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ENHANCED BOILING HEAT TRANSFER BY SUBMERGED ULTRASONIC VIBRATIONS

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ABSTRACT

This paper describes a new two-phase cooling heat transfer cell based on a submerged vibration-induced bubble ejection process in which small vapor bubbles attached to a solid surface are dislodged and propelled into the cooler bulk liquid. This ejection technique involves forcibly removing the attached vapor bubbles with a submerged pressure difference generated by a vibrating piezoelectric diaphragm operating at ultrasonic frequencies. The piezoelectric driver induces pressure oscillations in the liquid near the heated surface, resulting in vapor bubble and liquid instabilities. These pressure differences generated by the piezoelectric driver operating at resonance enhance boiling heat transfer by removing attached vapor bubbles that insulate the surface.

A small-scale vibration-induced bubble ejection module that produced a pressure difference at a heated surface using an ultrasonic piezoelectric actuator was used in this initial study. The initial experimental data that was obtained include the cooling capabilities of the cell. The efficacy of this cooling approach was tested on a calibrated heater that dissipated 107 W/cm^2 at 120ºC in the absence of the jet using natural convection. When the jet was on, the heat flux increased to 191 W/cm^2 (i.e., an improvement of 78%) at the same surface temperature.

1. INTRODUCTION

In the microelectronics industry, advances in technology have brought about an increase in transistor density and faster electronic chips. As electronic packages increase in speed and capability, the heat flux that must be dissipated to maintain reasonable chip temperatures has also risen. Cooling fluxes are projected to reach the 1000 W/cm^2 level for some high power electronic applications [1].

Two-phase heat transfer, involving the evaporation of a liquid in a hot region and the condensation of the resulting vapor in a cooler region, can provide the large heat fluxes needed for microelectronic packages to operate at acceptable temperature levels. By changing the phase of the working fluid, a two-phase heat transfer cooling scheme supports high heat transfer rates across moderately small temperature differences. Heat pipes and thermosyphons are examples of efficient heat transfer devices that exploit the benefits of two-phase heat transfer [2-4]. Immersion cooling, which involves the pool boiling of a working fluid on a heated surface, is another example of a two-phase cooling technology used in microelectronic applications [5].

Direct liquid immersion cooling is a highly effective cooling strategy for two reasons: 1) the liquid to vapor phase change greatly increases the heat flux from the heated surface, and 2) the high thermal conductivity of the liquid medium, as opposed to that of air, enhances the accompanying natural or forced convection. Previously viewed as incompatible with microelectronic packages, interest in liquid immersion coolers has increased recently because of the need for effective cooling in microelectronic devices (see the review by Bar-Cohen, 1993) [6]. The performance of an immersion cooler at the high heat fluxes required of applications both today and in the future is possible because of the nucleate boiling that occurs with direct contact between the liquid and the hot electronic package. Boiling heat transfer has been widely studied for the last fifty years and has been reviewed by many authors, e.g., Dhir (1998) [7]. A key reason for the efficient heat transfer that occurs during boiling is that buoyancy forces (i.e., gravity) remove the vapor bubbles generated at the heated surface. When the heat flux from the surface is increased past a critical level, a large, possibly catastrophic increase in temperature occurs. This critical heat flux marks the transition from nucleate boiling to film boiling. In film boiling, a thin insulating layer of vapor completely covers the heated surface, which then produces the large temperature increase. This transition occurs at much lower heat fluxes in a microgravity environment because buoyancy forces are almost negligible. Thus, the performance of immersion cooling in this environment is drastically reduced.

A cooling cell based on the submerged vibration-induced bubble ejection (VIBE) process in which small vapor bubbles attached to a solid surface are dislodged and propelled into the cooler bulk liquid is a new technology that capitalizes on the benefits of two-phase cooling while improving on traditional pool boiling heat transfer. The VIBE cell has the potential to exceed the performance of conventional immersion cooling devices because it delays the onset of the critical heat flux. By forcibly removing the attached vapor bubbles with pressure instabilities, the VIBE cell dissipates more energy for a given surface temperature than other immersion coolers.

