Thus equation (6) can only be valid if the condition of equation (9) is satisfied. By comparison with our rotating film data, the smooth wall condition corresponds to $k_s < 1\ \mu$m (based on the rotating film thickness data of Kirkpatrick, 1980). Since the heat transfer surface was fabricated by milling, most of the data were found to fall in the roughness range corresponding to equation (10).

Conclusions

This study has focused on boiling heat transfer to thin rotating water films. The primary objective was to study the effects of pressure, centrifugal acceleration, and flow rate on boiling incipience. The primary conclusions are as follows:

1 Acceleration increased the convective heat transfer coefficient prior to boiling and delayed boiling incipience.

2 Coriolis forces play a significant role in rotating film convective processes. Prior to boiling, these forces influence the turbulent velocity fluctuations within the film as well as the stability of the free film interface.

3 Rotating films are typically very thin, and as such, wall roughness is believed to destroy the laminar portion of the thermal boundary layer. Thus, common incipient boiling models based on the existence of a linear temperature profile in the vicinity of the heated surface should be avoided if the surface fails to satisfy the smoothness condition of equation (9). The present data also indicate the existence of a different mechanism for boiling incipience that may be the result of turbulent exchange of heat between the wall and the bulk of the film rather than molecular diffusion.

References

Bergles, A. E., and Rohsenow, W. M., 1964, "The Determination of Forced Convection Surface-Boiling Heat Transfer," ASME JOURNAL OF HEAT TRANSFER, Vol. 86, pp. 365-372.

Chun, K. R., and Seban, R. A., 1971, "Heat Transfer to Evaporating Liquid Films," ASME JOURNAL OF HEAT TRANSFER, Vol. 93, pp. 391-396.

Davis, E. J., and Anderson, G. H., 1966, "The Incipience of Nucleate Boiling in Forced Convection Flow," *AIChE Journal*, Vol. 12, pp. 774-780.

Han, C. Y., and Griffith, P., 1965, "The Mechanisms of Heat Transfer in Nucleate Pool Boiling. Part I: Bubble Initiation, Growth and Departure," *International Journal of Heat and Mass Transfer*, Vol. 8, pp. 887-904.

Hsu, Y. Y., and Graham, R. W., 1961, "Analytical and Experimental Study of Thermal Boundary Layer and Ebullition Cycle," NASA Technical Note TNO-594.

Kirkpatrick, A. T., 1980, "Wave Mechanics of Inclined and Rotating Liquid Films," Ph.D. Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA.

Mudawwar, I. A., El-Masri, M. A., Wu, C. S., and Ausman-Mudawwar, J. R., 1985, "Boiling Heat Transfer and Critical Heat Flux in High-Speed Rotating Liquid Films," *International Journal of Heat and Mass Transfer*, Vol. 28, pp. 795-806.

Limits to Critical Heat Flux Enhancement in a Liquid Film Falling Over a Structured Surface That Simulates a Microelectronic Chip

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Nomenclature

L = length of heater

q = heat flux based on the total base area of the enhanced surface

q_M = critical heat flux (CHF) based on the total base area of the enhanced surface

T = temperature

ΔT_{sat} = wall superheat at the base of the enhanced surface = $T_w - T_{\text{sat}}$

ΔT_{sub} = inlet subcooling = $T_{\text{sat}} - T_{in}$

U = mean inlet velocity

δ = film inlet thickness

Subscripts

in = inlet

sat = saturated

sub = subcooled

w = wall

Introduction

The combination of increasing power densities and stringent surface temperature constraints for microelectronic components has stimulated interest in cooling by means of pool boiling in a dielectric liquid. However, although dielectric fluorocarbons such as FC-72 (manufactured by 3M) are highly compatible with electronic components, small thermal conductivities and latent heats make them poor heat transfer fluids. Moreover, pool boiling studies concerned with CHF enhancement (Bergles and Chyu, 1982; Marto and Lepere, 1982) have shown that significant hysteresis (temperature overshoot) at the inception of boiling may violate component temperature limitations.

