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Enhancement of natural convection and pool boiling heat transfer via ultrasonic vibration

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Abstract

We report the relationship between the flow behavior induced by ultrasonic vibration and the consequent heat transfer enhancement in natural convection and pool boiling regimes. A thin platinum wire works as both a heat source and a temperature sensor. A high speed video imaging system is employed to observe the behavior of cavitation and thermal bubbles. Experimental results show that the effects of ultrasonic vibration on flow behavior are vastly different depending on the heat transfer regime and the amount of dissolved gas. In the natural convection and subcooled boiling regimes, behavior of cavitation bubbles strongly affects the degree of heat transfer enhancement. In saturated boiling, no cavitation occurs thus the reduced thermal bubble size at departure and acoustic streaming are major factors enhancing heat transfer rate. The highest enhancement ratio is obtained in natural convection regime where the effect of ultrasonic vibration is manifested through violent motion of cavitation bubbles.

1. Introduction

Imposing acoustic vibration onto a liquid pool has been proven to enhance natural convection and boiling heat transfer for several decades. Fand [1] and Li and Parker [2] reported enhancement of natural convection heat transfer by virtue of ultrasonic waves. Wong and Chon [3] and Iida and Tsutsui [4] investigated the effects of ultrasonic vibration on pool boiling heat transfer as well as natural convection heat transfer. They found that the natural convection heat transfer is enhanced more than pool boiling by ultrasonic vibration. Park and Bergles [5] and Bonekamp and Bier [6] studied the influence of ultrasound on nucleate boiling heat transfer, to find that the stronger enhancement is achieved at lower heat fluxes. Yamashiro et al. [7] showed enhanced quenching behavior for a hot wire in water when ultrasonic vibration is imposed.

The foregoing studies mainly focused on measuring the heat transfer rate change with such experimental parameters as the vibration frequency and the distance between the vibration transducer and heat source. In addition, a number of external conditions, such as ultrasonic wave power and frequency, dimension of heated wire, chamber dimension and liquid properties, affect the heat transfer enhancement degree. Therefore, it takes a considerable amount of effort to investigate the effects of individual parameter changes. Furthermore, without generalization of those observations into reduced or dimensionless parameters, the practicality of a mere collection of experimental data showing the influence of the factors above is severely limited unless the same conditions are realized in applications. More practical approach, rather, to the understanding of heat transfer enhancement phenomena due to ultrasonic vibration is relating flow behavior induced by ultrasonic vibration to the heat transfer enhancement. If such relationship is available, practitioners can rapidly

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Nomenclature

i	current
R	resistance
D	diameter
q''	heat flux per unit area
L	wire length
T	temperature
h	heat transfer coefficient
H	distance between wire and ultrasonic vibrator
Greek symbol	
η	heat transfer enhancement ratio
Subscripts	
s	sensor wire
f	fluid
v	vibration
o	no vibration
sat	saturation

optimize thermal apparatus and operation parameters by seeking conditions that induce optimal "flow behavior". It is this relationship that we aim to establish in this study. Therefore, we perform flow visualization and thermal measurement simultaneously to correlate them.

Ultrasonic vibration affects flow by transmitting acoustic wave in the liquid, which is manifested by cavitation bubbles and acoustic streaming. We image the bubble behavior and measure the heat transfer rate in natural convection and nucleate boiling conditions. We show that the ultrasonic vibration affects flow in a liquid pool in a variety of ways depending on the liquid conditions. Different flow behavior leads to different degree of heat transfer enhancement, hence valuable information on the enhancement mechanism can be collected by comparing those phenomena. In the following, we describe experimental apparatus and methods, and then discuss the relationship between flow behavior and heat transfer enhancement for each regime of natural convection, subcooled boiling and saturated boiling.

2. Experimental apparatus and methods

Fig. 1 shows the experimental setup for heat transfer measurement and flow visualization. An acrylic vessel containing liquid (FC-72) is wrapped at the side walls with the insulation except for a viewing window. The liquid level is kept at 60 mm in all the experiments. A piezoelectric transducer is attached to the bottom of the

