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EFFECT OF WIRE DIAMETER ON ULTRASONIC ENHANCEMENT OF SUBCOOLED POOL BOILING

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ABSTRACT

New methods for cooling of microelectronic elements have been recently developed, including application of ultrasonic fields. Ultrasonic fields enhance the heat transfer in two-phase cooling. The present work deals with ultrasonic enhancement of heat transfer from wires in sub-cooled pool boiling. The experiments have been carried out using three wires of different diameters: 0.05, 0.09, 0.2mm, submerged into a bath with water. The applied ultrasonic field was of frequency of 40 kHz and intensity of 0.5 W/cm^2. The wire wall temperature was measured as a function of wire surface heat flux. When the ultrasonic field was applied, the wall temperature reduced in the range of measured heat fluxes. The temperature difference increased with the heat flux. It also increased with the wire diameter. At the smallest diameter only a small decrease of the wall temperature, about 10-15 degrees, was observed, while at larger diameters the decrease of the wall temperature was about 30 - 35 degrees.

INTRODUCTION

Effect of sonic and ultra-sonic waves on heat transfer and boiling process was investigated by different authors since the 60's. The influence of cavitation induced by ultrasound on solid-liquid heat transfer was investigated [1, 2]. The acoustic waves induce turbulence and secondary acoustic streaming which increases convective heat transfer coefficient [3-7]. This effect could be very useful in microelectronic packaging. A theoretical study of heat transfer from a vibrating cylinder was done by Davidson [8].

The other aspect of ultrasonic waves is the affect on subcooled boiling. Isakof [9] and Wong and Chon [10] found that ultrasonic has negligible effect on heat flux and the enhanced convective curve merged with the established boiling curve for both water and methanol. Li and Parker [11] reported that there was a small reduction in the superheat for established boiling of water with ultrasonic waves.

Ornanskii and Scherbakov [12] reported significant increase as subcooling was increased. Park and Bergles [13] confirmed the effects of ultrasonic waves on boiling heat transfer for an inert, dielectric liquid in subcooled and pool boiling conditions. Their experimental test sections were cylinders of diameters in the range of 1.65 to 2.11 mm, the frequency of ultrasonic waves was 55kHz and transducer output was 75W. They observed substantial ultrasonic enhancement when the pool was subcooled, however, accurate data at low heat flux were not obtained due to temperature fluctuations. Iida and Tsudsui [14] carried out a study of the effect of ultrasonic waves at frequency of 28 kHz and 33.6 W on natural convection, nucleate boiling and film boiling from heated 0.2 mm diameter wire to water or ethyl alcohol. No effects were observed in nucleate boiling of water, a small effect was in low heat flux nucleate boiling of ethyl alcohol. An increase was observed of about 20% in the heat flux by applying ultrasonic waves in both liquids in natural convection and film boiling regimes. Bartoli and Baffigi [15] investigated the influence of ultrasonic waves on heat transfer enhancement. The heater immersed in the water was of 33 mm in diameter and 192 mm in length. The ultrasonic waves were generated at frequencies 37, 38, 39, 40 *kHz* and of power 200, 400 and 500 W. At the best conditions the heat transfer coefficient enhancement was equal to 62%.

The purpose of this work is to investigate the influence of ultrasonic waves on heat transfer from heated wires of various diameters submerged in a pool during subcooled boiling.

Nomenclature

D	[mm]	Wire diameter
I	[Amps]	Electrical current
L	mm]	Wire length
T	[C]	Temperature
R	[Ω]	Electrical resistance
h	[kWC/m^2]	Heat transfer coefficient
q	[kW/m^2]	Heat flux

Subscripts

w	Wire wall
f	Fluid

EXPERIMENTAL SETUP

The general schematic of the experimental setup is presented on Figure 1. It consists of ultrasound bath (DC80H with frequency of 40kHz, output power – 80W, volume 2*l*), thermometer, mixer, milliohm meter MO-2013, electrode system, digital multimeter DMM 4020, analogue ampere meter, two DC power supplies Lambda Gen 1500W with built-in digital ampere meter and voltmeter. The experiments were carried out into the ultrasound vessel filled with distillate water. The tested wires were of diameters 0.05, 0.09, 0.2mm, and length of 70 mm. The wires made of different cooper alloys were soldered to stainless steel bars and immersed in the water at atmospheric pressure. The wires were used as a heaters and a temperature sensors, simultaneously. The general view of the experimental setup can bee seen in Photo 1.

