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Sorption and agglutination phenomenon of nanofluids on a plain heating surface during pool boiling

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Abstract

The pool nucleate boiling heat transfer experiments of water (H_2O) based and alcohol (C_2H_5OH) based nanofluids and nanoparticles-suspensions on the plain heated copper surface were carried out. The study was focused on the sorption and agglutination phenomenon of nanofluids on a heated surface. The nanofluids consisted of the base liquid, the nanoparticles and the surfactant. The nanoparticles-suspensions consisted of the base liquid and nanoparticles. The both liquids of water and alcohol and both nanoparticles of CuO and SiO_2 were used. The surfactant was sodium dodecyl benzene sulphate (SDBS). The experimental results show that for nanofluids, the agglutination phenomenon occurred on the heated surface when the wall temperature was over 112 °C and steady nucleated boiling experiment could not be carried out. The reason was that an unsteady porous agglutination layer was formed on the heated surface. However, for nanoparticles-suspensions, no agglutination phenomenon occurred on the heating surface and the steady boiling could be carried out in the whole nucleate boiling region. For the both of alcohol based nanofluids and nano-suspensions, no agglutination phenomenon occurred on the heating surface and steady nucleate boiling experiment could be carried out in the whole nucleate boiling region whose wall temperature did not exceed 112 °C. The boiling heat transfer characteristics of the nanofluids and nanoparticles-suspensions are somewhat poor compared with that of the base fluids, since the decrease of the active nucleate cavities on the heating surface with a very thin nanoparticles sorption layer. The very thin nanoparticles sorption layer also caused a decrease in the solid–liquid contact angle on the heating surface which leaded to an increase of the critical heat flux (CHF).

Keywords: Nanofluid; Boiling; Sorption; Phase-change

1. Introduction

Nanofluid technology has emerged as a new enhanced heat transfer technique in recent years. Choi [1] firstly proposed the concept of "nanofluid", which is actually nanoparticles-suspension. A number of studies have been carried out to understand and describe the larruping behaviors of nanofluid, such as its effective thermal conductivity under the static conditions [2–6], the convective heat transfer associated with fluid flow and transfer phenomena [7–14] and phase-change heat transfer [15–20]. Most investigations indicated that the addition of nanoparticles could greatly increase the effective thermal conductivity with increasing the nanoparticles concentration. Therefore, so far, the studies concerning nanofluids focused mainly on the single phase convective heat transfer of nanofluids flowing in tubes to enhance the forced convective heat transfer by use of the increased thermal conductivity.

Compared with the research effort in thermal conductivity and forced convective heat transfer, relatively few studies have been carried out on pool boiling heat transfer.

Das et al. [15] conducted an investigation on the pool boiling of water–Al_2O_3 nanoparticles-suspension on horizontal tubular heater having diameter of 20 mm with different surface roughness at atmospheric pressure. The heat flux ranged from 2×10^4 W/m^2 to 1.2×10^5 W/m^2. No surfactant was added into suspensions. It was found that the nanoparticles-suspensions have poor heat transfer compared with pure water. Surface roughness could also

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Nomenclature

$c_{p,l}$	specific heat (J/kg K)
D	diameter of heat transfer surface (m)
h	heat transfer coefficient, (W/K m^2)
h_{fg}	latent heat of evaporation (J/kg)
p	pressure (Pa)
q_w	wall hat flux (W/m^2)
$q_{c,0}$	CHF of saturated water (W/m^2)
Ra	mean roughness, $\mathrm{Ra} = \frac{1}{L}\int_0^L \lvert Z(x)\rvert \mathrm{d}x$
Rq	standard roughness, $\mathrm{Rq} = \sqrt{\frac{1}{L}\int_0^L Z(x)^2\,\mathrm{d}x}$
x	axial position (m)
Z	orthogonal position (m)
ΔT_{sat}	wall superheat (K)

Greek symbols

λ	thermal conductivity (q/m^2 K)
ν	kinematics viscosity (m^2/s)
σ	surface tension (N/m)
ρ	density (kg/m$^{3)}$

Subscripts

l	liquid
v	vapor

greatly affect the nucleation superheat. The required superheat for a smooth surface was usually higher than that for a rough surface. When the volume concentration of nanoparticles was higher than 0.1%, the effect was well-regulated in their experimental conditions, and the superheat for high concentration nanoparticles-suspensions was higher than that for low concentration nanoparticles-suspensions at a specified heat flux. The subsidence of nanoparticles was considered as the main reason for the increase of superheat.

Vassallo et al. [16] carried out a pool experiment of silica–water nanoparticles-suspensions on a horizontal NiCr wire at atmospheric pressure. No surfactant was added into suspensions. An increase in critical heat flux (CHF) was observed compared with pure water. But, no appreciable differences in the boiling heat transfer were found for the heat flux less than the CHF.