More recently, the falling liquid film has been considered as a means of enhancing the performance of dielectric coolants by controlling boiling hysteresis and increasing the critical heat flux (CHF). From experimental studies performed for a gravity-driven liquid (FC-72) film flowing over a smooth surface (Mudawwar et al., 1987), the ability to suppress hysteresis was demonstrated, and the trend of increasing CHF with decreasing heater length was determined. However, even for the smallest heater length of the study (L = 12.7 mm), CHF values were not much higher than those associated with pool boiling.

To determine whether structured surfaces could be used to substantially extend CHF, Grimley et al. (1987) performed experiments for a thin film of FC-72 falling over a 63.5-mm-long surface with either longitudinal microfins or microstuds. Although both the microfin and microstud surfaces enhanced nucleate boiling heat transfer relative to a smooth surface, only the microfin surface provided significant enhancement of CHF. CHF was observed to be due to dryout of a thin subfilm, which remained on the boiling surface after the bulk of the fluid in the falling film had separated due to intense vapor generation. It was argued that the microfins extended CHF by allowing surface tension forces to maintain the liqud film on the surface more effectively and by inhibiting the lateral spread of dry patches after film separation. In contrast, the microstud surface acted to break up the film, thereby hastening film separation and decreasing CHF. In addition, it was found that CHF could be enhanced by subcooling the liquid or by installing a louvered flow deflector a short distance from the heated surface. While subcooling decreased the intensity of vapor effusion by supplying the heated surface with liquid of reduced temperature, the deflector inhibited film separation.

On the basis of the foregoing results, it is known that CHF in a falling liquid film may be enhanced by reducing the length of the heated surface, machining longitudinal grooves in the surface, shrouding the surface with a louvered flow deflector, or subcooling the liquid. However, experiments have yet to be performed in which these effects are considered collectively in

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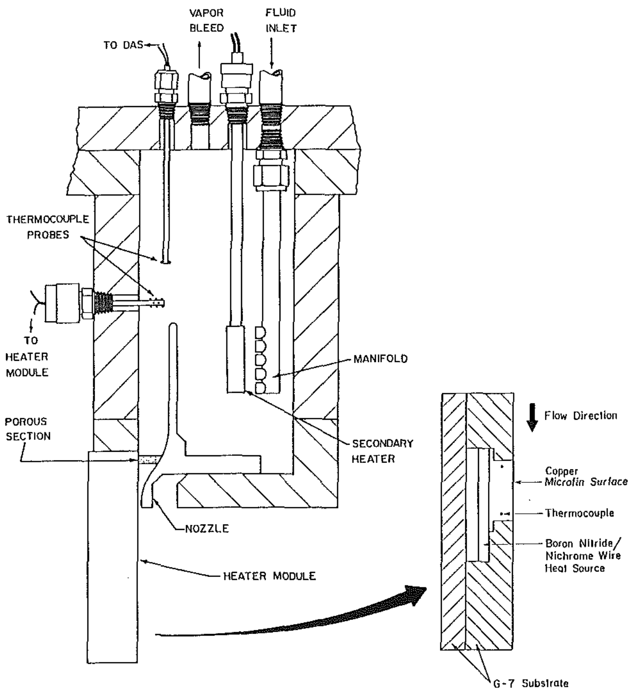
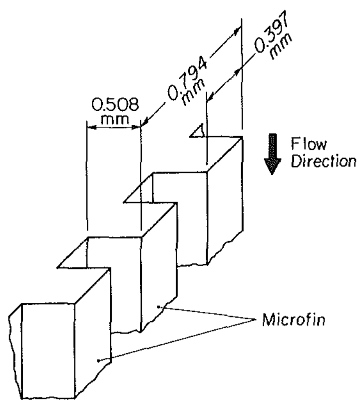
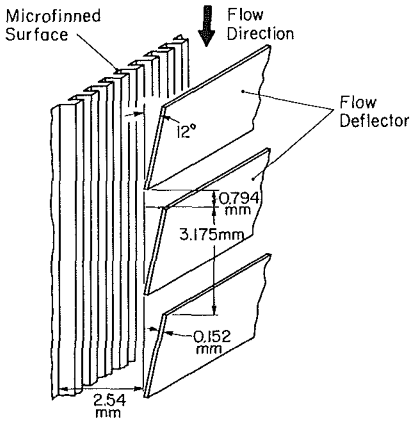