A schematic of one type of VIBE cell is shown in Figure 1. The cell consists of a vibrating driver operating at resonance that generates ultrasonic pressure variations directed at the immersed microelectronic component. As vapor forms on the chip surface, the action of the pressure differences generates instabilities removing the vapor bubbles allowing cooler bulk fluid to wet the hot boiling surface. The ejected vapor bubbles are cooled and condensed by the bulk liquid that is circulated through the cell. The entire cell can be very small, and the driver requires only a few watts of energy to operate.

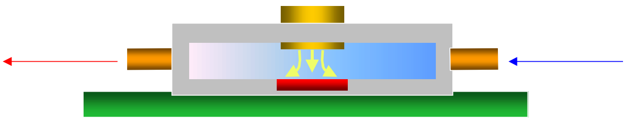

Figure 1. Schematic of a VIBE heat transfer cell.

The key technology in the VIBE cell is the submerged ultrasonic vibrations. An actuator comprised of a vibrating circular diaphragm mounted to a fixed surface produces these vibrations. A schematic depicting the details of the actuator and vibration induced bubble ejection is shown in Figure 2. The 19 mm diameter actuator is driven at the resonance frequency of its first axisymmetric mode of vibration (nominally 1.65 MHz) using a discrete electronic driving circuit consisting of a sinusoidal function generator and amplification chip. The motion of the actuator generates pressure waves that travel toward the vapor bubbles located on the hot surface. These pressure differences produce instabilities in the contact lines between the vapor and liquid. Bubble ejection is the result of these instabilities. Once the vapor bubbles are ejected from the hot surface, they condense in the cooler bulk liquid that is below the saturation temperature of the system. The separation distance and fluid properties (such as viscosity and surface tension) are important parameters that determine the efficiency of the ultrasonic VIBE process.

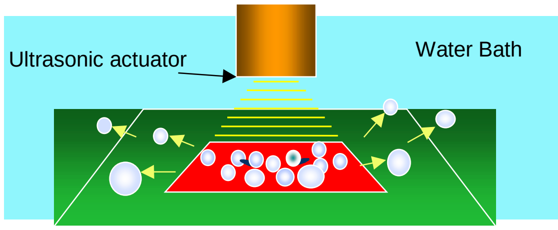

Figure 2. Detailed schematic of ultrasonic actuator and vibration induced bubble ejection.

2. VIBE MODULE HEAT TRANSFER RESULTS

In order to test the cooling efficacy of the ultrasonic vibrations, an immersion VIBE heat transfer module was constructed. The experimental set-up was open to the atmosphere and no effort was made to condense or collect the evaporated liquid. Each experiment was conducted in a small 2 gallon water tank as shown in the Figure 3 schematic. The ultrasonic actuator was mounted onto a variable height traverse attached to the bottom of the water tank. A copper calibrated heater was placed in the tank with the 1 cm by 1 cm exposed surface facing down. The calibrated copper heater contains several rows of thermocouples located in a one-dimensional conduction region. The output of these imbedded temperature sensors within heater was measured, displayed, and recorded with a data acquisition system. Resistance cartridge elements supplied heat to the calibrated piece of copper. The amount of heat dissipated on the surface of the copper heater as well as the surface temperature was calculated using the thermocouple data. In each of the experiments, the water tank was filled with a working fluid submerging the actuator and the surface of the calibrated heater.

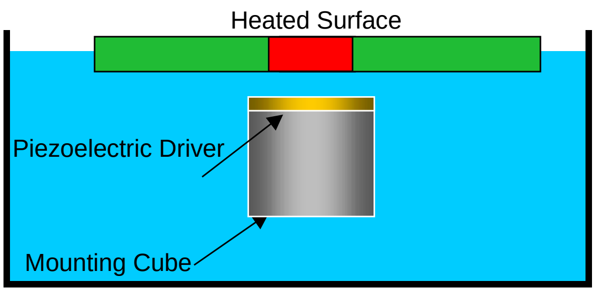

Figure 3. Schematic of initial VIBE heat transfer module test section.

