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Heat transfer enhancement of copper nanofluid with acoustic cavitation

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Abstract

Heat transfer characteristics of copper nanofluids with and without acoustic cavitation were investigated experimentally. The effects of such factors as acoustical parameters, nanofluid concentration and fluid subcooling on heat transfer enhancement around a heated horizontal copper tube were discussed in detail. The results indicated that the copper nanoparticles and acoustic cavitation had profound and significant influence on heat transport in the fluid. The addition of copper nanoparticles did not change the dependence of heat transfer on acoustic cavitation and fluid subcooling. The mechanism of heat transfer enhancement of the nanofluids was analyzed.

Keywords: Nanofluid; Acoustic cavitation; Heat transfer enhancement; Boiling hysteresis

1. Introduction

Many efforts have been devoted to heat transfer enhancement with ever increasing demand of cooling ultra high heat flux equipment on one hand and unprecedented pace of miniaturization on the other hand. Among of them, application of additives to liquids is often involved because conventional heat transfer fluids have poor heat transfer properties compared to most solids. In conventional cases, the suspended particles are of μm or even mm orders. Such large particles may cause some severe problems such as abrasion, clogging flow channels, eroding pipelines and increase in pressure drop in practical application. As a result, a clear need exists to develop new strategies for improving the effective heat transfer behavior of conventional heat transfer fluids [1].

The nanofluid appears with development of nanoscience and nanotechnology. It refers to a new kind of heat transfer fluids by suspending nanoscaled metallic or nonmetallic particles in conventional heat transfer fluids. Since nanoparticles offer extremely large total surface areas, the nanofluid exhibits superior thermal properties relative to conventional heat transfer fluids and fluids containing micrometer-sized particles. For example, a greater enhancement up to 40 % in thermal conductivity was recently reported by Eastman et al. [1] for Cu nanofluids with only a 0.3% volume fraction. The large surface-area-to-volume ratio also increases the stability of the suspensions. Thus, the nanofluid becomes a new promising heat transfer fluid in a variety of application cases.

There are only few previous studies involved in describing fluid flow and heat transfer performance of the nanofluids. With the nanofluids as the coolant, Lee and Choi [2] pointed out that the nanofluids dramatically enhanced cooling rates of microchannel heat exchanger compared with the cases of conventional water and liquid-nitrogen coolant. Das et al. [3] investigated the pool boiling characteristics of water–Al_2O_3 nanofluids. They found that the role of transient conduction of nanoparticles in pool boiling was overshadowed due to trapped particles on the heater surface, deteriorating the boiling characteristics of the fluid. Xuan and Li [4] studied convective heat transfer and flow performance of water–Cu nanofluids in a tube. Results showed that

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Nomenclature

C	nanoparticle concentration (g/l)
h	heat transfer coefficient, $q''/(T_w - T_l)$ (W/(m^2 K))
I	sound source intensity, expressed by the current input to the ultrasonic vibrator (A)
L	sound source distance between the vibrator head and the central horizontal plane (m)
q''	heat flux (W/m^2)
T_l	liquid temperature (K)
T_3, T_5	local temperature at upside and downside of the tube (K)
T_w	local wall temperature (K)
T_{sat}	saturation temperature (K)
ΔT_{sat}	wall superheat ($T_w - T_{sat}$) (K)
ΔT_{sub}	fluid subcooling ($T_{sat} - T_l$) (K)

the suspended nanoparticles remarkably enhanced heat transfer process with smaller volume fraction of nanoparticles. Xuan and Roetzel [5] concluded that heat transfer enhancement by copper nanoparticles resulted from the following two aspects: one was that the suspended particles increased the thermal conductivity of the two-phase mixtures; another was that chaotic movement of ultrafine particles accelerated energy exchange process in the fluid. Keblinski et al. [6] indicated that the key factors influencing the thermal properties of the nanofluids were the ballistic, rather than diffusive, nature of heat transport in the nanoparticles, combined with direct or fluid-mediated clustering effects that provide paths for rapid heat transport. As to the heat transfer characteristics of the nanofluids in an acoustic cavitation field, Zhou and Liu [7] confirmed that $CaCO_3$ nanoparticles deposited not only on the upside surface of the copper tube by gravity but also on the downside surface of it by absorption affinity because of its relatively smaller size. It caused the tube surface become smooth, leading to a reduction in both single-phase convection and boiling heat transfer.