Fig. 1 Schematic of heater module and flow supply chamber



Microfinned Surface



Flow Deflector Geometry

Fig. 2 *Microfin surface geometry with flow deflector*

order to establish upper limits for CHF enhancement. Hence, the purpose of this study has been to determine boiling characteristics for a subcooled film of FC-72 falling over a short microfinned surface with an attached flow deflector. Experiments have been performed for a 12.7-mm-long by 25.4-mm-wide microfinned surface and for subcooling in the range from 0 to 14°C. The length of the heater is representative of microelectronic chip sizes.

Experimental System

As shown in Fig. 1, the gravity-driven liquid film was supplied to a heater module by a nozzle attached to the base of a fluid containment chamber. The thickness of the film was controlled by adjusting the nozzle position, and a porous plate upstream of the nozzle provided sufficient back pressure to fill the chamber with fluid. The upper edge of the heater was located at the nozzle exit. The heater module consisted of an oxygen-free copper block, which was pressed against a nichrome wire heat source in a G-7 fiberglass substrate. The nichrome wire was wound along grooves machined in one of two adjoining boron nitride (BN) plates, while very fine BN powder was used to minimze the thermal contact resistance between the BN plates and at the interface between the heat source and copper block. A conduction analysis of the heater module indicated that heat losses to the surroundings were less than 2 percent of the power input. Temperature measurements made at upstream and downstream locations in the copper block indicated longitudinal variations of less than 0.5°C, thereby permitting the assumption of isothermal surface conditions.

As shown in Fig. 2, the microfin geometry consists of 0.508-mm-high by 0.397-mm-wide fins spaced on 0.797 mm centers machined into the copper block. Prior to use, the surface was cleaned with acetone, blown dry with nitrogen, and mounted in the insulating substrate with the fins aligned in the flow direction. The base of the fins was flush with the surface of the substrate. The deflector was formed from 0.152-mm-thick brass stock into which louvers were formed by cutting 0.794 mm slots spaced on 31.75 mm centers. The webs were then bent approximately 12 deg, and the deflector was mounted 2.54 mm from the base of the boiling surface. Since the deflector was not in good thermal contact with the boiling surface, it served to modify the separated flow of the film, rather than to act as an extended surface.

Fluid was supplied to the test chamber by a closed-loop fluid delivery system constructed of stainless steel and compatible plastics. To insure high fluid purity, the FC-72 was degassed in a charging system connected to the fluid delivery system. The fluid delivery system was then charged by evacuating it to 500 μm before allowing the FC-72 to be flashed from the charging system. During operation, control was maintained over the film velocity, the film thickness, the fluid temperature upstream of the heater module, and the chamber pressure. Subcooling was quantified in terms of the difference between the saturated temperature corresponding to the test chamber pressure (T_{sat}) and the fluid inlet temperature (T_{in}). System details are provided elsewhere (Grimley et al., 1987). At atmospheric pressure $T_{sat} = 56°C$ for FC-72.

Once the desired pressure, temperature, and film conditions were established, power was applied to the heat source. Boiling curves were generated by increasing the power to the heater module in discrete steps and then waiting for steady-state conditions. When steady-state was reached, the pressure, temperatures, power, and flow rate were recorded by an HP3054 data acquisition system. As CHF was approached, the magnitude of the power increment was decreased to reduce uncertainty in the reported value of CHF. CHF was detected by a rapid surge in the boiling surface temperature.