The procedure for the VIBE heat transfer experiments was as follows. The actuator was placed in the desired location relative to the calibrated copper heater. The liquid reservoir was filled with a working fluid, and then the driver and heater were energized. The power and heat flux dissipated by the heater were measured by monitoring the thermocouple output. The temperature of the heater surface was also calculated and monitored using the embedded temperature sensors.

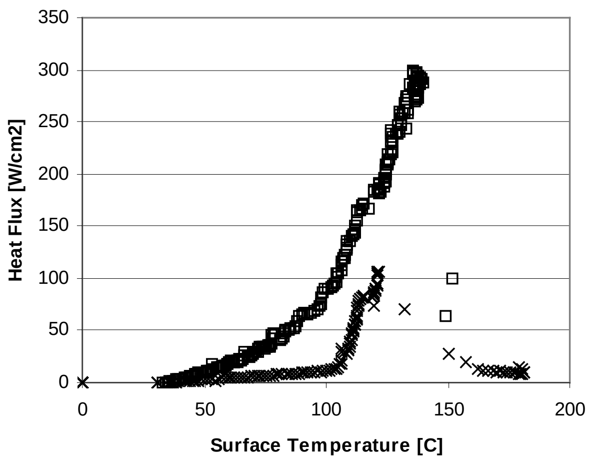

Figure 4. The heat flux dissipated using water with the actuator on (□) and with the actuator off (x).

In the first experiment, the effect of the actuator directed toward the calibrated heater was measured using distilled water. Data was obtained for two different scenarios: pool boiling with the actuator on and pool boiling with the actuator off. The results are shown in Figure 4. Below a heater temperature of 100ºC (the onset of boiling) the presence of the vibration increased the amount of heat dissipated for a given temperature. The pressure differences provided forced convection heat transfer from the chip to the pool of water. The added turbulent mixing and bulk motion present when the actuator was on compared to the free convection heat transfer when the actuator was off resulted in higher heat fluxes. Above 100ºC, the VIBE effect was present when the actuator was on. By removing the insulating vapor bubbles from the surface of the heater, the heat flux dissipated as a function of heater temperature increased at a faster rate. At a heater temperature of 120ºC, the heat flux dissipated increased from 107 W/cm^2 with the actuator off to 191 W/cm^2 when the actuator was on. This 78% improvement was a result of the VIBE process increasing the overall heat transfer coefficient through increased convection and the removal of insulating vapor bubbles.

Figure 5 shows the effect of actuator directed toward the calibrated heater when the working fluid is a 50/50 mixture of water and ethylene glycol (antifreeze). Below a temperature of 130ºC, the presence of the vibrations from the actuator has no effect on the level of heat dissipated. Above 130ºC, the instabilities generated by the vibrating actuator dislodge the vapor bubbles resulting in an extended critical heat flux (CHF). With no vibration present, the CHF was 235 W/cm^2 at a temperature of 157ºC. This CHF level increased 106% when the actuator was energized to a level of 485 W/cm^2 at a temperature of 153ºC. The increased viscosity of the mixture due to the addition of ethylene glycol to distilled water decreases the effectiveness of the ultrasonic vibrations. The additional viscosity dampens the pressure fluctuation resulting in reduced contact line instabilities.

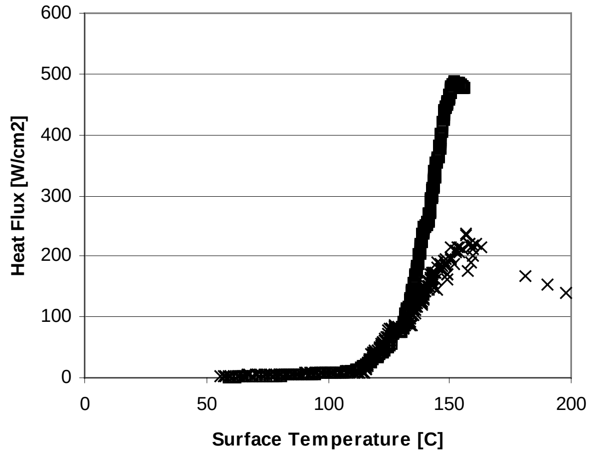

Figure 5. The heat flux dissipated using ethylene glycol and water mixture with the actuator on (□) and with the actuator off (x).