Acoustic cavitation refers to the formation of small bubbles and their subsequent growth and collapse within a liquid due to pressure change because of acoustic excitation [8]. The heat transfer enhancement by acoustic cavitation is to utilize energy released from collapsed micro-bubbles activated by ultrasonic wave. Therefore, it is not the same as that by ultrasonic vibration into the liquid. To the knowledge of the author, the applications of acoustic cavitation to enhance boiling heat transfer are scarce in literatures. Wong and Chon [9] studied the boiling heat transfer with acoustic cavitation and indicated that ultrasonic vibrations' effects became negligible in the fully developed nucleate boiling regime. Recently, Zhou and Liu [10] performed an experiment on the effect of acoustic cavitation on boiling heat transfer around a horizontal circular tube. They found that the boiling heat transfer was remarkably enhanced by acoustic cavitation due to the impingement and disturbance of cavitation bubbles, resulting in more effective dissipation of latent heat of vaporization and an increase in actual boiling areas. Subsequently, Zhou et al. [11] investigated theoretically and experimentally the effect of liquid cavitation on boiling heat transfer and concluded that the enhancement of boiling heat transfer by acoustic cavitation mainly depended on whether the vapor embryos was activated by the cavitation bubbles to initiate boiling.

Although the effects of nanoparticles and acoustic cavitation on heat transfer have been studied respectively, very little research has reported the combined effect of these parameters. The objective of this study is to investigate the effects of acoustical parameters, nanofluid concentration and fluid subcooling on heat transfer characteristics around a heated horizontal copper tube. The results of this study will provide a better mechanism understanding of heat transfer enhancement of the nanofluids and hence accelerate its practical application.

2. Experimental apparatus and procedure

The experimental apparatus and instrumentation are shown schematically in Fig. 1. The test chamber consisted of a cubical vessel made of stainless steel with inside dimensions of 200 mm × 200 mm × 230 mm. A horizontal copper tube, with an outer diameter of 20 mm and an inner diameter of 16 mm, was used as the test section. An electrical heating element inside the tube passed through one pair of opposing walls 50 mm above the vessel base. Two viewing windows were installed on opposite sides of the vessel in parallel with the test tube for easy observation and taking pictures of the boiling heat transfer phenomena outside the test section. Eight thermocouples attached to the outer surface of the inner tube were used to measure the surface temperature approximately. Two thermocouples located near the test section were used to measure the liquid pool temperature. Further details about the experimental apparatus and procedure can be found in [11].

The acoustical field was generated with an ultrasonic vibrator, which was operated by the electric current

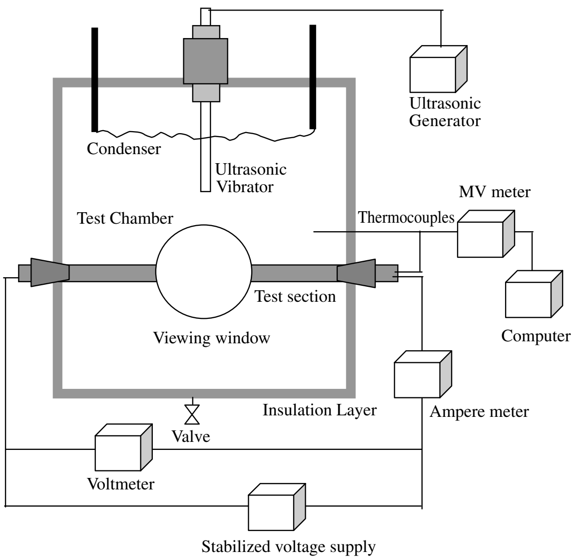

Fig. 1. Schematic layout of experimental system.

from an ultrasonic generator. The intensity of the acoustical field at the region of interested can, therefore, be expressed by three parameters, the ultrasonic source intensity I, the vibrator's location (left side, right side or center) and the distance from the vibrator head to the horizontal plane containing the tube axis (termed the sound distance L). Unless pointed out otherwise, the ultrasonic vibrator was located on the right side of the test section at sound source intensity and distance of 0.3 A and 40 mm. Acetone was employed as the working fluid and always maintained at least 70 mm above the centerline of the test tube with fluid subcooling of 27 K. The uncertainties in heat fluxes and heat transfer coefficients were estimated to be less than ±5.5% and ±6.0%, respectively.

3. Preparation of the nanofluid

The nanofluid is a simple solid–liquid mixture in which metallic or nonmetallic nanoparticles are suspended. There are several approaches to prepare nanofluids, aiming at changing the surface properties of suspended particles and suppressing formation of particles cluster. Among of them, acoustic cavitation is an effective method to produce a stable nanofluid due to ultrasonic vibration in the liquid. Depending on base fluid and particle combination, a number of nanofluids can be produced easily.

