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Ultrasonic enhancement of saturated and subcooled pool boiling

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INTRODUCTION

ULTRASONIC agitation is an active heat enhancement technique that has potential for improving heat transfer in immersion cooling of microelectronic components. For example, there is a possibility of providing the enhancement to an entire array of microelectronic chips in a pool.

When vibrations are applied to liquids or gases, natural convection heat transfer may be improved by acoustic streaming. With liquids, it is possible to operate with ultrasonic frequencies due to favorable coupling between a solid and a liquid. At frequencies of the order of a megacycle, another type of streaming called crystal wind may be developed [1, 2]. In addition, since intensities are usually high enough to cause cavitation [1, 3–5], that may become the dominant mechanism of heat transfer enhancement.

With ultrasonic enhancement of subcooled pool boiling heat transfer, Isakoff [6] and Wong and Chon [7] found that the enhanced convective curve merged with the established boiling curve for both water and methanol. Li and Parker [8] reported that there was a small reduction in the superheat for established boiling of water with ultrasonics. Yashchenko [9] indicated qualitatively that boiling heat transfer coefficients for water and glycerin were slightly increased at low heat fluxes but not at high heat fluxes. He speculated that the ultrasonic energy was inhibited from reaching the surface because of the large amount of vapor.

Wong and Chon [10] found negligible effect of ultrasonic vibrations on the burnout heat flux for subcooled methanol. On the other hand, Ornatskii and Shcherbakov [11] reported a 30–80% increase in burnout heat flux for water (above the effect of subcooling alone) as the subcooling was increased from 3 to 80 K. For saturated boiling, Isakoff [6] reported a 60% increase in the burnout heat flux for water and Markels *et al.* [12] reported a 50% increase for isopropanol.

The present study was undertaken to confirm the effects of ultrasonic vibrations on boiling heat transfer for an inert, dielectric liquid typical of those used for immersion cooling of microelectronic components. Refrigerant 113 (R-113) was chosen as the working fluid. No tests of R-113 with ultrasonic vibrations appear to have been reported even though this fluid is widely used in ultrasonic degreasing systems.

EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic diagram of the apparatus is shown in Fig. 1. The ultrasonic tank (Branson B-32H, 273 × 127 × 152 mm high) had three transducers (lead–zirconate–titanate)

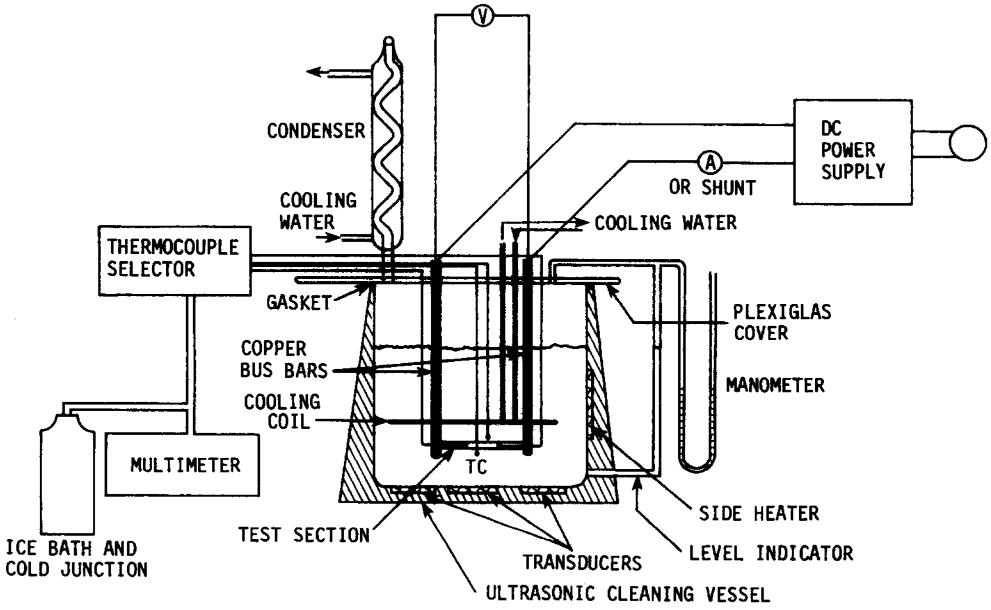

FIG. 1. Apparatus for ultrasonic enhancement of pool boiling.

attached to the bottom. The specifications included a basic frequency of 55 kHz, modulated with 120 Hz, and a combined transducer output of 75 W which resulted in an average intensity of 8000 W m^{-2}. A heater built into the side of the tank and a cold water coil were used to control the pool temperature. A reflux condenser connected to a plexiglas cover minimized loss of fluid. The pool was thoroughly degassed for all tests because Wong and Chon [10] noted that dissolved gas adversely affects the heat transfer.