Bang and Cheng [17] conducted an investigation on the pool boiling of water–Al_2O_3 nanoparticles-suspensions on a plain heated plate at atmospheric pressure. The test surface is a 4 × 100 mm^2 rectangle with a depth of 1.9 mm. As the cases of the two studies above mentioned, no surfactant was added into suspensions in their experiment. It was found that the boiling heat transfer characteristics of the nanoparticles-suspensions were poor compared with pure water in nucleate boiling region. For the horizontal test surface, however, the CHF increased 32% compared with the pure water case. These were related to a change of the surface characteristics by the deposition of nanoparticles on the heating surface.

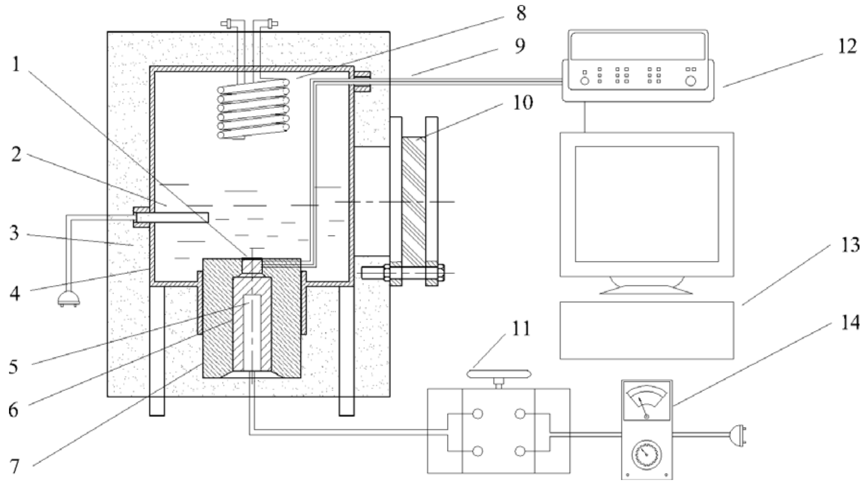
You et al. [19] carried out an investigation on the CHF of water–Al_2O_3 nanoparticles-suspensions in a pool boiling experiment with a flat square heater at the pressure of 2.89 Psia ($T_{\mathrm{sat}} = 60$ °C). The experimental results demonstrated that the CHF increases dramatically two times compared with pure water. However, the nucleate boiling heat transfer coefficients appeared to be about the same.

The above review of literature indicates that relatively few studies have been reported on the pool boiling of nanoparticles-suspensions or nanofluids on a plate surface and there exist some deficiencies in these studies. Firstly, in the most of the experiments, no surfactant was added into the suspensions. In fact, these kinds of suspensions have poor stability and uniformity because of great aggregate structures. These kinds of suspensions cannot be applied for actual engineering. Secondly, even in these few studies, there are some controversial results for boiling heat transfer and the CHF. Thirdly, the kinds of nanofluids used in the literature are few. Fourthly, although the most researchers guessed that the changes of the heating surface characteristics were main reasons which affected the boiling heat transfer of nanofluids, no visual microphotographs on the surface characteristics were shown to support their guesswork.

In order to understand the boiling heat transfer characteristics of nanofluids more extensively, the poor boiling behavior of both nanofluids and nano-suspensions are studied on a horizontal flat surface. The key objective of this experiment is to understand the sorption and agglutination phenomenon of nanofluids and nanoparticles-suspensions and their effects on pool boiling heat transfer. The visual microphotographs on the surface characteristics were shown to recover the mechanism of the boiling heat transfer of the nanofluids on a flat heating surface.

2. Experimental apparatus and procedures

Fig. 1 shows the schematic diagram of the experimental apparatus. The apparatus mainly consisted of a main vessel, an outer isothermal vessel, a heated copper block, an electronic supply and a digital data connecting system. The main vessel made of stainless steel had a diameter of 250 mm and a height of 400 mm. The upper part of the main vessel was a water tank to contain the working liquid and the lower part of the vessel was a closed heating box to mount the heater component. The heater component was a vertical copper bar having 80 mm diameter and 120 mm height. The copper bar was inserted into a vertical Teflon bar and the Teflon bar was mounted in the heating box. The space inside the outer isothermal vessel was filled by



1 heat transfer surface
2 auxiliary heater
3 adiabatic material
4 test vessel
5 main heater
6 copper column
7 tefflon column
8 condenser
9 thermocouples
10 observe window
11 transformer
12 HP data acquisition
13 computer
14 temperature controller

Fig. 1. Schematic diagram of the experimental apparatus.