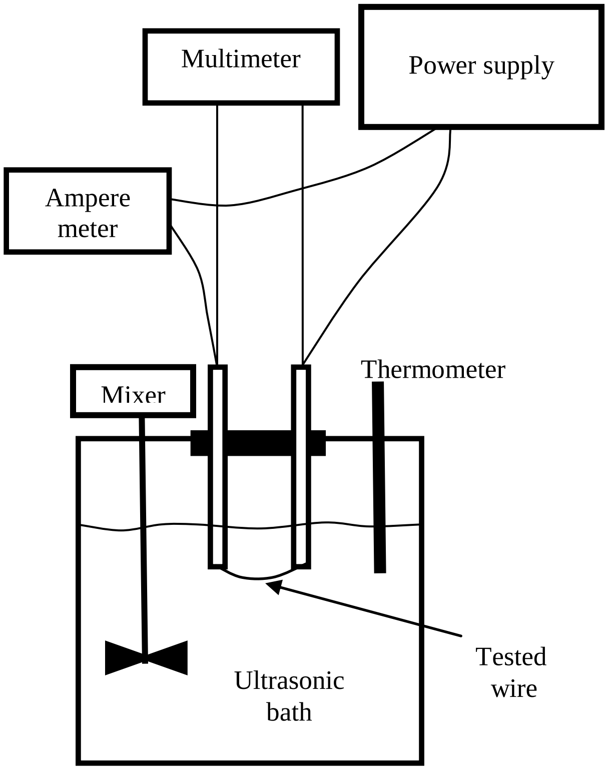

Figure 1 Experimental setup

Photo 1 General view of the experimental setup

The electrical resistivity of wires depends on their temperature. To use the wires as a temperature sensor, each wire was calibrated to obtain the connection between wire resistivity and temperature. The wires were calibrated using a calibration system shown on Figure 2. This system consists of ultra-thermostat bath, thermometer, milliohm meter MO-2013, and the electrode system with tested wire. The calibration media was distillate water or transformer oil.