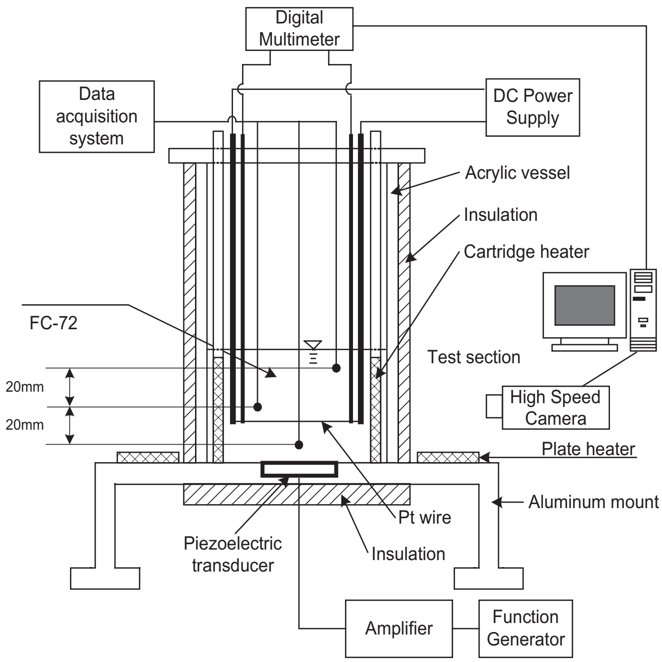


Fig. 1. A schematic of experimental apparatus.

vessel and is driven by an amplifier connected to a function generator (Tektronix AFG310). A platinum wire of 0.2 mm diameter is used as a heater and a temperature sensor. The wire is supported by copper rods which are connected to the current supply (Agilent E3633A). The voltage across the Pt wire is measured by a digital multimeter (Agilent B34401A) through aluminum wires soldered to the Pt wire. The length of the Pt wire between the soldered spots is approximately 55 mm. The voltage data are recorded by a personal computer with the rate of 2 Hz. Using the measured voltage and the supply current, the temporal evolution of resistance of the Pt wire is obtained. The resistance is converted to the temperature with the calibration table constructed by the 4-wire method [8]. Three thermocouples are immersed in the liquid as shown in Fig. 1, whose measured values are averaged to give the bulk liquid temperature. The temperature data collected by a data acquisition system (Yokogawa DA100) are transmitted to the aforementioned personal computer which records the temperature and the voltage simultaneously. A cartridge heater is immersed in the liquid to control the bulk temperature. In addition, a plate heater is attached to the aluminum vessel-support in order to homogenize the temperature in liquid. A high speed imaging system (Redlake PCI 2000S) is employed to visualize the flow around the Pt wire at 1000 frames per second.

In preliminary experiments to find the frequency inducing cavitation in liquid, we find 48 kHz to be the most effective for our experimental setup. It is also noted that the finite element analysis using ANSYS reveals that one of the resonance frequencies of the acrylic vessel is 48 kHz. We measure the temperature change of the heating wire to test the effects of vibration frequency on heat transfer in the range between 20 and 60 kHz. We observe that cavitation hardly arises accompanying negligible temperature change when the vibration is imposed at the frequency away from 48 kHz. Therefore, we present the experimental results obtained using vibration at a fixed frequency of 48 kHz.

We also test the cavitation behavior depending on the amount of dissolved gas in liquid. It is found that no cavitation arises in the liquid, which has been boiled for half an hour and cooled to room temperature, with nothing immersed. This suggests that the liquid is degassed thus there scarcely is an active nucleus of cavitation filled with dissolved gas. When the Pt wire is immersed in the degassed liquid, cavitation is observed between the wire and the liquid's free surface as shown in Fig. 2. We refer to this behavior as "local cavitation". Cavitation appears to be caused by immersed solid structures, such as the wire and the copper rod, having cavities on their surfaces. It is interesting to note that the bubble density adjacent to the wire is much lower than the area above when the wire is well below the liquid's free surface (Fig. 2(a)). However, when the wire is close to the free surface, the bubble cloud cannot be confined to a small area between the wire and the free surface thus cavitation bubbles densely surround the wire (Fig. 2(e)). On the other hand, cavitation bubbles occupy the entire liquid volume regardless of the existence of the alien objects when the liquid has not been pre-boiled (Fig. 2(b), (d) and (f)). We refer to this phenomenon as "global cavitation". The fact that a liquid can exhibit different cavitation behavior in the same thermal condition opens the opportunity to investigate the effects of cavitation-induced flow on heat transfer.

By varying the bulk liquid temperature, effects of ultrasound on different heat transfer regimes, such as natural convection, subcooled boiling and saturated boiling, are studied. The distance between the bottom, or the piezoelectric transducer, and the Pt wire is varied while the supply current is maintained constant. In saturated boiling regime, different values of current are supplied to examine effects of the heat flux on ultrasonic enhancement.