asbestos. The main heater was a cartridge electric heater which was inserted into the cooper bar. The top horizontal surface of the copper bar with diameter of 20 mm was smooth and used as the heat transfer surface in this experiment. Three $\varnothing$1.0 mm thermocouples were horizontally inserted at the center axial line of the upper column of the copper bar. The distances between the thermocouples were 3.0 mm and the distance between the top thermocouple and the heat transfer surface was 2.0 mm. Signals from these thermocouples were measured by a digital voltmeter (Agilent-34970A) and then fed into a computer, which converted them to the wall temperature and wall flux The wall temperature and the wall heat flux were calculated according to the linear relation of the temperature differences and distances between the surface and the three thermocouples by Fourier's Law. One of the temperature signals was fed into a PID temperature controller as a feed back signal, which adjusted the power supply. Prior to each run, the working liquid was boiled for one hour to drive out any dissolved gases by using the auxiliary heater. After the test run started, the auxiliary heater was switched off. All of the measurements were performed in steady state. An alarm thermocouple inserted at the bottom of the copper bar was connected to a temperature controller that prevented the maximum temperature of the copper bar from exceeding 750 °C. In this experiment, it has been confirmed that the assumption of one-dimensional heat conduction was well satisfied in the upper column of the copper bar by a numerical simulation and the measurement results. Experiment was first carried out from the lowest to the highest heat flux and it was again carried out in the reverse direction to eliminate the possibility of the case hysteresis exists. At each run, the wall flux was increased at an increment of about 100 kW/m^2. After the temperatures got stable, the data were saved and the wall flux was given another increase. This process was repeated till the temperatures couldn't keep stable any more. It meant that the CHF point was got across. Then the heat flux was increased in an increment of 10 kW/m^2 (about 1.0% of the former power) till the unstable temperature appeared once more. Saved the data, and the CHF could be calculated from them.

In the present experiment, both pure water and chemical pure alcohol were used as the base fluids, and the sodium dodecyl benzene sulphate (SDBS) was used as surfactant. Both CuO nanoparticles with an average diameter of 50 nm and SiO$_2$ nanoparticles with an average diameter of 35 nm were added into the base fluids to make suspensions. In order to differentiate the kinds of the working liquids, the working liquids consisted of base fluid, nanoparticles and surfactant was called as nanofluids, and the working liquids consisted of base fluid and nanoparticles was called as nanoparticles-suspensions. The mass concentration of nanoparticles changed from 0.2 wt% to 2 wt%, while the volume concentration of SDBS was fixed at 0.5%. Before each test, the nanoparticles, surfactant and the base fluid were put into a super-sonic water bath and surged for about 12 h to prepare the working liquids. The experimental results showed that the stability and uniformity of nanofluids were good at least in one month. The stability and uniformity of nanoparticles-suspensions were poor. However, during pool boiling, the suspensions could maintain good uniformity due to the disturbance effect of bubbles.

The calibration errors of the thermocouples were less than 0.2 K. The maximum location deviation between thermocouples was about 0.01 mm. The maximum uncertainties of the wall superheat and wall heat flux were about 4% and 6%.

3. Experimental results and discussions

3.1. The boiling characteristics of the water based nanofluids and nano-suspenssions

Fig. 2 shows the boiling experimental results for water, two water based CuO nanofluids and one water based CuO suspension under atmospheric pressure. The nanofluids consisted of water, 0.5% SDBS and CuO nanoparticles having, respectively, 0.5 wt% and 1 wt%. The suspension consisted of water and 0.5 wt% CuO nanoparticles.

It is found that the saturated temperatures of the nanofluids and suspensions decreased about 1–2 K compared with that of pure water due to the adding of nanoparticles and SDBS. In order to compare the boiling heat transfer among water, nanofluids and suspensions, the saturated temperatures of pure water (100 °C) was taken as the uniform standard of the saturated temperatures for both nanofluids and suspensions.

It can be observed that pool boiling heat transfer coefficient and the CHF of water agree reasonably well with Eq. (1) by Kutateladze [20] and Eq. (2) by Zuber [21]. The deviation of CHF is lower than 4%. The boiling curve of water increased fast at the boiling incipience, and then tended to superpose the Kutateladze curve. The maximum deviation of wall flux at the boiling incipience point is about 100%. The deviation at the latter part is below 20%

$$\frac{h}{\lambda_l}\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}} = 7.0\times10^{-4}Pr_l^{0.35} \times\left[\frac{q_w}{\rho_v h_{fg} v_l}\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}}\right]^{0.7} \times\left[\frac{p}{\sigma}\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}}\right]^{0.7} \quad (1)$$

$$\frac{q_{c,0}}{h_{fg}\rho_v^{0.5}[\sigma g(\rho_l-\rho_v)]^{1/4}} = 0.131 \quad (2)$$

For the CuO nanoparticle-suspension, its boiling heat transfer is close to that of water. In the natural convective boiling regime, the heat transfer for the CuO nanoparticles-suspension is somewhat lower than that of water, whereas in the fully developed boiling regime, the heat transfer for the CuO nanoparticles-suspension is somewhat higher than that of water. The CHF of the CuO nanoparticles-suspension increases about 27% compared with that of water. Summing the above mentioned, an increase in the CHF was observed compared with pure water. But, no appreciable differences in the boiling heat transfer for heat flux less than the CHF.

For the CuO nanofluids, when the wall superheat was lower than 12–14 K (the wall temperature was lower than 112–114 °C), the steady wall temperatures corresponding to the different heat flux could be measured, and the boiling curves could be obtained as shown in Fig. 2. However, when the superheat was higher than 12–14 K, the wall temperatures showed strongly undulation with an amplitude about ±2 °C and the steady boiling curve could never be obtained any more. If restarted the run from the lowest heat flux, the run was still unsteady and the steady boiling curve could not be obtained. This phenomenon indicated that some irreversible characteristics change had taken place on the heating surface.