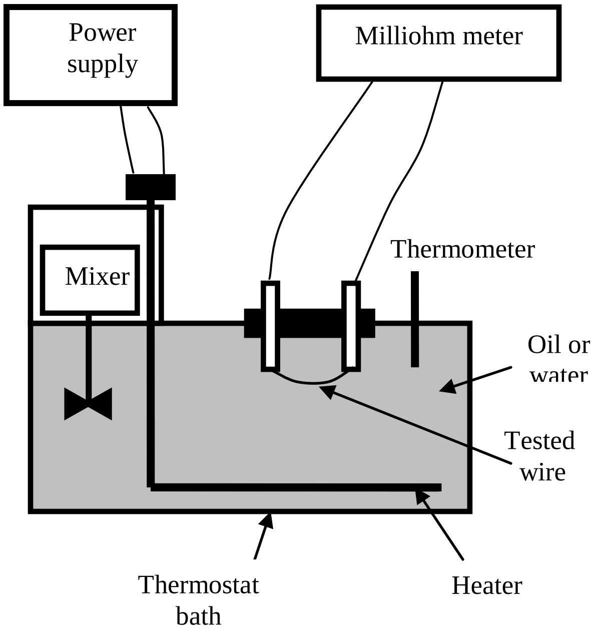

Figure 2 Calibration system

By measuring the temperature of liquid by a thermometer and the resistivity by electrical current and voltage the connection between temperature and resistivity could be obtained. The calibration was done in two series of tests for each wire diameter: series in water media 3-5 times, and series in oil - 3-5 times. Max temperature in the water was 100°C, and in oil - 220°C. The wires are made of different cooper alloys and the calibration curves for each wire are presented in Figure 3. The curves are different for each wire because there are made of different alloys. The wire of 0.2 mm in diameter was made of almost pure cooper as we can see from the figure by comparison with the table data of pure cooper. The resistivity of cooper and cooper alloys as a function of temperature has the highest gradient. Small changes of temperature lead to high changes of resistivity, which allow accurate calculation of temperature from the calibration curve in comparison with other possible metal wires.

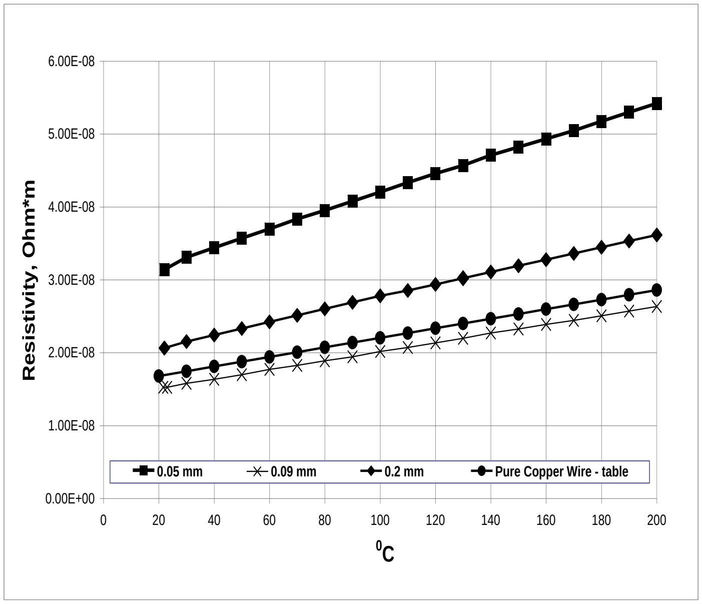

Figure 3 Calibration lines for cooper alloy wires, diameters 0.05, 0.09, 0.2 mm.

EXPERIMENTAL PROCEDURE

The wires were fixed in a horizontal position at a distance of 40 mm from the bottom; the liquid level was kept at 80 mm in all the experiments. The wires were heated by electric current supplied through stainless steel bars to a wire by the DC power supply. The voltage and current in the wire were measured by a digital multi-meter and ampere meter. The voltage and current were measured with accuracy of 0.5% and 1 %, respectively.

Using the measured voltage and current, the resistivity, ρ, of the given alloy copper wire is calculated as

$$\rho = \frac{4R}{\pi D^2 L} = \frac{4U}{\pi D^2 L \cdot I} \qquad (1)$$

where I denotes the electric current in the wire, U – voltage on the wire, R - the wire resistance, D - the wire diameter, L - the wire length.

The resistivity is converted to the temperature, T_w, using calibration data obtained previously, Figure 3. Because the diameters of the wires were small, we assume that the mean temperature of wires is equal to the temperature of wire wall surface.

The electrical energy applied to the wire, I^2R, is converted to thermal energy. This heat transfers from the wire to the surrounding fluid and therefore, the heat flux, q'', is calculated by dividing of the electrical energy by the wire wall surface:

$$q'' = I^2R/\pi DL \qquad (2)$$

Using the wire wall temperature T_w, the bulk liquid temperature T_f and the heat flux from the unit wire surface q, the heat transfer coefficient h is calculated as:

$$h = q''/(T_w - T_f) \qquad (3)$$

where the bulk liquid temperature in the experiments was kept $20 \pm 0.2\ ^0$C and measured with accuracy ± 0.1 K.

Using wires of different diameters the effects of ultrasound on heat transfer and boiling process have been studied. All the tests have been done by heating the wires by the DC current from the two DC power suppliers Lambda Gen 1500W. The current through the electrode system and wire was measured every 0.1V and, using the calibration, was converted in temperature.