The effect of an actuator in a 70/30 mixture of water and methanol is shown in Figure 6. This non-flammable mixture begins to change phase below 100ºC providing increased opportunity to take advantage of the phase change boiling enhancements when lower device temperatures are desired. Below a temperature of 105ºC, the presence of the vibrations from the actuator has no effect on the level of heat dissipated. Above 105ºC, the instabilities generated by the vibrating actuator dislodge the vapor bubbles resulting in an extended CHF. With no vibration present, the CHF was 103 W/cm^2 at a temperature of 103ºC. This CHF level increased 425% when the actuator was energized to a level of 655 W/cm^2 at a temperature of 133ºC. The lower viscosity of this mixture compared to the ethylene glycol/water mixture improves heat dissipation performance. The synergy of the methanol/water mixture properties and the ultrasonic-induced pressure fluctuations produces significant heat dissipation compared to the pool boiling situation.

Another initial set of experiments examined the effect of the pool bulk temperature with pure water as the

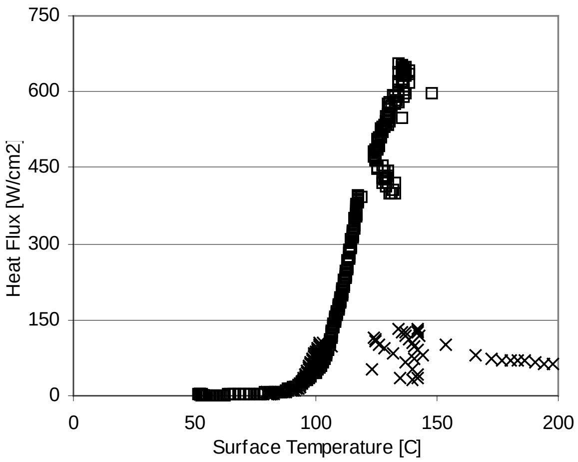

Figure 6. The heat flux dissipated using methanol and water mixture with the actuator on (□) and with the actuator off (x).

working fluid. Figure 7 shows the heat flux from the calibrated heater as a function of the surface temperature for an elevated pool temperature of 80ºC. This data shows that the vibration extended the CHF, but did not improve the heat dissipation at lower surface temperatures. At a temperature of 125ºC, the CHF increased from 127 W/cm^2 to 302 W/cm^2 as the actuator was energized. This ability of the VIBE process to improve the heat dissipation as elevated bulk temperatures provides further design flexibility in the implementation of a VIBE heat transfer module for microelectronic cooling applications.

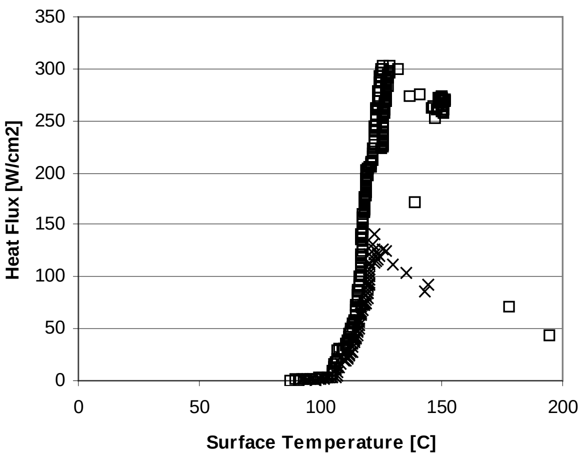

Figure 7. The heat flux dissipated using water with a bulk temperature of 80ºC with the actuator on (□) and with the actuator off (x).

4. VIBE FLOW CELL HEAT TRANSFER RESULTS

A VIBE heat transfer cell similar to the device shown in Figure 1 was experimentally evaluated. This cell has an inlet and outlet to allow for a flow of liquid removing the heat dissipated by the thermal test vehicle. The module was machined from an existing aluminum heat sink. The internal dimensions of the module are 43 mm wide x 12 mm high x 51 mm long. In order to control the bath temperature within the module, a cross flow was instigated within the cell. A pump was used to force liquid from a constant temperature bath through the cell and back to the bath reservoir. Using hose connections, subcooled fluid was supplied to the cell from the chilled bath.