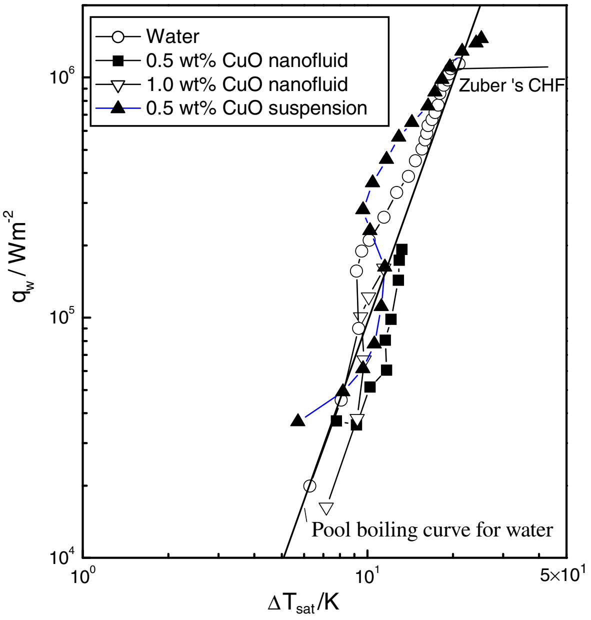


Fig. 2. Boiling experimental results for the water based CuO nanofluids and suspensions.

Similar to the cases of using CuO particles, Fig. 3 shows the boiling experimental results for the 0.5 wt% SiO_2 nanofluid and 0.5 wt% SiO_2 nanoparticles-suspension under atmospheric pressure.

For the SiO_2 nanoparticles-suspension, it has poorer heat transfer than pure water in all nucleate boiling. The CHF increased about 18% compared with pure water. These experimental results of SiO_2 particles suspension are qualitatively the same as the pool boiling experiment using water–Al_2O_3 nanoparticles-suspensions reported by Das et al. [15], Vassallo et al. [16] and Bang and Cheng [17]. In their experiments, the boiling heat transfer of water- Al_2O_3 nanoparticles-suspensions had a poorer heat transfer than that of water.

The present experimental results show that the materials of the used nanoparticles have significant effect on the boiling heat transfer and the CHF. Since thermal conductivity of CuO is much larger than those of SiO_2 and Al_2O_3, the

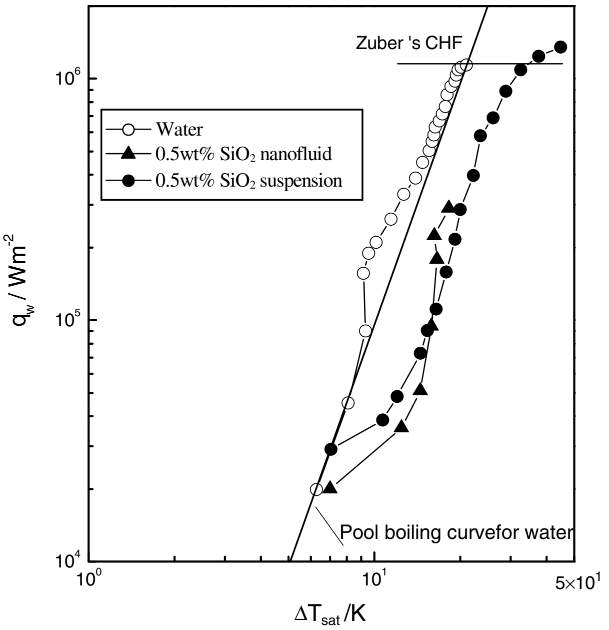


Fig. 3. Boiling experimental results for the water based SiO_2 nanofluids and suspensions.

boiling heat transfer of water–CuO suspensions are better than those of water–Al_2O_3 and water–SiO_2 suspensions.

For the SiO_2 nanofluids, as the case using CuO nanofluids, when the wall temperature was lower than 112 °C, steady boiling curves could be obtained as shown in Fig. 3. However, when the wall temperature was higher than 112 °C, the wall temperatures would present strongly undulation and the steady boiling curve could never be obtained.

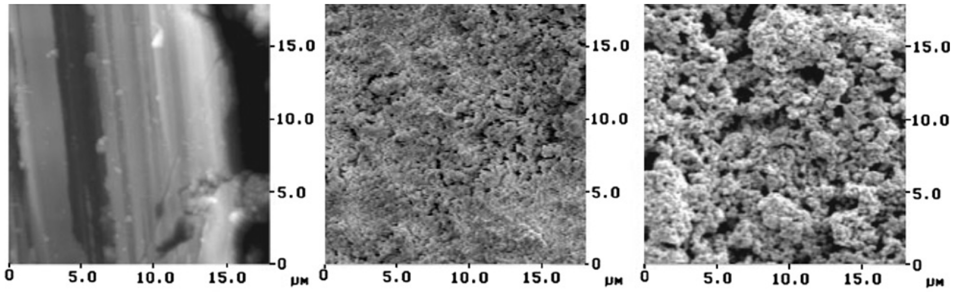
By Eq. (1), the boiling heat transfer of the nanofluids and nanoparticles-suspensions should be much better than that of water due to that the thermal conductivities of the nanofluids and nanoparticles-suspensions are bigger than that of water either for CuO or SiO_2. However, the present experimental results as well as all previous experimental results of nano-suspensions in literature [15–19] are contrary to the expectation by Eq. (1). The reason should result from the change of the heating surface characteristics.