Heat flux per unit area, q'', from a heating wire is obtained by the following:

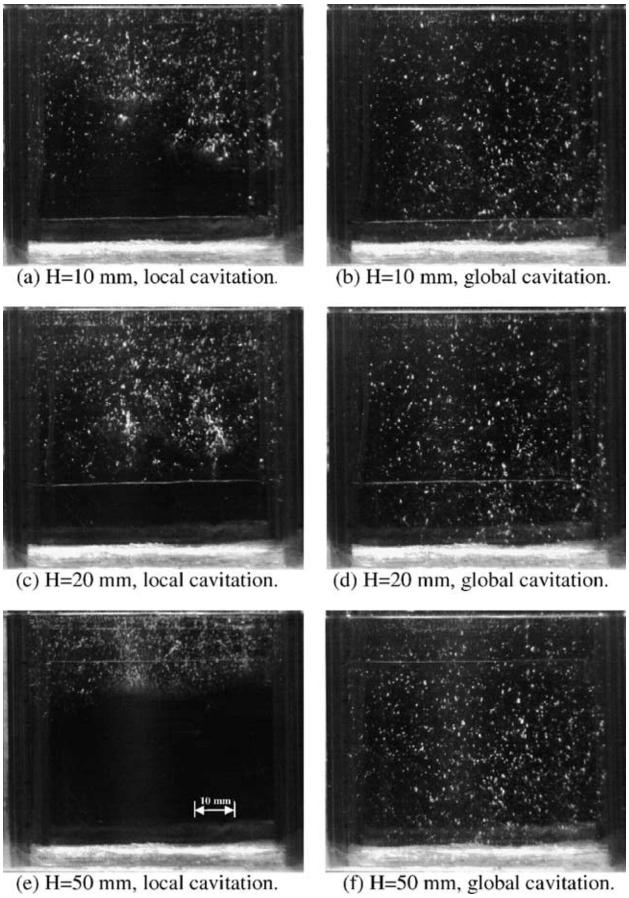
$$q'' = \frac{i^2 R}{\pi D L}, \tag{1}$$

where i denotes the supply current, R the Pt wire resistance, D the wire diameter, L the wire length. Using the wire temperature T_s, which is calibrated from R, the bulk liquid temperature T_f, and q'', the heat transfer coefficient h is given by

$$h = \frac{q''}{T_s - T_f}. \tag{2}$$

In the saturated boiling regime, T_f is 56 °C, the boiling temperature of FC-72 at 1 atm. Uncertainty analysis reveals that the maximum measurement error in h is likely to occur in the subcooled boiling regime and that the corresponding maximum error is ±7.7%.

As the ultrasonic vibration is imposed on liquid, the acoustic pressure wave transmits into the liquid. In this work, we measure the acoustic pressure amplitude inside liquid using a hydrophone (Specialty Engineering, SPRH-H-1000). We find the pressure distribution as a function of the axial distance from the piezoelectric transducer. This is achieved by taking the average of the pressure amplitudes measured along the direction perpendicular to the axis. However, even for a degassed liquid, the ultrasonic vibration gives rise to cavitation as soon as the hydrophone is immersed in liquid at room temperature. Then the pressure signal is overridden by violent noises caused by the bubbles. Hence the acoustic wave amplitude is measured only for liquid heated close to the boiling point ($T_{sat} = 56$ °C), where no cavitation is induced because the gas solubility of liquid approaches zero.



(a) H=10 mm, local cavitation. (b) H=10 mm, global cavitation.

(c) H=20 mm, local cavitation. (d) H=20 mm, global cavitation.

(e) H=50 mm, local cavitation. (f) H=50 mm, global cavitation.

Fig. 2. Images of global and local cavitation with different wire locations at room temperature.

3. Results and discussion

3.1. Enhancement of natural convection heat transfer

Heat transfer measurement results in the natural convection regime are shown in Fig. 3. No cavitation is observed without ultrasonic vibration as shown in Fig. 4 thus only natural convection takes place. When the ultrasound is imposed, the heat transfer coefficient increases in both degassed and non-degassed liquids. However, as shown in Fig. 3, the enhancement ratio differs greatly for the distance, H, between the wire and the bottom. We find the difference to be closely correlated with the cavitation behavior imaged by the high speed video system. Therefore, the mechanism of heat transfer enhancement can be elucidated by associating the cavitation images with the heat transfer enhancement ratio. The heat transfer enhancement ratio, η, is defined as

$$\eta = \frac{h_v - h_o}{h_o}, \quad (3)$$

where h_v and h_o are the heat transfer coefficients, as given by Eq. (2), with and without ultrasonic vibration, respectively. The maximum error in evaluating η is found to be ±10% of the nominal value of η in natural convection. In the other heat transfer regimes, similar magnitude of relative error is calculated by uncertainty analysis.