A single calibrated copper heater was attached to the heat sink such that heat was supplied to the center of the fluid flow region. Thermal grease was applied between the calibrated heater and the aluminum VIBE heat transfer cell. A single ultrasonic transducer was aligned directly opposite the calibrated heater in an acryllic cover which formed the bottom of the cell. In this experimental set-up, the fluid temperature and the flow rate into the cell were varied and controlled using the chilled water bath and pump.

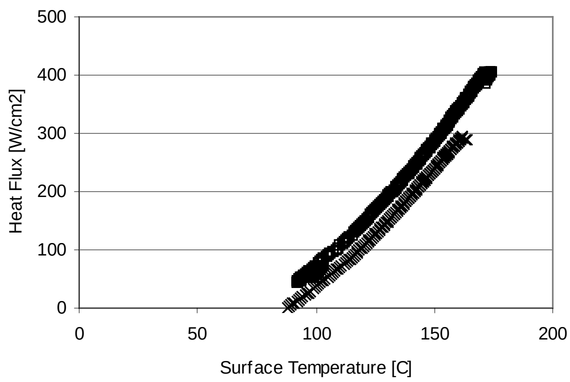

Figure 8. The heat flux dissipated using water with a fluid inlet temperature of 85ºC with the actuator and a cross flow of 1 gpm (□) and 3.3 gpm (x).

Figure 8 presents the heat flux dissipated by the VIBE flow cell with elevated fluid inlet temperatures. The subcooled water temperate was 85ºC, and the actuator was 12 mm from the heated surface. The flow rate through the cell was changed from 1.0 gpm to 3.3 gpm. For both of these flow rates, the presence of vibration resulted in a 30% improvement in heat dissipation compared with no ultrasonic actuation. To extend the level of improvement above 30%, the actuators need to be closer to the heated surface. The pressure differences generating the vapor bubble ejection decrease with increased separation distance. The acoustic energy produced by the actuator is dissipated in the fluid as the pressure waves travel through the fluid. The smaller separation distance should produce larger pressure differences due to less acoustic energy dissipation.

5. CONCLUSIONS

A pool boiling enhancement heat transfer technology based on a new ultrasonic vibration-induced bubble ejection mechanism called VIBE has been demonstrated. In this technology, a piezoelectric diaphragm is used to produce a series of pressure oscillations that are directed at a microelectronic package. These pressure oscillations generate instabilities in the vapor/liquid contact lines resulting in the ejection of vapor bubbles that form on the package during nucleate boiling. The pressure forces eject the vapor bubbles back into the cooler bulk liquid where they condense.

The present set of experiments used a variety of working fluids including water, ethylene glycol/water (50/50 mix), and methanol/water (70/30 mix) under atmospheric conditions. Heat fluxes over 600 W/cm^2 (methanol/water mixture) were achieved in a compact geometry requiring approximately 1 W of input power. This is a heat flux increase of 425% compared to traditional pool boiling with no jet, for the same surface temperature.

The performance of the VIBE process in terms of the heat flux for a given surface temperature increased as the separation distance between the actuator and the surface of the die decreased. The added viscosity of the ethylene glycol mixture dampens the pressure oscillations generated by the actuator resulting in less heat dissipation compared to pure water and a methanol/water mixture. Increasing the bulk temperature also decreases the heat flux dissipated by the VIBE module, however, at a bulk temperature of 80ºC, the VIBE process dissipated over 300 W/cm^2 at a surface temperature of 127ºC.

The VIBE heat transfer flow cell described above indicates the ability of the ultrasonic actuators to improve over traditional channel flow boiling. At an elevated inlet temperature of 85ºC, a single ultrasonic actuator produces a 30% improvement in heat dissipation at a variety of cross flow rates (from 1 to 3.3 gpm).

These heat transfer results demonstrate the potential of this VIBE process to effectively manage heat removal from high power microelectronics and for the thermal management of microprocessors and other electronic hardware. Future work will focus on incorporating an array of ultrasonic actuators into a sealed small-scale heat transfer cell in which the internal pressure will be controlled.

6. ACKNOWLEDGMENT

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7. REFERENCES

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