RESULTS AND ANALYSIS

The results of the experiments are presented in Figures 4 – 6 in terms of wire wall temperature, T_w, as a function of heat flux, q. The values of heat flux are calculated from the experimental data using Equation (2). Further, using these data, the heat transfer coefficients are calculated from Equation (3) and presented in Figures 7 – 9 as a function of heat flux.

From the figures that show change of the wall temperature, Figures 4-6, we can see that when the ultrasonic field has been applied, the wall temperature reduces in the whole range of the measured heat flux. The difference of the temperatures between the cases with and without acoustic waves increases with the heat flux; the higher the heat flux the difference is higher. The temperature difference increases also with wire diameter. At smallest diameter, d = 0.05 mm it only a slight decrease of the wall temperature about 10°C was observed. For wire with d = 0.09 the temperature decrease was about 20°C, and for wire of the largest diameter, d = 0.2 mm, the decrease of the wall temperature was about 30 - 35 degrees.

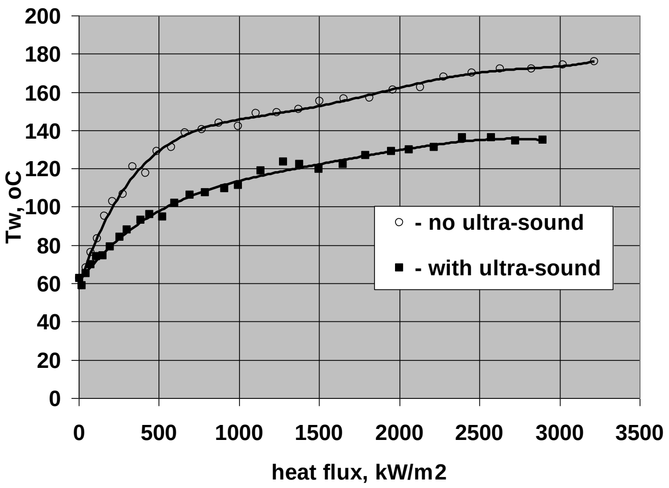

Figure 4 Change of wire wall temperature as a function of heat flux, with and without ultrasound, wire diameter *D* = 0.2 mm.

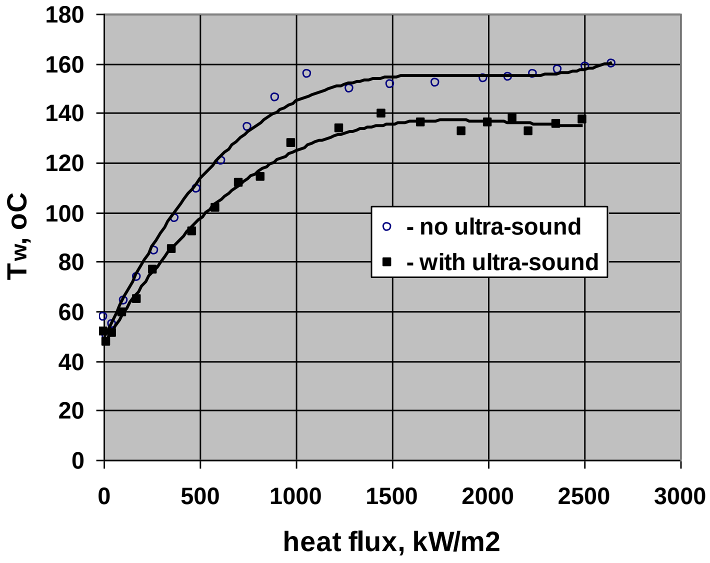

Figure 5 Change of wire wall temperature as a function of heat flux, with and without ultrasound, wire diameter *D* = 0.09 mm.