3.2. The surface characteristics after nanofluids and nano-suspensions tests

Fig. 4 shows the microphotographs of the heating surface status after the boiling tests by a field emissive scanning electric microscope (FEI SIRION 200), respectively, for water based CuO nanoparticles-suspensions and CuO nanofluids.

For the surface after the test using water, the surface was smooth and had a metallic brilliancy. The surface was slightly oxidized.

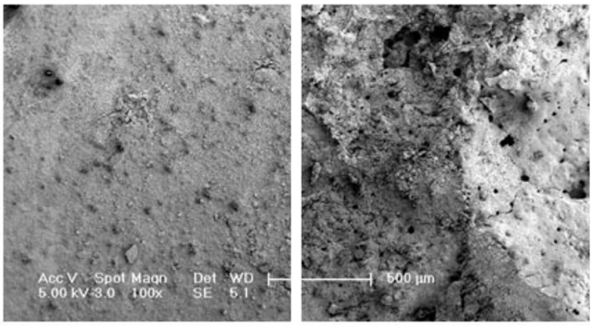
For the surface after the test using CuO nanoparticles-suspension, there existed a thin sorption layer formed by nanoparticles on the surface as shown in Fig. 4. The thickness of the sorption layer was about several ten micrometers.



copper surface before boiling experiment

surface state after boiling experiment of CuO nanofluid (4000x)

surface state after boiling experiment of CuO nanoparticles-suspension



surface state after boiling experiment of CuO nanofluid (left) and nanoparticles-suspension (right) (100x)

Fig. 4. Photographs of the heating surface after the water, CuO suspensions and CuO fluids tests.

The sorption layer could be cleaned out by water jet. However, after the surface was cleaned by water jet, the heating surface was still covered by a very thin, smooth, block coating layer, which should be formed by the nanoparticles tapped in the cavities on the copper surface shown in Fig. 5.

For the surface after the test using CuO nanofluids, there existed a quite thick, solid, porous agglutination layer formed by the mixture of the SDBS and the nanoparticles on the surface as shown in Fig. 4. The thickness of the agglutination layer was measured by an atomic force microscope and it was about several hundred micrometers. The agglutination layer could not be cleaned out by water jet. It could be observed that there existed many remnant marks of the dropped agglomerates on the agglutination layer as shown in Fig. 4 (100 × photograph). According to the photograph of the agglutination layer, we can guess the reason why the boiling experiments could not continue when the wall temperature was over about 112 °C for the experiments using nanofluids. After the wall temperature was over about 112 °C, an unsteady agglutination layer was formed on the heating surface. Since the thickness of the agglutination layer irregularly changed due to the agglomerates irregularly dropped from the surface, the heat resistance between the copper surface and the working liquid changed also irregularly. Therefore, the measured wall temperature was in an irregular change and the steady boiling curve could not be obtained.

After boiling tests using the CuO suspension, the surface were cleaned by water jet Fig. 5 shows the 2D and 3D atomic force microscope (Nanoscope IIIa) microphotographs of the surface status, after the leaning process. It can be observed that the sorption layer has been cleaned out, but surface was still covered by a very thin nanoparticles coating layer with a maximum thickness of 500 nm, which should be formed by the concentrated nanoparticles tapped in the cavities on the copper surface.

According to Figs. 4 and 5, it was firmed that a very thin nanoparticles coating layer would bond on the copper surface after boiling experiment using the nanoparticles-suspensions.

After boiling tests using the nanofluids and nano-suspensions, the surface were cleaned by water jet, then the elements distributions were measured by an energy spectrum instrument (OXF DRD INCA). Fig. 6 shows the elements distribution charts on the both surfaces. For the surface after a nanofluid test and a cleaning process, the main elements in the agglutination layer are O, Cu and S, which are from the CuO nanoparticles and SDBS. For the surface after a suspension test and cleaning process, the main elements in the coating layer are O and Cu, which are only from the CuO nanoparticles.

Das et al. [15] reported that a reduction in the surface roughness had taken place after the boiling test using nano-suspensions. Since the size of the nanoparticles are one to two orders of magnitude smaller than the roughness of the copper surface, the particles sit on relatively uneven surface during boiling. They guessed that the decrease of the surface roughness decreases the boiling heat transfer of the nanoparticles-suspensions. In the present experiment, the same phenomenon was also observed. Fig. 7 shows the comparison of the surface roughness between the both surfaces after the boiling test using water and nano-suspensions. It is clear that the surface roughness after the nanoparticles-suspension test was greatly smaller than that after the water test.