In this study, acetone based nanofluid of copper particles with average particle sizes in the 80–100 nm range have been used. The ultrasonic vibrator turned on while copper nanoparticles were added into the pool of acetone. Copper nanoparticles disperse rapidly under the impingement and disturbance of cavitation bubbles cluster and then the working fluid seems to be turbid. With the increasing of the impingement time of cavitation bubbles and nanofluid concentration, the turbidness degree of the nanofluid increased and its color became blue. It usually took half an hour to obtain an even distributed and stabilized nanofluid. It is concluded from observations with naked eyes that the nanofluids are extremely stable and exhibit no significant setting under static condition, even after a week.

4. Experimental results and discussion

The nanofluids with different concentrations are used in the experiment to investigate its pool boiling heat transfer performances. At given fluid subcooling of 14 K, the pool boiling curves with 0 and 0.267 g/l were obtained and presented in Fig. 2. Since the heater surface was smooth and the acetone having smaller surface tension was employed as the working fluid, the boiling hysteresis occurred. Thus, the tests of the nanofluids were repeated to verify the data's reproducibility [12]. Fig. 2(a) and (c) showed that the boiling curves with identical nanoparticles concentration of $C = 0.267$ g/l had a good consistency. For comparison, the pool boiling curve of the $CaCO_3$ nanofluids obtained by Zhou and Liu [7] at subcooling of 25 K was also included in Fig. 2(a). For the conventional pool boiling curves (without nanoparticles) with subcooling of 14 and 25 K, the boiling hysteresis had wall superheat overshoot of 19.03 and 8.7 K, respectively. Independent of nanoparticles added into the working fluid, a two-step overshoot happened. The occasional two-step overshoot was observed only a few times and reported by Park and Bergles [13] and Zhou and Liu [7]. It is believed to be closely related with the irregular distribution of bubble nucleation sites around the copper tube and action of upstream bubbles.

Fig. 2(a) shows that pool boiling curves of Cu nanofluids remain unchanged for identical nanoparticle concentration after the fully developed nucleate boiling became established. It is inferred that the nanofluid behaviors more like a fluid than the conventional solid–liquid mixtures in which relatively larger particles with micrometer or millimeter orders are suspended. However, the nanofluid is a two-phase fluid in nature and has some common features of the solid–liquid mixtures. The gravity, Brownian force and friction force between the fluid and nanoparticles may coexist in the nanofluid. The stability of the nanofluids primarily depends on their combined results. Since the average size of copper nanoparticles used in this study is less than that of $CaCO_3$ nanoparticles, the deposition of Cu nanoparticles occurred for the present pool boiling heat transfer,