An Electronic Measurement Co. rectifier of 36 A capacity was used to supply power to small diameter stainless steel tubes. The 200 mm long tubes, 1.65 mm o.d. and 1.19 mm i.d. or 2.11 mm o.d. and 1.60 mm i.d., were chosen so that the rolled-out vertical height, $\pi D/2$, corresponded approximately to the height of a microelectronic chip. To extend testing to burnout, a motor–generator was used. A standard ammeter and a voltmeter were used to establish the test section amperage and voltage drop with the rectifier while a precision digital multimeter was used to measure the amperage (via a shunt) and the voltage drop across the test tube when using the larger power supply. The heat flux was based on the voltage drop, current, and outside surface area.

Two copper–constantan thermocouples (30 gauge) with insulated beads were inserted into the tubes (at one third of the heater length from each end) and sealed. Outside wall temperatures were inferred by subtracting the calculated tube wall temperature drop from the average inside tube temperature. The maximum correction was 2.5 K. Two thermocouples were immersed near the test tube to measure the pool temperature. Saturated conditions were corroborated by a pressure measurement. The wall superheat, ΔT_S, was based on the average outside wall temperature and the saturation temperature corresponding to the pressure at the test section.

According to the study of Hoshino *et al.* [5], the best placement of the test section is at the maximum in force which occurs midway between the zero and maximum values of pressure and velocity. Furthermore, for maximum transmission of ultrasonic energy, the free surface is at zero pressure. These locations are readily related to the wavelength of the ultrasound, λ, which is 13 mm for R-113 at 20°C and 55 kHz. Four combinations of the test section vertical location and liquid level (indicated in Figs. 2 and 3) were chosen to determine the sensitivity of heat transfer enhancement to position.

RESULTS AND DISCUSSION

Data for natural convection without ultrasonics are in good agreement with the recommended curve of McAdams [13] for saturated and subcooled conditions, as shown in Figs. 2 and 3, respectively.

Boiling curves were generated by increasing and then decreasing test-section power. As shown in Fig. 2, the saturated boiling performance with ultrasonics is not dependent on heater location. There is negligible temperature overshoot prior to incipient boiling, which in itself is a form of enhancement. On the other hand, heat transfer is degraded in fully established boiling. These effects are most likely due to cavitation at the heated surface which triggers early boiling inception, but which probably contributes to there being too much vapor near the surface at moderate heat flux. At higher heat flux, boiling is so intense that vapor attenuates the ultrasonic energy before it reaches the surface; hence, a normal boiling behavior is resumed. The insensitivity to the test-section location and pool depth is possibly due to the vapor produced by boiling and cavitation, which disturbs the propagation of the ultrasonic waves.

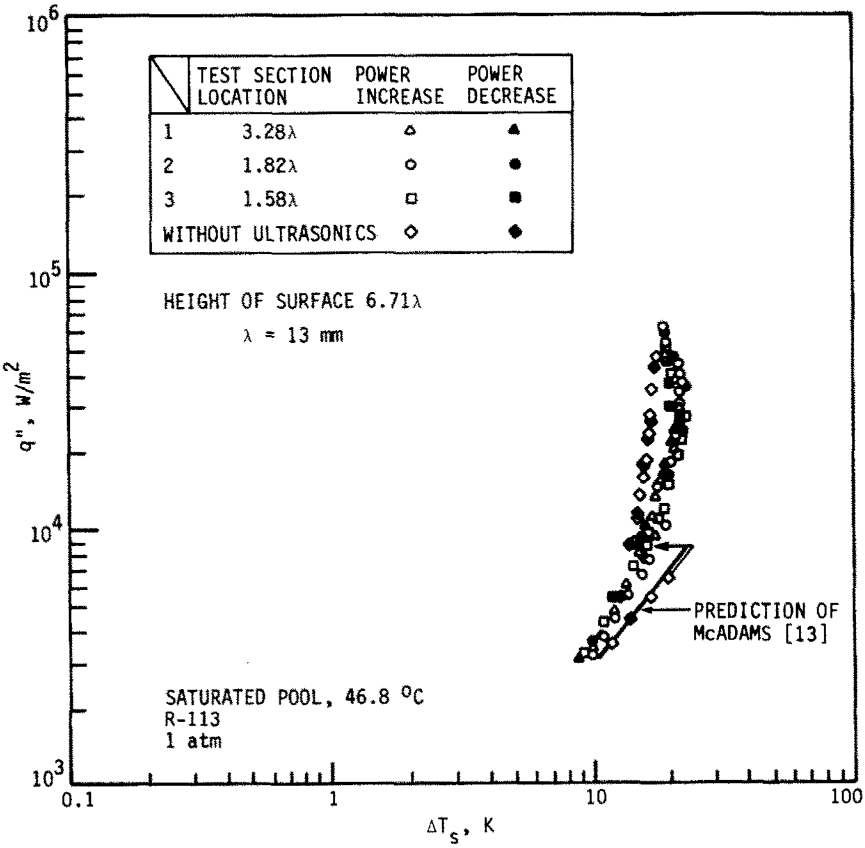

FIG. 2. Influence of test-section position and liquid level on saturated pool boiling heat transfer with ultrasonics.