Summing the words above, the steady boiling experiments using the nanoparticles-suspensions can be carried out. The boiling heat transfer of the nanoparticles-suspensions is opposite to their properties and deteriorates compared with that of water. However, the steady boiling experiments using the nanofluids cannot be carried out when the wall temperature is over about 112 °C. The reasons for these conflicting performances may be related to differences in the surface characteristics after the boiling tests using different working liquids. For the nanoparticles-suspensions, two reasons may decrease the boiling heat transfer. One is the decrease of the surface roughness due to the formation of the sorption layer on the heating surface which decreases the active nucleation. Another is the increase of the heat resistance between the heating surface

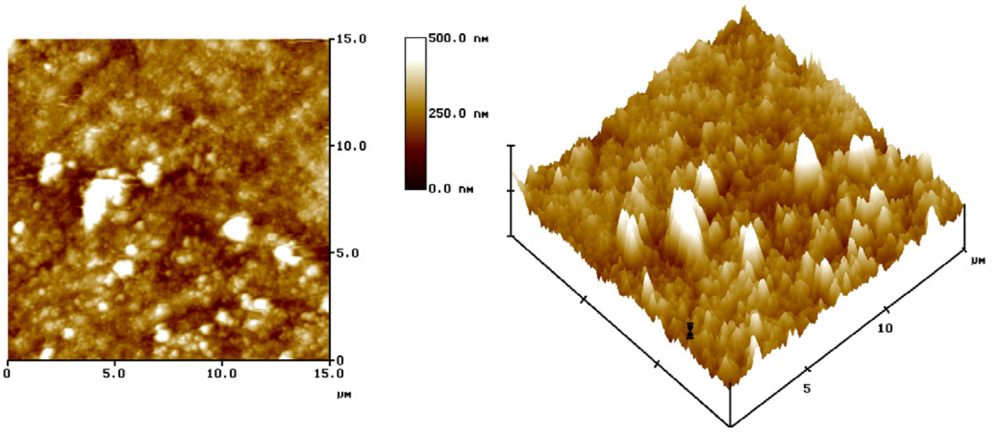
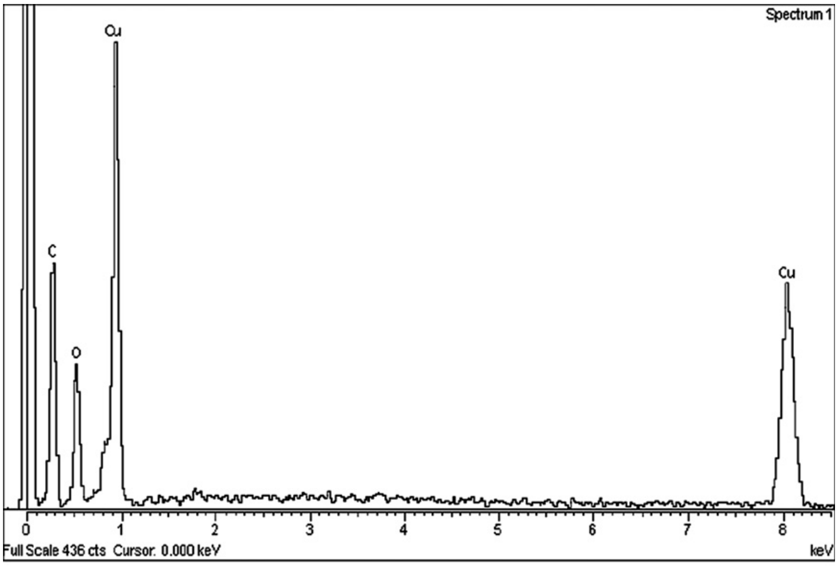
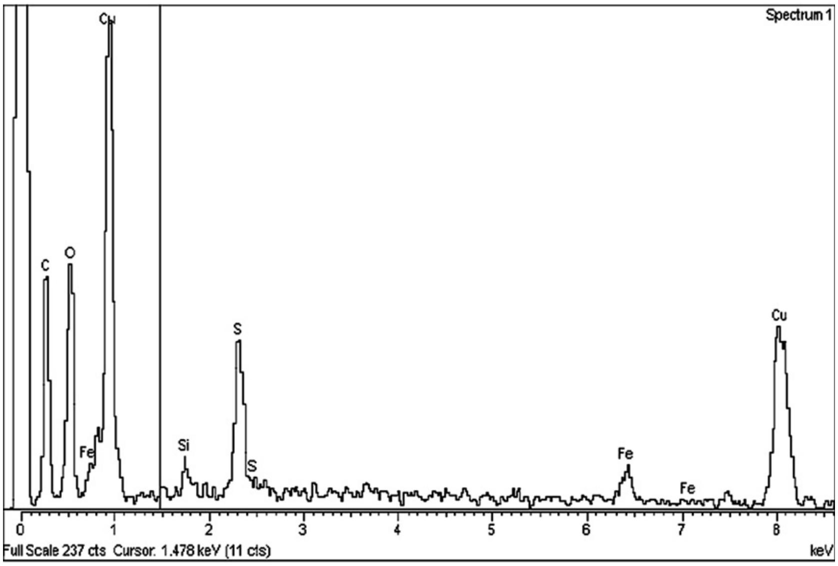


Fig. 5. 2D and 3D microphotographs of the surface status after CuO suspension test and cleaning process.