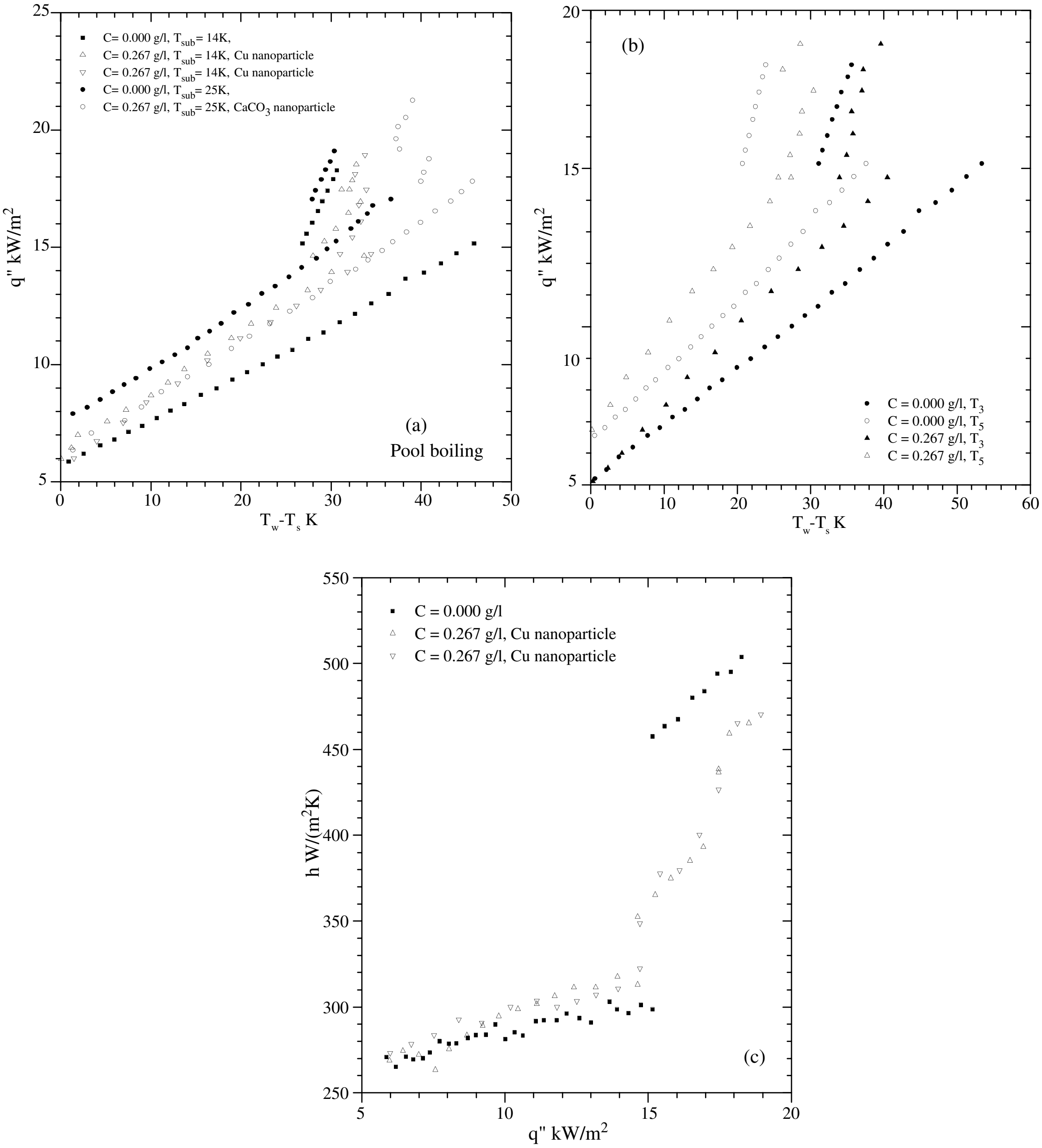

Fig. 2. Pool boiling curves of the nanofluids: (a) q'' versus ΔT_{sat}; (b) local boiling curves; (c) h versus q''.

indicating that the gravity is predominate compared to other factors.

Fig. 2(a) also showed that pool boiling heat transfer of the nanofluids was reduced, irrespectively of thermophysical properties of nanoparticles. Das et al. [3] reported similar result. The decrease in heat transfer rate of nucleate boiling is mainly ascribed to the deposition of nanoparticles on the heater surface. Benjamin and Balakrishnan [14] indicated that fluid conduction in micro layer evaporation under the bubbles as well as in reformation of thermal boundary layer at the nucleation site played a major role in heat transfer during pool boiling. With such a substantial increase in thermal conductivity, the nanofluids are expected to enhance pool boiling heat transfer. In case of pool boiling on horizontal tubes at moderate heat flux, Cornwell and Shuller [15] conclusively prove the importance of sliding bubbles where again conduction plays an important role. Comparison of heat transfer results with and without nanoparticles showed that nanoparticles had a vital influence on fluid flow and boiling heat transfer performance around the heater surface. Contrary to the case of $CaCO_3$ nanofluids, the boiling curves of Cu nanofluids had a lower incipient boiling superheat and the corresponding heat flux in comparison with conventional pool boiling curve. It should be noted that aggregation may take place and clusters may be formed in the nanofluids. All these chaotic movement modes of the nanoparticles will affect the distribution of the particles, transport properties and heat transfer performance of the nanofluids. The dispersion of nanoparticles flattens the transverse temperature gradient of the fluid due to its higher heat conductivity. This makes the fluid subcooling of the nanofluid be relatively low. The boiling curve with higher fluid subcooling has a lower incipient boiling superheat.