Fig. 3 reveals that the stronger heat transfer enhancement is achieved for liquid with global cavitation than with local cavitation up to $H = 40$ mm. At $H = 50$ mm, local cavitation enhances heat transfer more effectively than global cavitation. We explain this trend with the images in Fig. 4. Fig. 4(b) and (c) compare the typical bubble behavior at local and global-cavitation conditions. When local cavitation occurs, bubbles move around the wire erratically to stir the surrounding fluid. Thus caused fluid mixing promotes the transport of cool liquid to the hot wire, thereby augment heat transfer. For global cavitation, bubbles occupy entire liquid volume and tend to rise due to buoyancy. These bubbles also bring the cool liquid to the hot wire thus the heat transfer is enhanced. As the figures suggest,

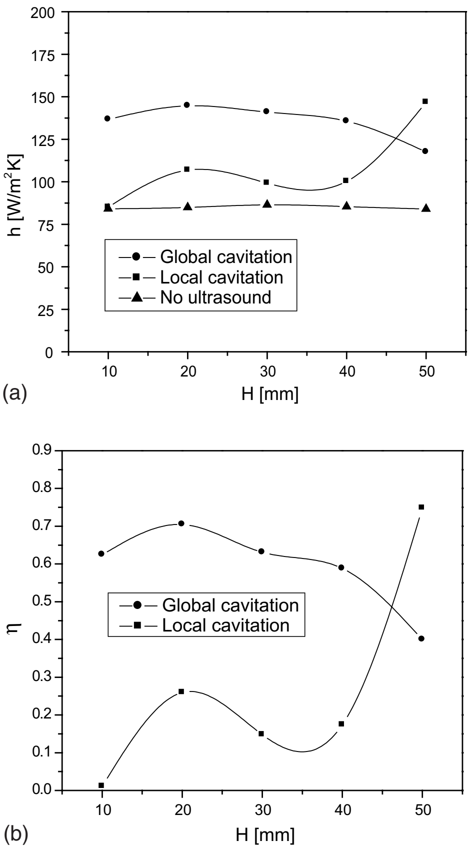


Fig. 3. Heat transfer measurement results for natural convection with $q'' = 1.5$ kW/m^2. (a) h vs H and (b) η vs H.

the bubble density around the wire in the global-cavitation condition (Fig. 4(c)) is much higher, thus the mixing rate is higher as well. Therefore, the heat transfer enhancement ratio of global cavitation is consistently higher than that of local cavitation up to $H = 40$ mm.

At $H = 50$ mm, bubbles generated in the degassed liquid densely surround the wire. Therefore, it is hard to differentiate the bubble behavior between the global cavitation and local cavitation at this wire location by taking a single image shot. This implies that the mobility of bubbles as well as their number density affects the fluid mixing, and we visualize the bubble mobility by arrows inserted in the digital pictures. The arrows indicate the locations of the corresponding bubbles 10 ms after the current shot. Comparing Fig. 4(d) and (e) reveals that the arrows of Fig. 4(d) are, in general, longer than those of Fig. 4(e). More importantly, a number of bubbles move downward in Fig. 4(d) although such bubbles are absent in Fig. 4(e). The coexistence of downward and upward bubble motions is the result of the formation of standing waves by the original acoustic waves from the vessel bottom and the acoustic waves reflected from the upper free surface. We suppose that such a standing wave cannot be formed in global cavitation where the entire liquid volume is occupied by bubbles which cause noises overwhelming original acoustic waves. A bubble cloud by local cavitation, which contains bubbles moving both upward and downward, can bring about more violent fluid mixing as compared with a group of bubbles moving in one direction. Therefore, the heat

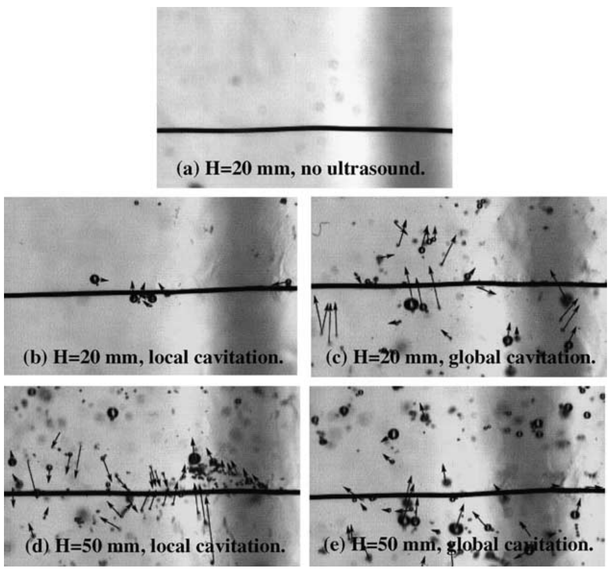


Fig. 4. Flow images in natural convection. The arrows indicate locations of the corresponding bubbles in 10 ms. The wire diameter is 0.2 mm.