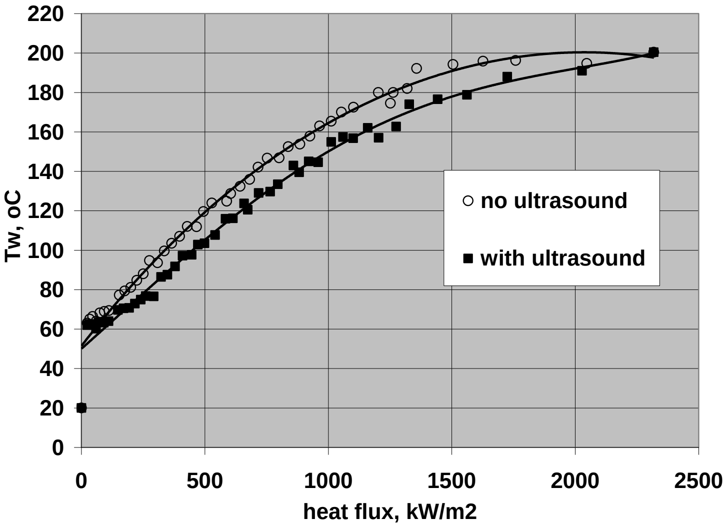

Figure 6 Change of wire wall temperature as a function of heat flux, with and without ultrasound, wire diameter *D* = 0.05 mm.

Figures 4-9 show three main regions: convective heat transfer, transient and boiling. Roughly, in the first region heat flux less than 200 – 500 kW/m2, the boiling – more than 1000 kW/m2, and in between – the transient region. For the wire of 0.05 mm in diameter in all these three regions the temperature changes are almost the same, however in the two other cases of larger diameters (0.09 and 0.2 mm) the temperature difference increases as the heat flux is higher. From the calculated heat transfer coefficient (Figures 7 -9) it could be seen that at low heat fluxes, in the region of convective heat transfer, the effect of acoustic waves is not significant. However as boiling starts, the effect of acoustic in transient and intensive boiling is much more pronounce. It could be also seen that for the wire with smallest diameter of 0.05 mm the decreases in the temperature is small and almost the same for all values of heat flux.

There are three main mechanisms generated by ultrasonic waves that affect the heat transfer from wires to water in subcooled pool boiling. The acoustic fluctuations generate turbulence which increases the convective heat transfer from the wall surface. Moreover, the fluctuations generate secondary acoustic streaming, which increase the convective heat transfer as well. The third mechanism which causes an increased heat transfer in the boiling regime is the high shear forces on the wire surface generating by acoustic fluctuations. These forces detach bubbles from the wire surface and in this way increase the heat transfer coefficient. The present experiments show that all three mechanisms take place. The convective mechanisms, fluctuations and secondary streaming, are observed for low temperature of less than 100^{o}C. In the transient and boiling regions the temperature difference increases, which can be explained by enhanced detachment of bubbles from the wire surface in addition to convective effects, when acoustic waves are applied.

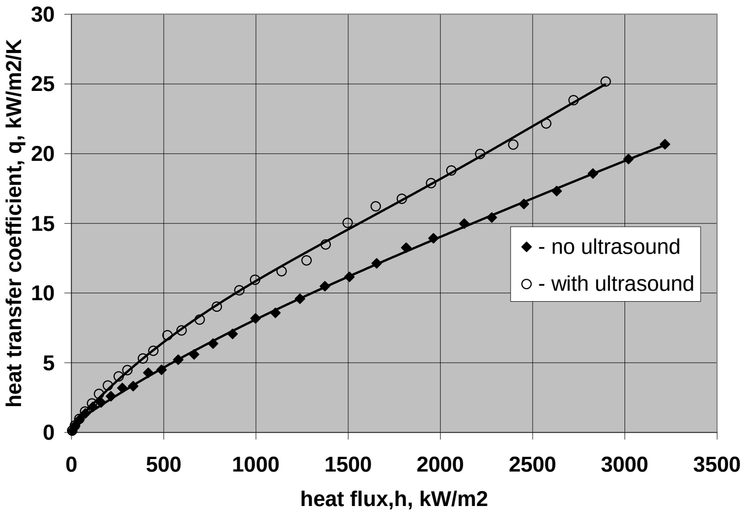

Figure 7 Heat transfer coefficient as a function of heat flux, with and without ultrasound, wire diameter D = 0.2 mm.