Although the boiling curves of different nanofluids shown in Fig. 2 have similar profile, the addition of Cu nanoparticles enhances single-phase convection heat transfer and decreased the incipient boiling superheat. Furthermore, at the single-phase convection regimes, the difference between wall superheats for various nanoparticles concentration was found to increase with increasing heat flux. It seems whether single-phase convection heat transfer of the nanofluids is enhanced or not depends on the thermophysical properties of nanoparticles. Compared to conventional heat transfer fluids, all nanofluids containing metallic nanoparticles enhance heat transfer as reported by Lee and Choi [2] and Xuan and Li [4]. Contrary to the case of metallic-containing nanofluids, all nanofluids containing nonmetallic or metallic oxide nanoparticles reported by Das et al. [3] and Zhou and Liu [7] reduced convection heat transfer. Heat transfer enhancement by metallic-containing nanofluids is primarily attributed to the fact that the metallic nanoparticles have a much higher intrinsic thermal conductivity than that of the nonmetallic or metallic oxide nanoparticles, as well as a higher stability in the base liquid. The mechanism of convection heat transfer enhancement by copper nanoparticles in this study is believed to be the same as that reported by Xuan and Roetzel [5].

Fig. 2(b) depicted local boiling curves obtained from the upside (T_3) and downside (T_5) of the tube respectively. Since upstream bubbles brushed the top heater surface and suppressed the boiling inception there, local boiling curve obtained from the upside (T_3) of the tube located right of that from the downside (T_5). As the copper nanoparticles were added into the working fluid, the same trend occurred. The deposition of nanoparticles makes the whole surface of the tube become smoother, which in turn shifts the boiling curve to the right [16]. Das et al. [3] verified this conclusion through reexamining the surface characteristics of the heaters using a profilometer after the runs. The nonuniform deposition of nanoparticles around the tube surface caused irregular distribution of bubble nucleation sites. Comparisons of local boiling curves with and without nanoparticles showed that nanoparticles had a much or less different influence on boiling heat transfer occurring on the upside and downside of the tube, with a larger decrease in heat transfer rate around the upside of the tube. After the nanofluids remained at static condition for seven days, the observation with naked eyes showed that more Cu nanoparticles deposited on the upside surface of the tube.

Fig. 2(c) presented the pool boiling curves in the form of h versus q''. Note that h is defined as $q''/(T_w - T_l)$, i.e., the ratio of applied heat flux to temperature difference between the corrected arithmetic average value of the eight thermocouples and the fluid temperature. Comparison of boiling curves with and without copper nanofluids showed that, with the increasing of nanofluid concentration, heat transfer rate of single-phase convection was increased. The sudden increase in h near $q'' = 1.46 \times 10^4$ W/m^2 is because of the sudden change in temperature owing to boiling hysteresis. Thereafter, heat transfer rate of nucleate boiling of the nanofluids is lower than that of conventional nucleate pool boiling because of higher thermal conductivity of copper nanoparticles.

For given acoustical source intensity and distance of $I = 0.3$ A and $L = 40$ mm, the tests were carried out to investigate the effect of copper nanoparticles on boiling curves. The results were presented in Fig. 3(a) and (b). As shown in Fig. 3(a), at lower fluid subcooling of 18 K, the boiling hysteresis with temperature overshoot of 1.3 K occurs irrespective of acoustic cavitation. However, as the nanofluid concentration reached 0.400 g/l, the heat transfer was enhanced markedly and the boiling hysteresis disappeared. Fig. 3(b) showed the corresponding local boiling curves. Independent of the location of the thermocouple, the addition of copper nanoparticles enhanced heat transfer there. It also can be concluded that there was higher augmentation ratio on the downside of the tube than that on the upside of the tube. Due to direct impingement and disturbance of cavitation bubbles, acoustic cavitation has a relatively stronger influence on fluid flow and heat transfer around the upside of the tube. Consequently, it is concluded here that higher heat transfer enhancement on the downside of the tube mostly comes from the addition of Cu nanoparticles.

The effect of nanofluid concentration on boiling curves was illustrated in Fig. 4(a) and (b). Fig. 4(a) showed Cu nanoparticles effect on conventional pool boiling curves. The boiling hysteresis with wall superheat of 8.74 K occurs for conventional pool boiling. As Cu nanoparticles were added into the working fluid, heat transfer was enhanced and the boiling hysteresis disappeared. However, as the nanofluid concentration was increased from 0.133 to 0.267 g/l, the heat transfer remained nearly unchanged. This shows that the