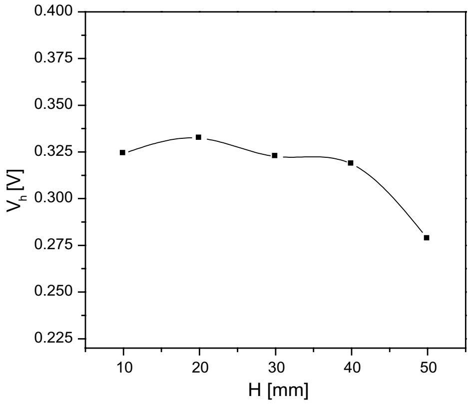


Fig. 5. Mean sound pressure amplitude measured in voltage vs H.

transfer enhancement ratio of local cavitation is higher than that of global cavitation at $H = 50$ mm as shown by Fig. 3.

We note that no enhancement is made by local cavitation at $H = 10$ mm although global cavitation enhances the heat transfer over 60% at the same location. The difference is readily explained by comparing the flow images at $H = 10$ mm in Fig. 2. No bubbles are found around the Pt wire in degassed liquid as contrary to the image of the wire surrounded by cavitation bubbles in the case of global cavitation. Here it is important to note that the acoustic pressure measurement in Fig. 5 indicates that acoustic pressure signal at $H = 10$ mm is as high as those at other locations. This clearly shows that the cavitation bubbles play dominant roles in enhancing heat transfer rate and that the effects of acoustic pressure pulsation and of acoustic streaming are limited at least when bubbles are absent.

3.2. Enhancement of subcooled boiling heat transfer

In the subcooled boiling regime, cavitation still arises when the ultrasonic vibration is imposed since the liquid temperature is below its boiling point. The most significant difference between subcooled boiling and natural convection is that subcooled boiling involves formation of thermal bubbles, in addition to cavitation bubbles, on the heating wire. Fig. 6 shows the heat transfer measurement results in subcooled boiling conditions. Since thermal bubbles agitate microconvection around the heating wire as well as carry away latent heat of vaporization [9], the heat transfer coefficient without ultrasound is much higher as compared with that of natural convection. As a result, the heat transfer enhancement due to ultrasound is not as dramatic as in natural convection. Especially, heat

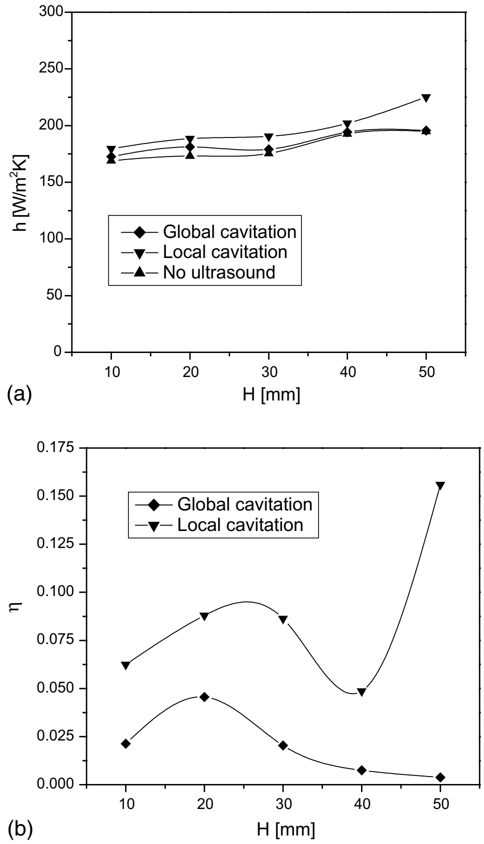


Fig. 6. Heat transfer measurement results for subcooled boiling with $q'' = 4.4$ kW/m^2, $T_f = 37$ °C and $T_s = 60$ °C. (a) h vs H and (b) η vs H.

transfer enhancement by global cavitation is measured to be very small.