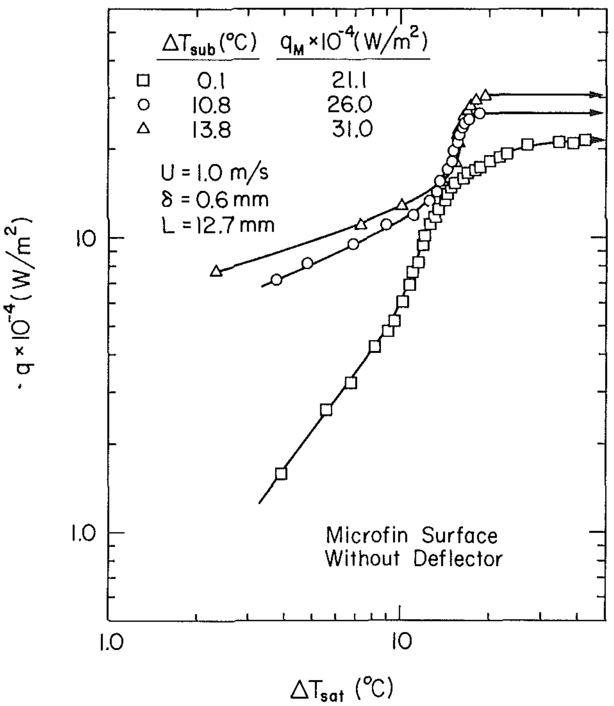


Fig. 3 Effect of subcooling on the boiling curve for the microfin surface without the flow deflector

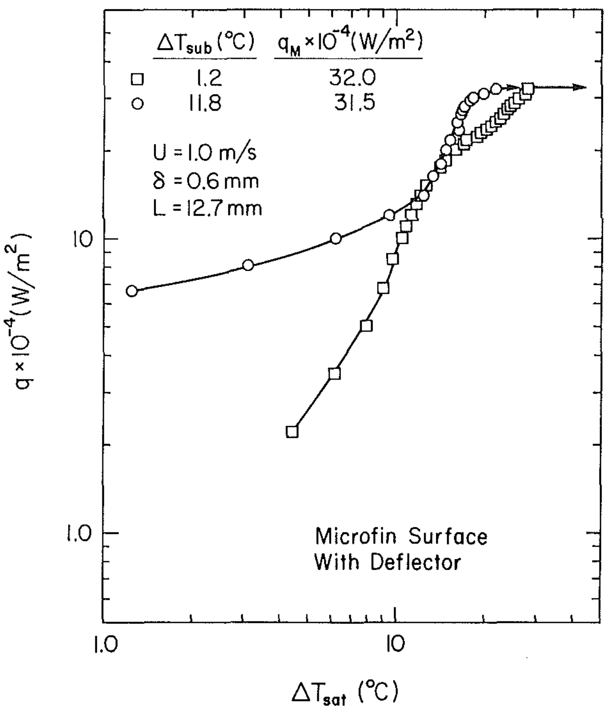


Fig. 4 Effect of subcooling on the boiling curve for the microfin surface with the flow deflector

Experimental Results

The results are presented in the form of boiling curves that plot the average heat flux q as a function of the temperature difference, $\Delta T_{\mathrm{sat}} = (T_w - T_{\mathrm{sat}})$. All experiments were performed with an average film velocity of $U = 1.0$ m/s and a film thickness of $\delta = 0.6$ mm.

For saturated conditions ($\Delta T_{\mathrm{sub}} = 0$), the boiling process was similar to that previously described (Grimley et al., 1987; Mudawwar et al., 1987). Nucleation first occurred near the lower edge of the heated surface between the microfins. As the heat flux was increased, nucleation sites became active in the upstream region and nucleation patches formed across the span of the heater. The nucleation patches coalesced and the void fraction increased in the flow direction. For saturated conditions, film separation occurred near the lower edge of the heater when the void fraction became too large to maintain a continuous liquid film on the heated surface. When the bulk of the film separated, a thin sublayer remained on the surface and was visible between the microfins. CHF occurred when non-rewetting dry patches formed in the sublayer.