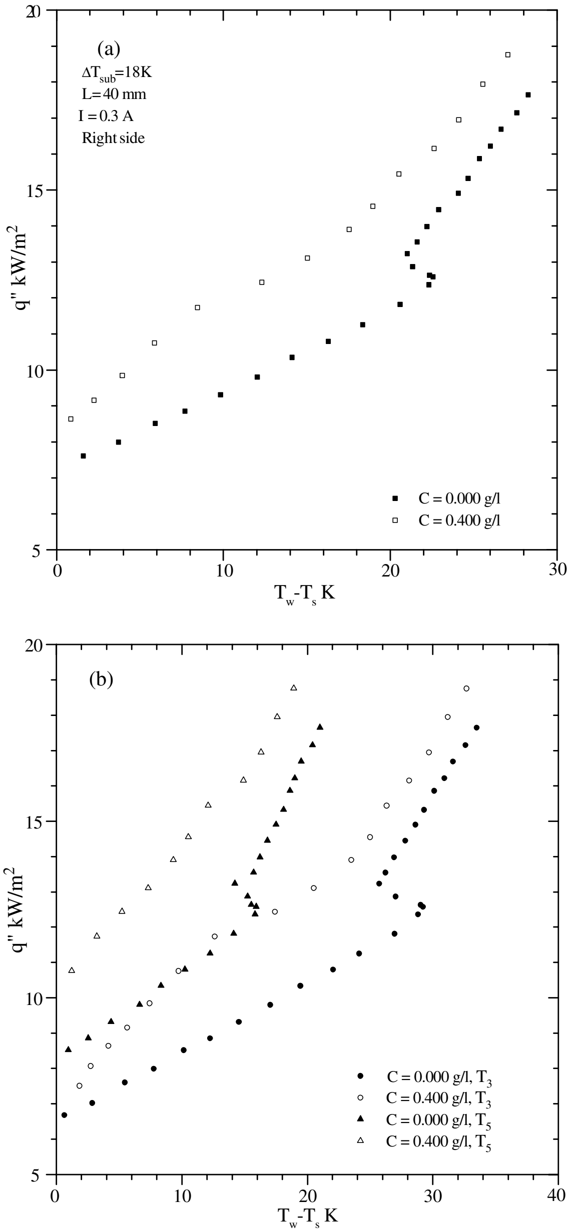

Fig. 3. Effect of nanoparticles on boiling curves with acoustic cavitation: (a) q'' versus ΔT_{sat}; (b) local boiling curves.

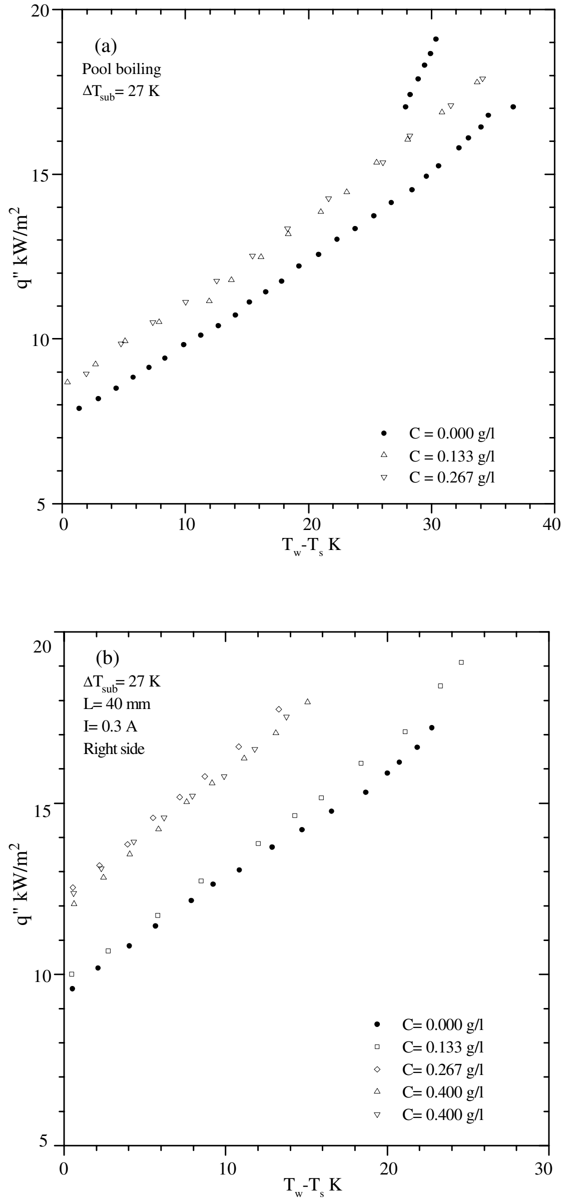

Fig. 4. Effect of nanofluid concentration on boiling heat transfer: (a) without acoustic cavitation ($I = 0$); (b) with acoustic cavitation $I = 0.3$ A.

addition of Cu nanoparticles with very small concentration such as 0.133 g/l can fully change the thermal transport properties of the acetone. It is substantially different from the experimental result of Das et al. [3] who found that pool boiling heat transfer was reduced with the increasing of nanofluid concentration. This discrepancy in nanofluid concentration effect on heat transfer is believed to be closely related with the thermophysical properties of nanoparticles.

