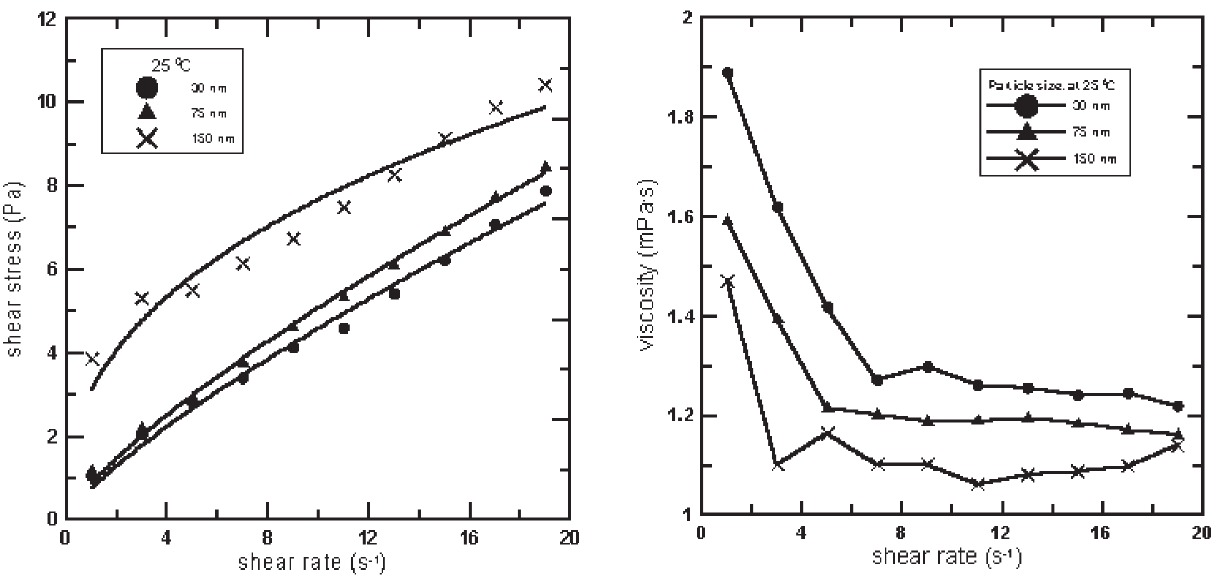

Fig. 2. Rheology of CuO nanofluid (a) and relationship between viscosity and shear rate of CuO nanofluid with different mean particle sizes.

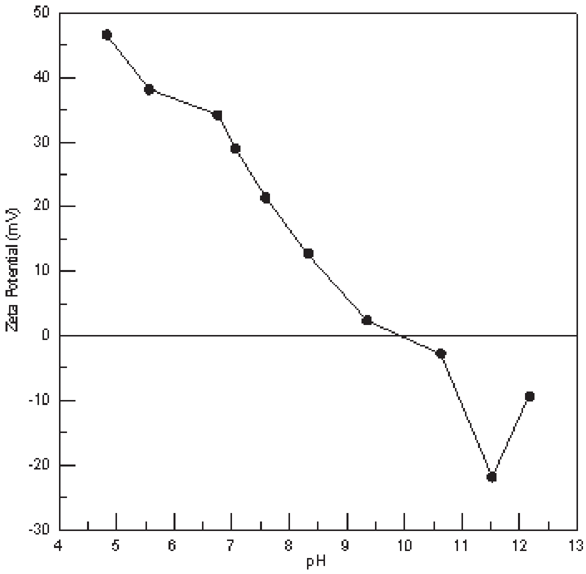

Fig. 3. Relationship between the pH value and Zeta potential of CuO nanofluid.

with the increase in shear rate, and such kind of nanofluid can be regarded as pseudoplastic fluid. Moreover, the CuO nanofluid having an average particle size of 150 nm can be regarded as pseudoplastic fluid having a yield stress. Moreover, by fitting the experimental data obtained from mean particle sizes of 30, 75, and 150 nm into Eq. (1), the *A* and *n* values are 0.75807, 0.87158, and 0.76607, as well as 0.78249, 3.10883, and 0.39257, respectively. Fig. 2b shows the relationship between viscosity and shear rate of the CuO nanofluid with different mean particle sizes. As can be seen, when the shear rate is smaller than 5 s^{-1}, the viscosity of CuO nanofluid would rapidly drop. In other words, when the CuO nanoparticle exists in the deionized water, it would affect the flow of the nanofluid, causing the viscosity to increase. The concentration of the nanofluids with different mean particle sizes are the same. The figure shows the smaller the mean particle size of the CuO nanofluid, the higher its viscosity. On the contrary, when the shear rate is larger than 5 s^{-1}, there is no apparent change in the viscosity of CuO nanofluid, indicating that it remains at a relatively steady level. As to the CuO nanofluid having a mean particle size of 30 nm, when the shear rate is smaller than 4 s^{-1}, its viscosity is higher than the CuO nanofluids having the mean particle size of 75 and 150 nm. It is because the smaller the particle size, the larger the specific surface area is, and the electrostatic force between particles will also be increased, ultimately causing the increase in viscosity. Fig. 3 shows the relationship between the pH value and Zeta potential of CuO nanofluid. When the pH value of nanoparticle suspension is 10, the Zeta potential is 0 mV (i.e.p), but when the pH value is smaller than 10, it becomes a positive value. From this, when the pH value is far greater or smaller than 10, the particles can hardly agglomerate because the nanoparticle suspension has a higher surface potential, thus yielding particles of a smaller size. The pH value of the CuO nanofluid fabricated in this study is 6.5, which is far smaller than the i.e.p (pH 10). Therefore, the fabricated CuO nanofluid carries the characteristics of highly stabilized and dispersed suspension.

4. CONCLUSIONS

According to the basic principles of the gas condensation method, this study has developed a vacuum Arc-Submerged Nanoparticle Synthesis System (ASNSS) for preparing CuO nanoparticle suspensions. From the experimental results and the discussion above, the following conclusions are made.

(1) The CuO nanoparticle suspension already possesses good dispersion; and even without dispersant, they can still remain in stable suspension for a fairly long time.

(2) The CuO nanofluid with larger mean particle sizes has a larger shear stress when the shear rate of different mean particle sizes are the same. Moreover, the smaller the mean particle size of the CuO nanofluid, the higher its viscosity is because of the larger the specific surface area, and the electrostatic force between particles would also be increased.

(3) The pH value of the CuO nanofluid fabricated in this study is 6.5, which is far smaller than i.e.p of pH 10. Therefore, the fabricated CuO nanofluid shows highly stabilized and dispersed suspension.

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