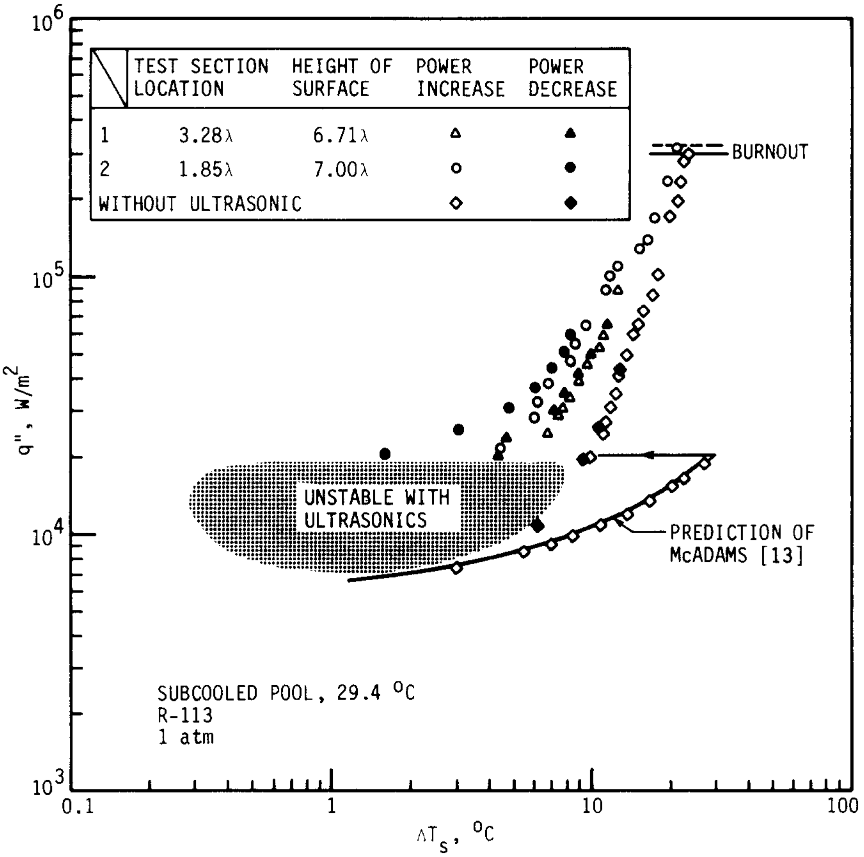

FIG. 3. Influence of test-section position and liquid level on subcooled pool boiling with ultrasonics, $T_b = 29.4°C$.

Substantial ultrasonic enhancement was observed when the pool was subcooled, as shown in Fig. 3. However, it was impossible to obtain accurate data at low heat flux due to temperature fluctuations. Even without heating, a dramatic increase in the activity of the pool was evident as the pool temperature, T_b, was raised to about 25°C. The wall temperature fluctuations resulted from cavitation bubble implosion which heated both the test section and pool thermocouples. (The pool temperatures were recorded in the absence of ultrasonics.) Low heat flux boiling is particularly enhanced. Position makes a difference, and position 4 (which is optimum) is definitely superior for both increasing and decreasing heat flux. The differences in boiling heat transfer for positions 1 and 4 are insignificant at the higher pool temperature of 37.6°C. The different behavior in high and low temperature pools is likely due to the smaller size of bubbles, either cavitation or nucleate boiling, in the latter tests.

Burnout heat fluxes without ultrasonics are in the range of the burnout flux envelope of Sun and Lienhard [14] as adjusted with the subcooling correction of Ivey [15]. On average, the ultrasonics produce a slight increase in burnout heat flux for saturated and subcooled pools (Fig. 3) of 10 and 5%, respectively. The improvements are less than those reported in the literature.

CONCLUSIONS

Experiments were performed with horizontal cylinders exposed to an ultrasonic field under saturated or subcooled conditions. A degradation of low heat flux boiling occurred when the pool was saturated, but boiling was improved when the pool was subcooled. The vertical test-section location and pool depth were significant only for the latter. Burnout heat fluxes for saturated and subcooled conditions were slightly increased by an ultrasonic field.

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