Without the flow deflector, the effect of subcooling on the boiling curve is shown in Fig. 3. The large convection coefficient associated with the upstream region of the 12.7 mm heater delayed boiling incipience to $q \approx 12$ W/cm^2, which is approximately three times larger than that required for a 63.5-mm-long heater (Grimley et al., 1987). CHF corresponded to $q_M = 21.1$ W/cm^2 for saturated conditions, which is approximately 30 percent larger than that obtained for a smooth surface of the same length (Mudawwar et al., 1987). In contrast Grimley et al. (1987) had previously found a 50 percent increase in CHF when microfins were used with a 63.5-mm-long heater. Hence, the effectiveness of the microfin surface is diminished by a reduction in the heater length. As shown in Fig. 3, in addition to increasing the value of CHF, subcooling reduced the temperature difference at the onset of CHF. The surface temperature was reduced from approximately 97°C for the saturated condition to about 78°C for the subcooled conditions. As for the long heater (Grimley et al., 1987), subcooling delayed nucleation and inhibited bubble growth once nucleation had occurred. However, for the short heater, bubble growth was inhibited to a greater degree and CHF occurred without significant film separation.

The fact that CHF occurred without significant film separation suggests that a different CHF mechanism exists for highly subcooled films. Although the wall temperature exceeds the saturation temperature, the bulk of the film remains subcooled, thereby inhibiting the growth of bubbles produced at the wall and reducing the downstream void fraction. CHF could then occur when the heat flux is large enough to generate a thin vapor blanket at the wall, for which the attendant void fraction is not large enough to cause significant film separation.

Figure 4 shows boiling curves obtained with the deflector and the liquid film at nearly saturated conditions and 11.8°C subcooling. For saturated conditions, CHF occurred at $q_M = 32$ W/cm^2, which is a 50 percent increase relative to the value obtained without the deflector. This increase was similar to the 44 percent increase that occurred for the 63.5 mm heater (Grimley, 1987). Moreover, interaction of the film with the deflector was similar to that observed for the 63.5 mm heater. Initially, the film flowed over the heater without contacting the deflector. As the heat flux was increased, nucleation occurred and the film thickened, allowing the outer surface of the film to contact the deflector. At higher fluxes, bubbles vented between the louvers and an increasing fraction of the film flowed outside the deflector. The contact point moved upstream until it approached the top of the heater, and enough pressurization occurred to project a liquid stream away from the deflector.

As shown in Fig. 4, CHF showed no improvement when subcooling was used in combination with the deflector. The boiling curve did change, however, and the temperature difference at the onset of CHF was reduced. Subcooling delayed the onset of backflow over the deflector to $q \approx 29$ W/cm^2, in contrast to 12 W/cm^2 for saturated conditions. The fact that backflow was delayed to more than 90 percent of CHF indicates that, as in the absence of the deflector, CHF for the subcooled conditions was not accompanied by significant