As the acoustic cavitation is generated in the working fluid, this trend still exists. The effect of Cu nanofluid concentration in the range from 0.000 to 0.400 g/l on heat transfer with acoustic cavitation was illustrated in Fig. 4(b). Compared with these data shown in Fig. 4(a) without acoustic cavitation, the effect of nanofluid concentration on heat transfer with acoustic cavitation is complicated. Independent of nanofluid concentration, heat transfer was enhanced due to the addition of Cu nanoparticles while the shift of the curve to the left is not proportional to nanofluid concentration. A small shift of the curve to the left was observed with 0.133 g/l nanofluid concentration and then a considerable shift of the curve occurred everywhere with only 0.133 g/l increase in nanofluid concentration. Thereafter, as the nanofluid concentration was increased further to 0.400 g/l shown in Fig. 4(b), opposite trend occurred. It implies that there exists a critical nanofluid concentration for enhancing heat transfer. For the case of $CaCO_3$ nanofluids, heat transfer is slightly enhanced with increasing nanofluid concentration though all the boiling curves of the nanofluids shifted prominently to the right in comparison with conventional pool boiling curve. The boiling curves with same nanofluid concentration of 0.400 g/l reveals again that the experimental data had good reproducibility.

Energy transport of the nanofluid is affected by the thermal properties and dimension of nanoparticles as well as the nanofluid concentration. Heat transfer enhancement here consists of two parts: one is related with the thin boundary layer around the tube surface caused by cavitation bubbles while another is small temperature gradient of the nanofluids flattened by Cu nanoparticles. With the increasing of nanofluid concentration, the thermal conductivity of the nanofluid and the chaotic movement of copper nanoparticles are increased, leading to an acceleration of the energy exchange process in the fluid. However, one can infer that excess copper nanoparticles suspended in the liquid impacted cavitation bubbles influence on heat transfer. The combined effects of above-mentioned factors produce lower heat transfer rate for higher nanofluid concentration.

Now, we turn our attention to acoustical parameters effects on boiling curves of Cu nanofluids. At given acoustic source distance of 60 mm, the experimental data were collected to investigate the acoustic source intensity effect on boiling heat transfer. The results with nanofluid concentration of 0.133 g/l were presented in Fig. 5. Compared with the pool boiling of the nanofluids, heat transfer was enhanced due to acoustic cavitation, irrespective of the vibrator location. As the vibrator location was moved from the right side to the center of the test section, more cavitation bubbles impinged the tube surface. Therefore, heat transfer rate was further increased. At fixed heat flux of $q'' = 1.54 \times 10^4$ W/m^2, wall superheat was correspondingly decreased from 25.54 to 18.89 K and then to 8.04 K. It is concluded that the effect of acoustic cavitation on heat transfer of the nanofluid has the same trend as that reported by Zhou and Liu [10]. Zhou and Liu [7] reported similar results for $CaCO_3$ nanofluids.

The sound source distance represents the distance between the vibrator head and the central horizontal plane. Since the ultrasonic intensity is attenuated with distance from the source, the source distance affects heat transfer behaviors of the copper tube. For fixed nanofluid concentration of 0.267 g/l, the effect of the source distance on heat transfer were presented in Fig. 6. Independent of the sound source distance, acoustic cavitation enhanced remarkably the heat transfer of the tube in comparison with the corresponding pool boiling

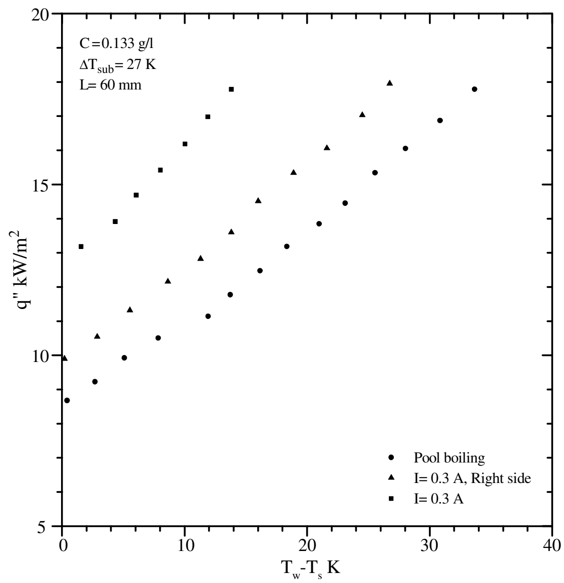

Fig. 5. Variations of boiling curves of the nanofluids with sound source intensity and the vibrator location.