Fig. 7 reveals that ultrasound generates additional cavitation bubbles and also affects bubble motion on the heating wire. However, experimental results of Fig. 6 suggest that mere addition of cavitation bubbles around the heating wire does not bring about heat transfer enhancement as observed in the case of global cavitation. As Fig. 7(b) shows, the vigorous movement of cavitation bubbles around heating wire, quantified by relatively long arrows, is necessary to enhance subcooled boiling heat transfer. We suppose that enhanced bubble motility in local cavitation results from an effective transmission of acoustic wave through liquid without cavitation bubbles. The heat transfer rate at $H = 50$ mm for degassed liquid is much enhanced as in natural convection. Similar to Fig. 4(d), cavitation bubbles in Fig. 7(d) move both up and down as affected by the reflected wave near the free surface. Such bubble behavior is again proven to achieve a fairly effective heat transfer enhancement through subcooled boiling experiments.

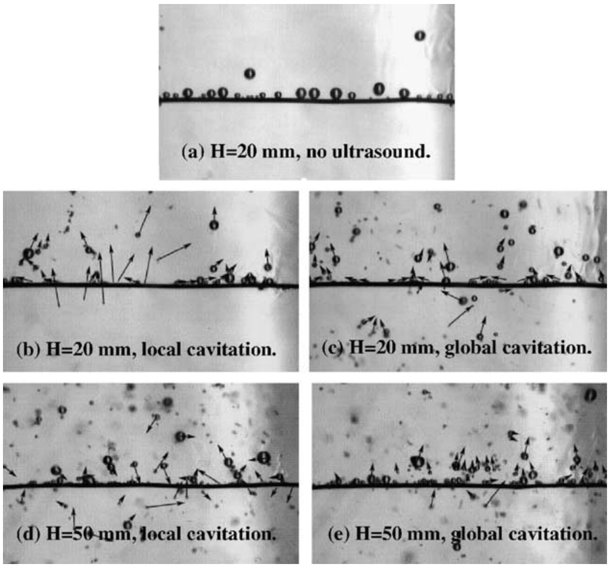


Fig. 7. Flow images in subcooled boiling. The arrows indicate locations of the corresponding bubbles in 10 ms. The wire diameter is 0.2 mm.

3.3. Enhancement of saturated boiling heat transfer

When the liquid temperature reaches its saturation point, no cavitation occurs under ultrasonic vibration for an extremely low gas solubility. Therefore, to pre-degas liquid makes no difference in flow behavior. Fig. 8 compares the heat transfer coefficients of saturated boiling with and without ultrasonic vibration. Higher heat transfer coefficients are obtained for saturated boiling than for subcooled boiling (Fig. 6(a)). It is because the bulk liquid temperature rather than the saturation temperature is used for T_f in Eq. (2) for subcooled boiling, thus the temperature difference is greater in the subcooled boiling. However, it turns out that the enhancement ratio is similar to that of subcooled boiling of degassed liquid. Since no cavitation bubbles are present, ultrasonic vibration affects motion of only thermal bubbles as shown in Fig. 9. The effects of ultrasound in the saturated boiling regime are that the size of bubbles interacting with the heating wire gets much smaller and that a strong streaming sweeps the bubbles horizontally. Reduced bubble size indicates smaller thermal resistance from the heating wire to the ambient cold fluid and increased bubble departure frequency. A strong acoustic streaming, owing to the absence of cavitation bubbles to distort the acoustic wave profile, is visualized by concerted trajectories of each bubble group. A magnified image of tiny bubbles driven by acoustic streaming is compared with an image of normal thermal bubbles without ultrasonic vibration in Fig. 10.

Since thermal bubble behavior plays dominant roles in determining heat transfer rates in the saturated

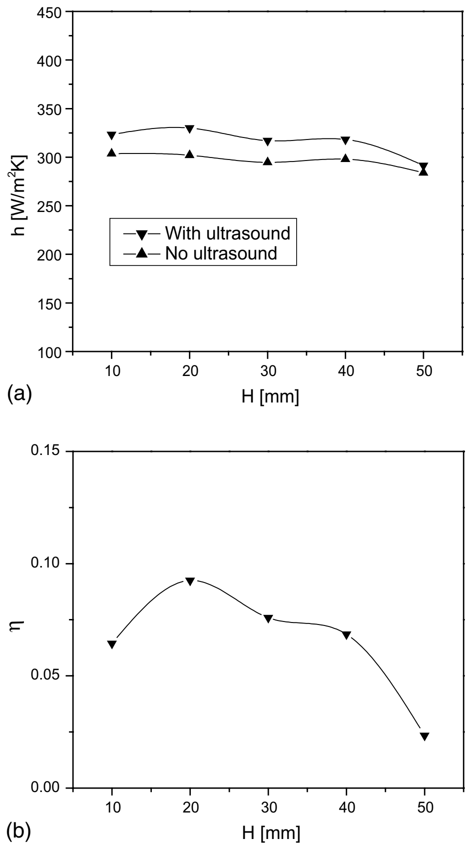


Fig. 8. Heat transfer measurement results for saturated boiling with $q'' = 4.4$ kW/m^2 and $T_s = 69$ °C. (a) h vs H and (b) η vs H.