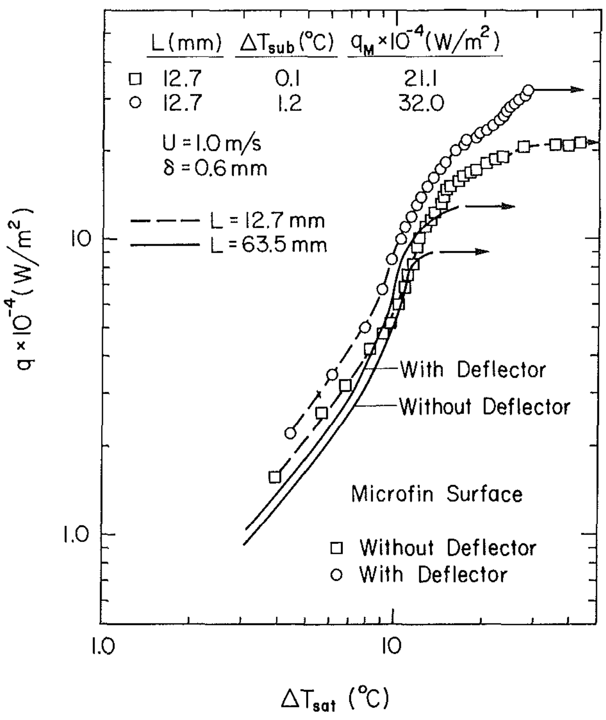


Fig. 5 Comparison of boiling curves for different heater lengths with and without flow deflector (liquid film is at or near saturated conditions)

separation. Because subcooling reduced film separation, the combination of the flow deflector and subcooling did not increase the value of CHF relative to that corresponding to use of the deflector with a saturated film.

Figure 5 compares boiling curves for 12.7 and 63.5-mm-long heaters with and without flow deflection. Although larger heat fluxes may be achieved with the short heater, the surface temperature at the onset of CHF is also considerably larger for the short heater. For applications with low surface temperature limits, flow deflection or subcooling may therefore be required to reduce the surface temperature.

Conclusions

This study has focused on boiling heat transfer from a vertically mounted, structured surface to a falling liquid film of FC-72. The primary objective was to study the cumulative effect of a small heater length, microfins, liquid subcooling, and a louvered flow deflector on the critical heat flux. The primary conclusions are as follows:

1 The 12.7-mm-long microfinned surface enhanced CHF relative to a smooth surface of equal length and a microfinned surface that was five times longer.

2 Subcooling increased CHF and decreased the temperature difference at the onset of CHF. The effect of subcooling on CHF was less pronounced for the 12.7-mm-long heater than for a 62.5-mm-long heater.

3 For subcooled conditions on the short heater, CHF occurred without significant film separation.

4 Although the louvered flow deflector enhanced CHF for saturated conditions, no improvement was found when subcooling was used in combination with the deflector.

5 CHF may be improved by a combination of reduced heater length, subcooling, and flow deflection, but the effects are not independent and superposition does not apply. For a 12.7-mm-long heater and film velocities typical of passive or semi-passive electronic cooling systems, it appears that the combination of microfins, subcooling and a flow deflector cannot enhance CHF much above 30 W/cm^2.

In summary the concept of boiling in a falling film is attractive for cooling electronic components by virtue of its suppression of the hysteresis phenomenon and its compatibility with passive or semi-passive flow arrangements. Morever, significant enhancement may be achieved by using microfinned surfaces in combination with liquid subcooling or a flow deflector to achieve critical heat fluxes as large as 30 W/cm^2 for FC-72 and a 12.7-mm-long heater. However, unless the film is supplied to relatively large extended surfaces to increase the heat transfer area, it is unlikely that existing or future augmentation schemes will render the concept suitable for dissipating the large fluxes ($>$ 100 W/cm^2) projected for VLSI devices.

Acknowledgments

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References

Bergles, A. E., and Chyu, M. C., 1982, "Characteristics of Nucleate Boiling From Porous Metallic Coatings," ASME JOURNAL OF HEAT TRANSFER, Vol. 104, pp. 279-285.

Grimley, T. A., Mudawwar, I. A., and Incropera, F. P., 1987, "Flowing Fluorocarbon Liquid Films Using Structured Surfaces and Flow Deflectors," *International Journal of Heat and Mass Transfer*, in press.

Marto, P. J., and Lepere, V. J., 1982, "Pool Boiling Heat Transfer From Enhanced Surfaces to Dielectric Fluids," ASME JOURNAL OF HEAT TRANSFER, Vol. 104, pp. 292-299.

Mudawwar, I. A., Incropera, T. A., and Incropera, F. P., 1987, "Boiling Heat Transfer and Critical Heat Flux in Liquid Films Falling on Vertically Mounted Heat Sources," *International Journal of Heat and Mass Transfer*, Vol. 30, pp. 2083-2095.