Critical Heat Flux (CHF) Enhancement of the Nanofluids by the Electrical Explosion of Wire in Liquids(EEWL) Process

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ABSTRACT

Nanofluids, dispersed nanoparticles in base fluids, have been drawing the attention as heat transfer fluid for enhancement of the critical heat flux (CHF). The enhancement of CHF contributes to increase the safety margin of the thermal system. In this study, the water-based Ag, CuO, and Al_2O_3 nanofluids were produced by the electrical explosion of wire in liquids. We have been performed pool boiling experiments to characterize the CHF enhancement of the produced Ag, CuO, and Al_2O_3 nanofluids. It is observed that the change of surface morphology contributed to the CHF variation of these metallic nanofluids. The surface characterisitics of the heating wire was observed using field-emission scanning electron microscopy after pool boiling experiment to identify the change of surface properties.

Keywords: Electrical explosion of wire in liquids(EEWL), Critical heat flux(CHF), Nanofluids

1 INTRODUCTION

Nanofluids, which contain dispersed nanoparticles in base fluids such as water, ethylene glycol, and polymer solutions, have drawn tremendous interest from the scientific and industrial communities [1-3]. One of the most interesting characteristics of nanofluids is the enhancement of the critical heat flux(CHF). Nanofluids have significantly increased in the nucleate boiling critical heat flux at low concentrations[4, 5]. The CHF enhancement caused by nanofluids has been studied by many researchers for different nanofluids and concentrations. Common consensus of CHF enhancement is that the surface properties such as morphology and wettability are changed by the deposited nanoparticle layers on wire heater.

The fabrication method of the nanofluids can be catagoized as the one-step method and two-step method. The two-step method forms nanoparticles using physical or chemical techniques and dispersed them in base fluid. The one-step method forms nanoparticles directly in the base fluid. A promising one-step method, physical synthesis technique, is the electrical explosion of wire in liquids (EEWL). The EEWL process has advantages, such as high-purity nanoparticle production without surfactants, oxidation control by using various media, and mass production.

In this study, various water-based metallic nanofluids were fabricated using the EEWL process. These nanofluids were characterized using the zeta potential and high-resolution transmission electron microscopy (HR-TEM). Pool boiling experiments were also performed to characterize their CHF enhancement. The morphologies of heating wire surface were observed using field-emission scanning electron microscopy (FE-SEM). To identify the relationship between wettability and CHF enhancement, we measured the contact angle on heating wire.

2 EXPERIMENTAL SETUP

2.1 Preparation of nanofluids

A experimental system for manufacturing nanofluids is shown in Figure 1. The pure Al, Cu, and Ag wire of 100 ㎛ in diameter was installed in a cylinder filled with distilled water. The capacitor was charged to 3kV, and pulsed current flowed through the when the spark-gap switch was closed. High temperature plasma was generated by the electrical energy deposited in the wire and was condensed by the base fluid.

2.2 Pool boiling experiment

The EEWL apparatus consisted of a rectangle vessel, a teflon cover, a reflux condenser to maintain the volume concentration of the working fluid during boiling, two copper electrodes, and a power supply. A horizontally suspended NiCr wire was located between two electrodes.

Figure 1:Experimental setup for the EEWL process

The experiments were conducted in a stabilized atmosphere at a saturated temperature of about 100℃. Power was supplied to the NiCr wire until the CHF was reached. The power was increased in a small step as the heat flux approached the CHF.

3 RESULT AND DISCUSSION

3.1 Characteristics of nanofluids

Figure 2 shows the shape and size of nanoparticles produced by EEWL. All nanofluids were prepared at 0.001% vol. The Ag nanoparticles produced through the EEWL process were spherical in shape, and only one phase existed. However, the phase of the other nanoparticles differed from the phase in the wire used for the explosion. Cu and Al nanopacticles facilitate reaction with oxygen in the water. Energy dispersive spectroscopy (EDS) results for the oxygen content of the Al_2O_3 and CuO nanofluids are shown in Table 1.

To compare the phase of the Al_2O_3 alumina nanofluids manufactured by EEWL, we prepared the Al_2O_3 (40-80nm in diameter) nanofluids by the two-step method. The atomic ratio of aluminum and oxygen of the Al_2O_3 alumina nanofluids manufactured by EEWL was 57.7:42.3. This ratio of composition is almost same with common Al_2O_3 particles. The Al_2O_3 nanoparticles manufactured by EEWL were spherical in shape and had smooth surfaces compared to that of the Al_2O_3 nanoparticles manufactured by the two-step method. Furthermore, the dispersion of the Al_2O_3 nanoparticles manufactured by EEWL was superior to that of the two-step Al_2O_3 nanoparticles. Average size and zeta potential of nanoparticles produced by EEWL is summaerized in Table 2.