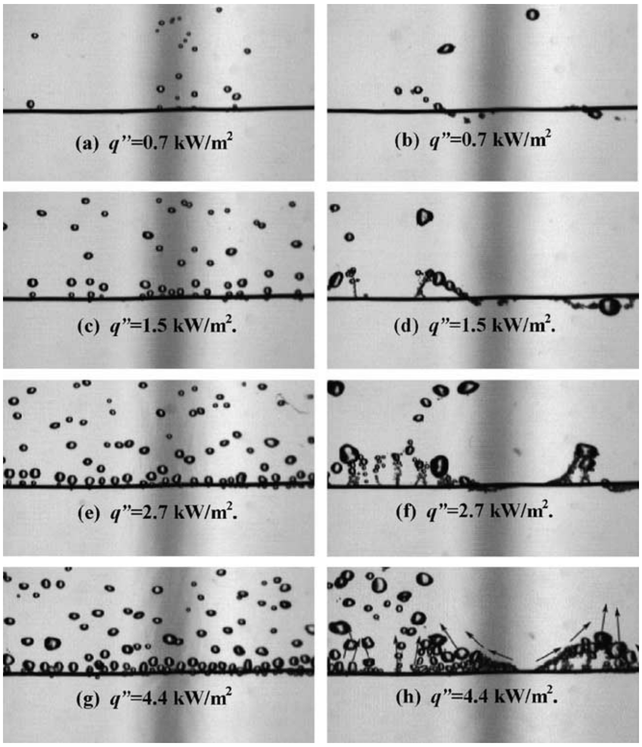


Fig. 9. Bubble behavior in saturated boiling under different heat fluxes. (a,c,e,g) No ultrasound imposed. (b,d,f,h) Ultrasound imposed.

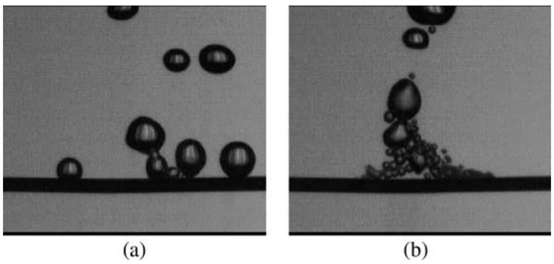
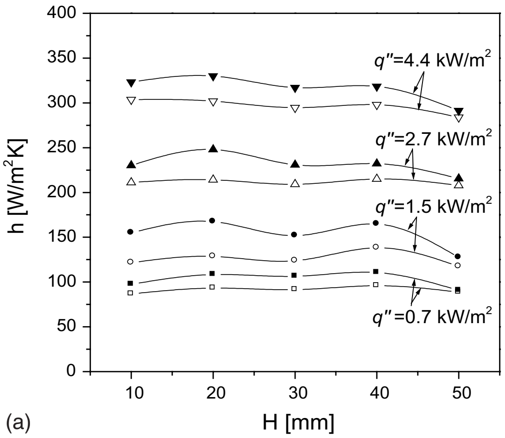


Fig. 10. Magnified images of heating wire in saturated boiling with $q'' = 2.7$ kW/m^2. (a) No ultrasound imposed and (b) ultrasound imposed.

boiling regime, we investigate the effects of thermal bubble density around the wire on the heat transfer enhancement ratio. The thermal bubble density is dependent on the heat flux at the wire thus the heat transfer measurement results are shown for varying heat flux in Fig. 11. We find that the enhancement becomes stronger when the heat flux increases from 0.7 to 1.5 kW/m^2. Comparing Fig. 9(b) and (d) reveals that when the thermal bubble density is relatively low, increased number of bubbles gives rise to stronger microconvection under ultrasonic vibration. However, when the heat flux further increases to 2.7 and 4.4 kW/m^2, so many thermal bubbles are formed that microconvection is fairly vigorous even in the absence of ultrasonic vibration. Therefore, the heat transfer enhancement is not as pronounced as in the cases of low heat flux. It is also noteworthy that the magnitude of heat transfer enhancement ratio along the distance from the vibrator is similar to the acoustic pressure amplitude profile as shown in Fig. 5. It is easily understood when considering that the acoustic streaming is more promoted in the region of a higher acoustic pressure amplitude. Measurement data plotted in Fig. 11 can be summarized into characteristic boiling curves as shown in Fig. 12. The curves with ultrasonic vibration are shifted to the left, which corresponds to enhancement of heat transfer.