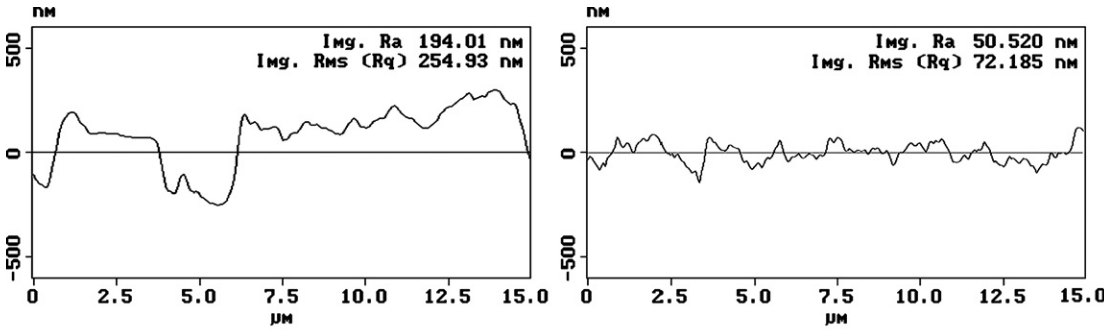


(a) nano-suspension



(b) nanofluids

Fig. 6. The energy spectrum charts on the both surfaces after the nanofluid and nano-suspension tests and the cleaning process.



(a) Surface after water test

(b) Surface after the CuO nano-suspensions

Fig. 7. The roughness of the surface roughness after water and the CuO suspension tests.

and the working liquid which results also from the formation of the sorption layer. The effect of the thermal conductivities of the working liquids on the boiling heat transfer is secondary. On the other hand, for the water based nanofluids, since the porous agglutination layer on the surface was formed by the mixture of SDBS and the nanoparticles, the wall temperature was in an irregular change and the steady temperature measurements could not be carried out.

The present CHF data as well as the CHF data in literature [15–19] indicated that the CHF of nanoparticles-suspensions boiling increases compared with that of water. The increased values are related to the materials of nanoparticles. In pool boiling, except the effect of the liquid properties on the CHF as predicted by Eq. (2), the CHF values are also affected by the various surface characteristics, such as the solid–liquid contact angle. Bang and Cheng [17] guessed that the reason on the CHF performance change might due to the surface coating effect. The present microphotographs shown in Figs. 4 and 5 supported this guessing. The sorption layer on the copper surface would decrease the active nucleation and the contact angle. Less active nucleation and contact angle would generate fewer bubbles, then less coalescence or large vapor blankets to interfere with the supply of liquid to the surface. As shown in Figs. 4 and 5, the sorption layer also gives the causes of the CHF enhancement for trapping of liquid near the heating surface due to porous characteristics of the sorption layer, breaking up the void near the heating surface and preventing blanketing from easily occurring. Generally, the value of contact angle may be used for estimating the effect of the surface characteristics on the CHF [22]. In the present experiment, the contact angle was measured by means of sessile drop method in room temperature. The contact angle for the fresh copper surface was between 45° and 70°; the contact angle for the surface after the nanoparticles-suspensions tests was between 15° and 30°. No appreciable differences were found for different nanoparticles-suspensions.

3.3. The boiling characteristics of the alcohol based nanofluids and nanoparticles-suspensions

In order to investigate the effect of surfactant in the nanofluids on the boiling heat transfer at relatively low wall temperatures under atmospheric pressure, the alcohol based nanofluids and nanoparticles-suspensions were also used as the working liquids in the present experiment.

Fig. 8 shows the boiling experimental results for the nanofluid consisted of alcohol, 0.5% SDBS and 0.5 wt% CuO and the suspension consisted of alcohol and 0.5 wt% CuO. It is also found that the saturated temperatures of the nanofluids and suspension decreased about 1–2 K compared with that of chemical pure alcohol due to the adding of nanoparticles and SDBS. In order to compare the boiling heat transfer among the base fluid, nanofluids and nanoparticles-suspensions, the saturated temperatures of chemical pure alcohol (78 °C) was taken as the uniform standard of the saturated temperature for both nanofluids and nanoparticles-suspensions. It can be observed that pool boiling heat transfer and the CHF of alcohol agree reasonably well with Eq. (1) by Kutateladze [20] and Eq. (2) by Zuber [21].