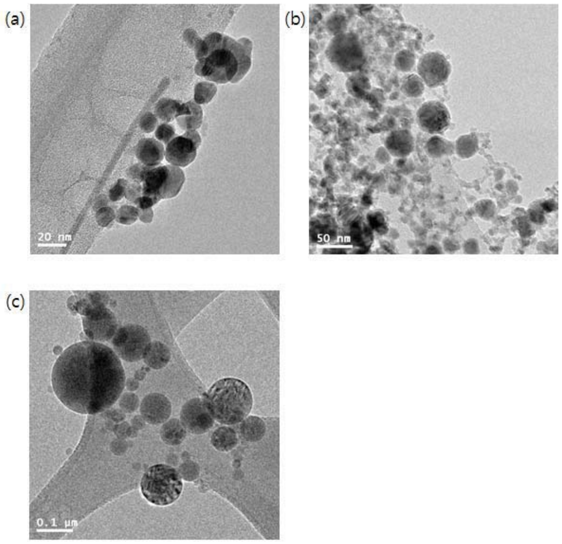
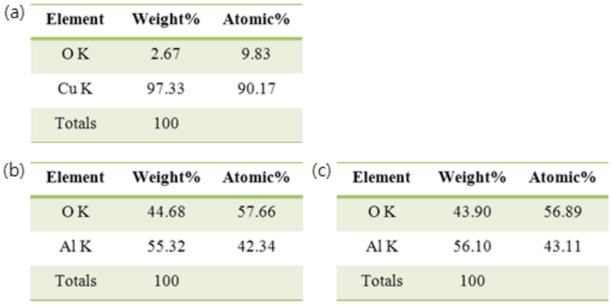


Figure 2: TEM images of various nanofluids, such as (a) Ag, (b) CuO, and (c) Al_2O_3 nanofluids manufactured by the EEWL process



(a)

Element	Weight%	Atomic%
O K	2.67	9.83
Cu K	97.33	90.17
Totals	100	

(b)

Element	Weight%	Atomic%
O K	44.68	57.66
Al K	55.32	42.34
Totals	100	

(c)

Element	Weight%	Atomic%
O K	43.90	56.89
Al K	56.10	43.11
Totals	100	

Table 1: EDS results of (a) CuO, (b) Al_2O_3 (one-step), and (c) Al_2O_3 (two-step) nanofluids

Type	Avg. nanoparticle size(nm)	Zeta potential(mV)
Ag nanofluids	123.5	–37
CuO nanofluids	160	26
Al_2O_3 nanofluids (one-step)	345.5	37.4
Al_2O_3 nanofluids (40-80nm) (two-step)	608	26.9

Table 2: Average size of nanoparticles and zeta potential of four different metallic nanofluids

3.2 Results of pool boiling experiment

The EEWL Al_2O_3 nanofluids showed the largest CHF enhancement of 187% at 0.001 vol%. In comparison, two-step Al_2O_3 nanofluids showed only 108% enhancement. The CHF of the Ag nanofluids was enhanced by 58% over pure water, while the CHF of the CuO nanofluids was enhanced by 99%.

The CHF enhancement can be explained by the surface roughness, deposited layer structure, and the wettability of the heater surface. Figure 3 shows the deposited nanoparticles on the heating surface after pool boiling experiment. The surface of the heater wire showed build-up and disordered structures. The deposition of nanoparticles was caused by nucleate boiling. Changing the surface structure can improve the CHF by separating the liquid and vapor paths. The surface roughness and wettability is changed by deposition structure of nanoparticles and materials properties. In case of the Al_2O_3 nanofluids manufactured by EEWL, the deposited surface was relatively uniform compared to that of the Al_2O_3 nanofluids by two-step.