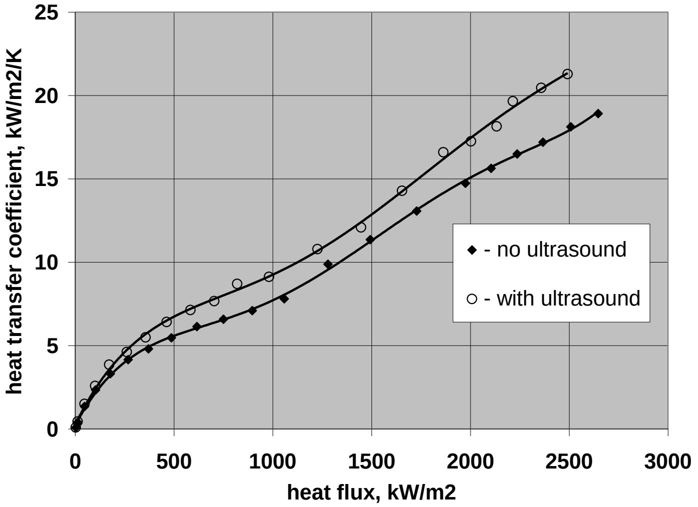

Figure 8 Heat transfer coefficient as a function of heat flux, with and without ultrasound, wire diameter D = 0.09 mm.

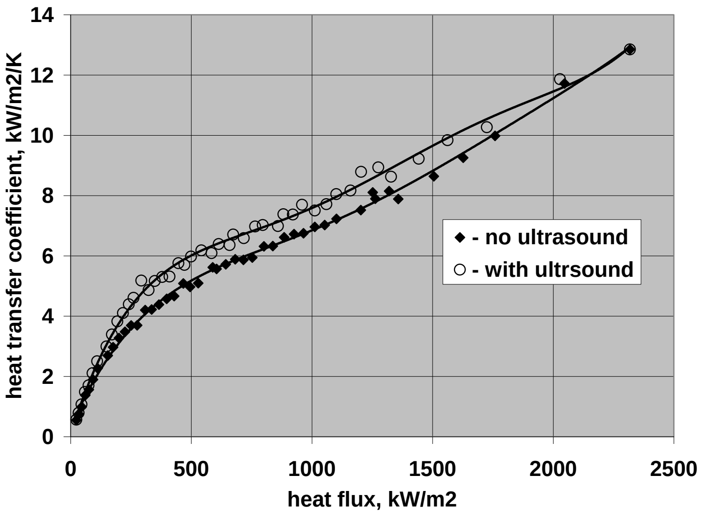

Figure 9 Heat transfer coefficient as a function of heat flux, with and without ultrasound, wire diameter D = 0.05 mm.

CONCLUSIONS

The present work deals with enhancement of heat transfer from wires in sub-cooled pool boiling by ultrasonic waves. The experiments have been carried out using three wires of various diameters: 0.05, 0.09, 0.2mm, submerged in a bath of water. The wire wall temperature was measured as a function of wire surface heat flux. The experiments show that influence of acoustic waves on heat transfer increase with the diameter of a wire. At smallest diameter, d = 0.05 mm the decrease of the wall temperature was about 10^{o}C. For wire with d = 0.09 the temperature decrease was about 20^{o}C, and for wire of the biggest diameter, d = 0.2 mm, the decrease of the wall temperature was about 30 - 35 degrees. The intensification of heat transfer generated by acoustic waves is observed also with increase of the wire temperature which could be explained by enhanced detachment of bubbles during the boiling process. At pre-boiling region, the effect of ultrasonic waves is connected with increase of convection around the wire.

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