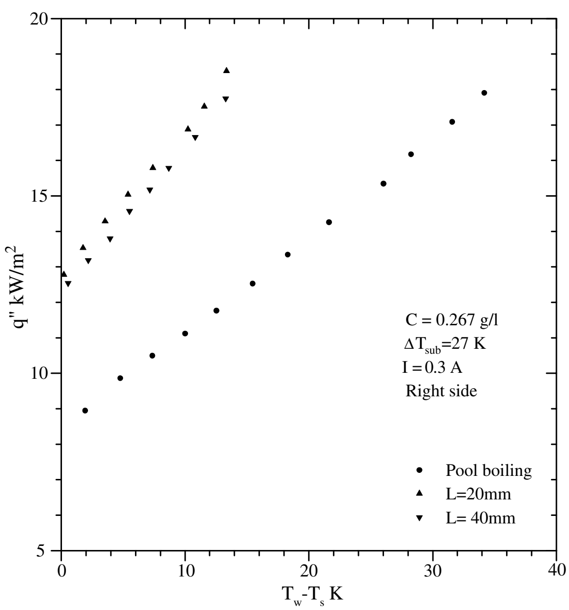

Fig. 6. Effect of sound source distance on boiling curves of the nanofluids.

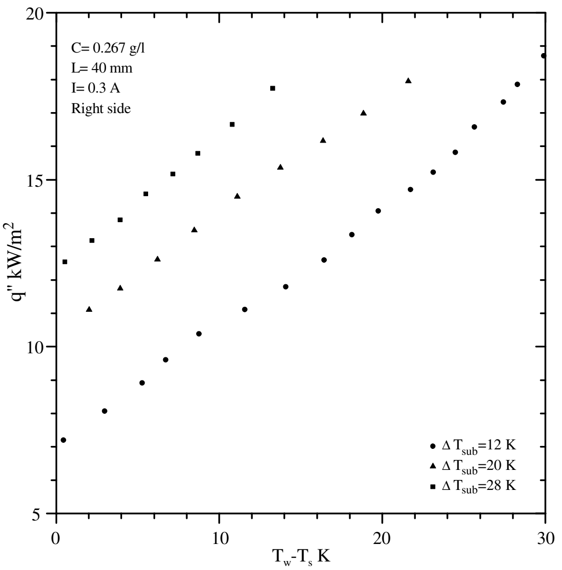

Fig. 7. Effect of fluid subcooling on boiling curves of the nanofluids.

curve. However, as the sound source distance is increased from $L = 20$ mm to 40 mm, heat transfer is reduced slightly.

Information of fluid subcooling influence on nucleate boiling is relatively scant in open literature. When the vibrator located on the right side of the test section at acoustic source intensity and distance of 0.3 A and 40 mm respectively, the tests were carried out to investigate the fluid subcooling influence on heat transfer. The results with nanofluid concentration of 0.267 g/l at three subcooling levels of 12, 20 and 28 K were presented in Fig. 7. With the increasing of fluid subcooling, heat transfer was enhanced. This conclusion is in agreement with the results reported by Valle and Kenning [17] and Huang and Witte [18] for flow boiling and Zhou and Liu [10] for pool boiling. It indicates that the effect of fluid subcooling on heat transfer is invariant to the addition of Cu nanoparticles.

5. Conclusions

The most important findings of this study are:

(1) With regard to pool boiling of the nanofluids, single-phase convection heat transfer was enhanced due to addition of a small amount of Cu nanoparticles while boiling heat transfer was reduced.
(2) With an acoustic field generated into the working fluid, heat transfer was enhanced by Cu nanoparticles, irrespectively of heat flux. The trend becomes more obvious with the increasing of fluid subcooling, sound source intensity and nanofluid concentration.
(3) Independent of Cu nanoparticles, the effects of acoustic cavitation and fluid subcooling on heat transfer characteristics of the tube remain unchanged.
(4) Whether convection heat transfer is enhanced by nanoparticles or not largely depends on its thermophysical properties.

Acknowledgements

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