4. Concluding remarks

In this work, we measure the heat transfer enhancement due to ultrasonic vibration in natural convection, subcooled boiling and saturated boiling regimes, and correlate the results with the high speed flow images. Our results show that the effects of ultrasonic vibration on flow behavior are vastly different depending on the heat transfer regime and the amount of dissolved gas. Such difference in flow behavior eventually affects the



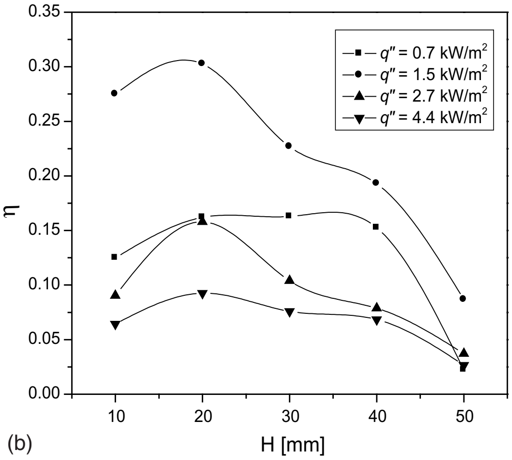


Fig. 11. Heat transfer measurement results for saturated boiling under different heat fluxes. (a) h vs H. Open and filled symbols indicate data point without ultrasound and with ultrasound, respectively. (b) η vs H.

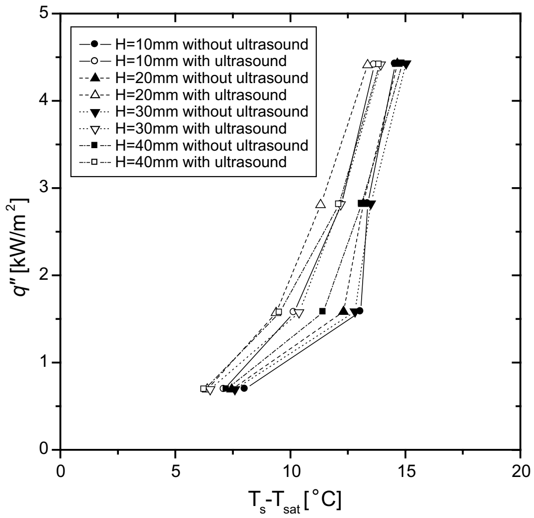


Fig. 12. Comparison of boiling curves with and without ultrasonic vibration at different heater locations.

degree of heat transfer enhancement. We conclude with summarizing the heat transfer enhancement mechanisms elucidated in this work.

In the natural convection regime, heat transfer enhancement by cavitation bubbles is stronger than boiling heat transfer regimes. It is because when natural convection occurs without ultrasonic vibration, no bubbles are present to bring the cold fluid to the heating wire. Through the experiments in the natural convection regime, we show that the bubble formation by cavitation is the most important mechanism of ultrasonic heat transfer augmentation. We find that the number density of cavitation bubbles plays a critical role in enhancing the heat transfer when comparing the enhancement ratios by global cavitation and local cavitation. However, vigorous bubble motion in addition to increased bubble number density is also revealed to greatly enhance heat transfer rate as shown at $H = 50$ mm for local cavitation.

We obtain much lower heat transfer enhancement ratios for both subcooled and saturated boiling regimes as compared with the natural convection regime. It is because even without ultrasonic vibration, thermal bubbles are formed by boiling, which induce microconvection to promote heat transfer. Cavitation bubbles generated by ultrasound in subcooled boiling augment such microconvection that is already brought about by thermal bubbles. Therefore, strong bubble motility is necessary to achieve additional heat transfer enhancement to the effect of nucleate boiling. Local cavitation provides such motility owing to absence of cavitation bubbles below the wire to prevent effective transfer of acoustic waves from the ultrasonic vibrator. However, global cavitation does not exhibit sufficiently strong bubble motility to enhance subcooled boiling heat transfer. On the other hand, experiments in the saturated boiling regime show that the heat transfer enhancement is owing to the reduction of bubble size departing the heating wire and to the acoustic streaming sweeping the bubbles over the heating wire.

Acknowledgements

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