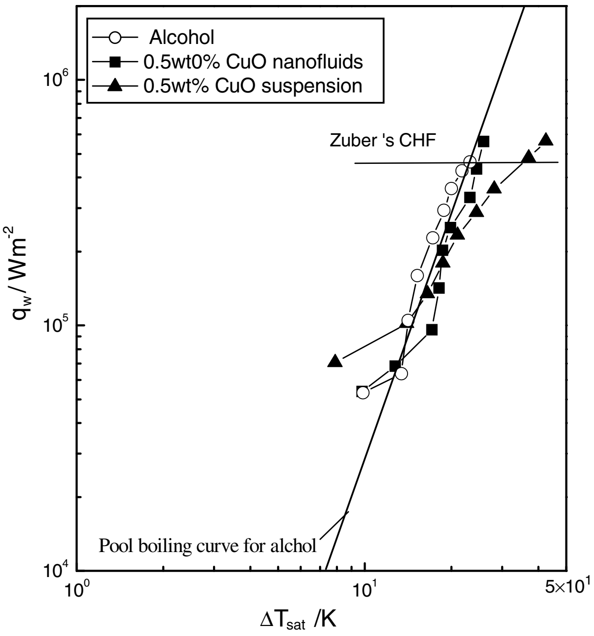


Fig. 8. Boiling experimental results for the alcohol based CuO nanofluids and suspensions.

No significant differences are found between the boiling heat transfer of the CuO nanoparticles-suspension and the CuO nanofluid. Their boiling heat transfer is somewhat lower than that of alcohol. The CHFs of the suspension and nanofluid are also close to each other, and increase about 31% compared with that of alcohol. No meaningful effect of surfactant is found on the boiling heat transfer.

Fig. 9 shows the boiling experimental results for the nanofluid consisted of alcohol, 0.5 wt% SiO_2 and 0.5% SDBS and the nanoparticles-suspension consisted of alcohol and 0.5% SiO_2. The experimental results are similar to those using CuO particles. No significant differences are found between the boiling heat transfer of the SiO_2 nanoparticles-suspension and the SiO_2 nanofluid. The CHFs of the suspension and nanofluid are also close to each other, and increase about 20% compared with that of alcohol. Their boiling heat transfer coefficients are significantly lower than that of alcohol.

The heat transfer surface was observed after each experiment. It was found that no matter SDBS existed in the fluid or not, there was no agglutination formed on the surface but a sorption layer was found, like the water based nano-suspensions. In the present experiments using the alchol base liquid, the wall superheat corresponding to the CHF was about 30 K and then the wall temperature was about 108 °C (lower than 112 °C). In this case, the boiling could keep stable.

Summing the above words, these experimental results of alcohol based nanofluids are qualitatively the same as those

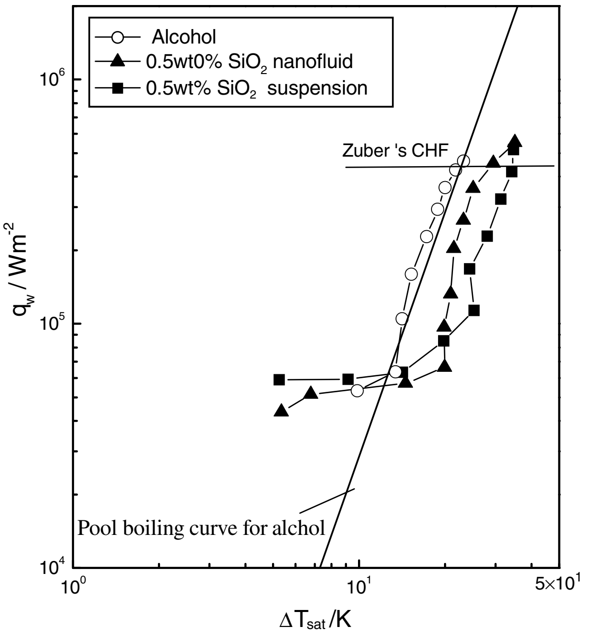


Fig. 9. Boiling experimental results for the alcohol based SiO_2 nanofluids and suspensions.

using alcohol based nano-suspensions. The alcohol based nanofluids can be used for a pool boiling experiment under atmospheric pressure, since its relatively low saturated temperature.

4. Conclusions

1. For the water based nano-suspensions, the boiling curves can be obtained in nucleate boiling regime. The boiling heat transfer is close to or somewhat lower than that of water. The CHF is enhanced compared with that of the base liquids. The materials of the nanoparticles have effect on the boiling heat transfer and the CHF.
2. For the water based nanofluids, the boiling curves cannot be obtained in nucleate boiling regime. When the wall temperature is over 112 °C, the steady wall temperature could never be obtained.
3. For both alcohol based nanofluids and nanoparticles-suspensions, boiling curves can be obtained in nucleate boiling regime. No meaningful differences of the boiling heat transfer are found between both working liquids.
4. For the water based nano-suspensions, a sorption layer is formed on the heating surface during pool boiling. After the sorption layer is cleaned by water jet, there still exists a very thin coating layer on the surface. The surface roughness and the contact angle are decreased due to the formation of the sorption layer.
5. For the water based nanofluids, a solid agglutination layer is formed on the heating surface during pool boiling when the wall temperature was over about 112 °C. Since the thickness of the layer irregularly change due to the agglomerates irregularly drop from the surface, the wall temperature is in an irregular change and the steady temperature measurements could not be carried out.

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