The deposited nanoparticles on the heater surface significantly improved the wettability. According to the Wenzel model [6], the contact angle was affected by the surface tension, the adhesion tension, and the roughness factor(the ratio of the effective contact area to the smooth contact area). A porous surface with oxide nanoparticles increased the adhesion tension and roughness factor, reducing the contact angle:

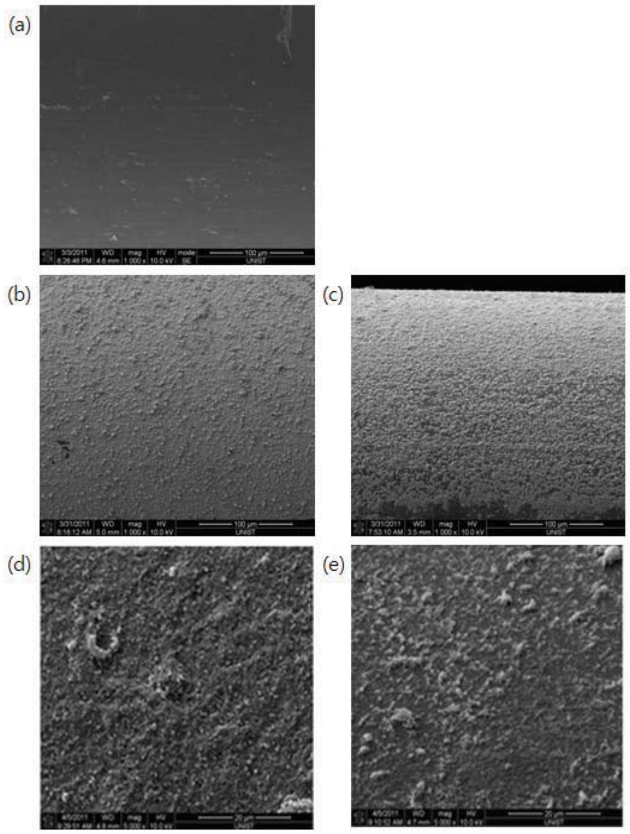


Figure 3: Surface Morphology of the wire heater after pool boiling experiment, (a) pure water, (b) Ag, (c) CuO, (d) Al_2O_3 (one-step), and (e) Al_2O_3 (two-step) nanofluids

Kandlikar's CHF model is a well-known prediction model that incorporates surface conditions. This model is based on the force balance on a bubble[7]. Thus, Kandlikar's model includes both bubble and contact angle parameters.

Figure 4 compared the experimental and theoretical CHF results. The hot/dry spot theory of Kandlikar supports the idea of CHF enhancement due to increasing surface wettability. This result is in accord with the trend of the theoretical results. Although the wettability of the Al_2O_3 nanofluids manufactured by EEWL was similar to that of the two-step Al_2O_3, the CHF enhancement was much higher because the Al_2O_3 nanofluids manufactured by EEWL was very pure and well dispersed.

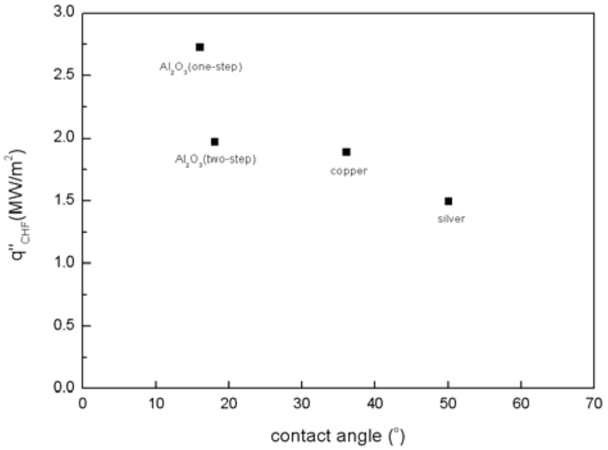


Figure 4 : Experimental result of CHF and contact angle on wire surface after pool boiling experiment for four metallic nanofluids

4 CONCLUSION

We produced Ag, Cu, and Al_2O_3 nanofluids from electrical explosions of wires in liquid using pure Ag, Cu, and Al wires. The metallic nanoparticles produced by EEWL were spherical in shape and had smooth surfaces. Compared with metallic nanofluids produced by the two-step method, the nanofluids manufactured by EEWL were well dispersed in the base liquid. We also performed pool-boiling experiments using the Ag, CuO, and Al_2O_3 nanofluids produced by EEWL. The Ag, CuO, and Al_2O_3 nanofluids show significant CHF enhancement during boiling experiments: 187% at 0.001 vol% for Al_2O_3, 58% at 0.001 vol% for Ag, and 99% at 0.001 vol% for CuO nanofluids.

Nanoparticles were deposited on the heater during pool boiling. Nanoparticles reduce the number of active nucleation sites while changing the surface roughness. Therefore, the deposited nanoparticles improved the wettability because there is the reduction of contact angles of the surfaces after metallic nanofluids boiling compared with surfaces after pure water boiling. The higher wettability increased the CHF enhancement, according to both theoretical and experimental observations. The more dispersed nanofluids produced by EEWL exhibited greater CHF enhancement than nanofluids produced by the two-step method.

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