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High Heat Flux Cooling for Spacecraft Electronics

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Abstract

An experimental investigation of flow boiling in a curved channel has been performed to ascertain its value in electronics cooling applications. Results have been obtained for flow velocities of 1 to 5 m/s and subcooling of 0.5 to 40 K. These results were compared to those of a straight channel under identical velocity and subcooling conditions. The critical heat flux of the curved channel was found to be greater than that of the straight channel. In some cases the increase was found to be marginal, however. An unexplained temperature shift in the nucleate boiling regime was experienced during some experiments. Because this shift only occurred for the first test of the day, it is thought to be related to the incipience phenomenon often experienced in pool boiling experiments. Finally, true incipience overshoot and nucleate boiling regime hysteresis were found to be negligible.

INTRODUCTION

Future spacecraft electronics and high power transmission devices will require cooling capacities that far surpass the capabilities of currently developed capillary fed evaporative devices (Mahefkey 1982 and Hager and Chang 1990). Very large scale integrated (VLSI) circuits for military aircraft and commercial computers will soon exceed heat fluxes of 200 W/cm^2 (Chang and Hager 1990). Many single and two–phase cooling schemes have been proposed to meet these demands. The most popular employ direct contact cooling using a dielectric fluid. A comprehensive review is given by Incropera (1988).

Boiling is attractive because a large increase of heat flux is possible for a small change in surface temperature. There are, however, some characteristics such as incipience temperature overshoot and transition to film boiling (critical or burnout heat flux) that must be understood and predicted so that these can be avoided for actual applications.

DISCUSSION

The present study pursues an experimental investigation of flow boiling in a curved channel (Figure 1) as a means of increasing boiling effectiveness. Gu et al. (1989) have shown an increase in critical heat flux (CHF) of over 40 percent for curved versus straight channels. One of the reasons for this increase is the enhancement of bubble removal created by centrifugal acceleration. Buoyant forces are increased proportional to V^2/r where V is fluid velocity and r is the radius of curvature of the flow channel.

The effect of acceleration on boiling was first deduced by Kutateladze (1950) who derived a correlation for CHF by dimensional analysis. This correlation is widely known as the Zuber's equation and applies to pool boiling. Experimental studies confirmed the $(a/g)^{1/4}$ dependence of pool boiling CHF (a/g is dimensionless acceleration). For flow boiling, the effect of acceleration is much harder to determine because the effects of flow velocity alone are difficult to quantify. Gambill and Greene (1958) performed tests with water in vortex flow through a cylinder and found that CHF is proportional to the fluid velocity. Heat fluxes of over 17 kW/cm^2 were achieved which illustrates the potential of this method.

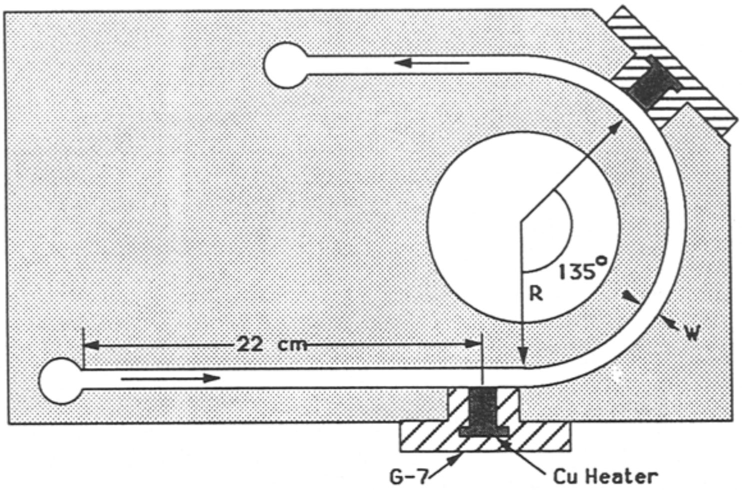

FIGURE 1. Straight and Curved Channel Test Section (R = 2.54 cm, W = 0.32 cm).

In the present investigation FC–72 (a stable fluorocarbon produced by 3M Corp.) is circulated through a curved channel over a copper heater block (Figure 1). Results at low velocities and moderate subcooling, are shown in Figure 2. The relative increase in CHF of the curve channel versus the straight configuration is much less than that reported by Gu

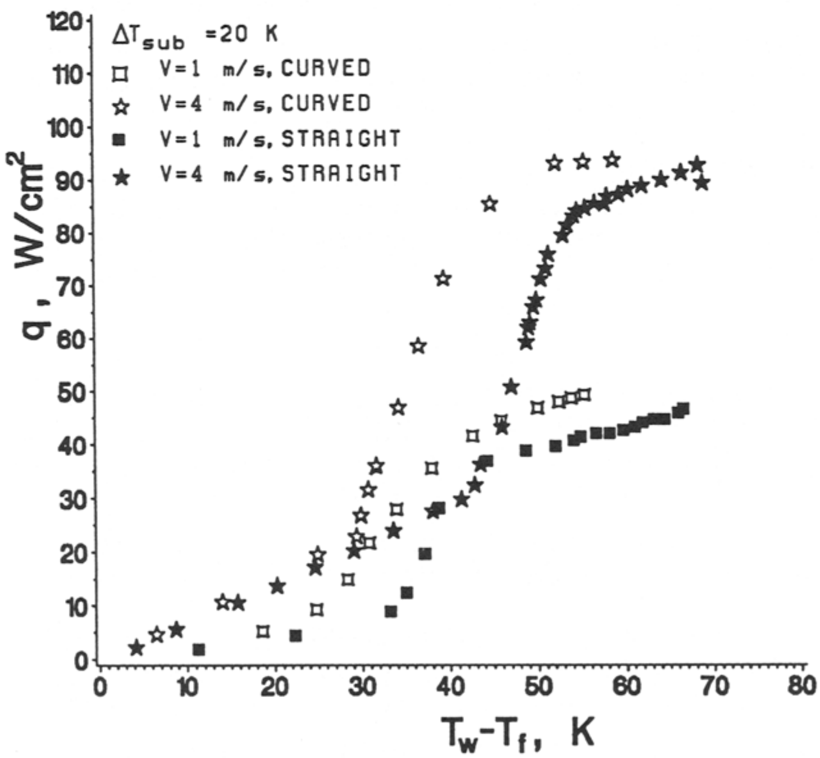

FIGURE 2. Velocity and Geometry Dependence of Nucleate Boiling.

et al. (1989). This may be because of the reduction in channel height (0.32 versus 0.56 cm) which causes a reduction in in the secondary flow induced forced convection contribution. CHF varies as $(a/g)^{0.3}$ for this case. It should be noted that boiling incipience temperature overshoot did not occur for any of the cases. This is significant because incipience overshoot is a trait of highly wetting fluids such as FC–72. Temperature excursions of over 20 K were reported by You et al. (1990) for pool boiling experiments using FC–72.

Possible incipience related phenomena is, however, shown in Figure 3 and is denoted by the curve marked "Wall Temperature Shift." This is the most extreme case recorded to date. While an incipience and nucleate boiling offset of about 20 K is shown, CHF occurs at about the same point as for a typical case under the same conditions. This indicates that nucleation sites did not become active as quickly compared to the typical case throughout most of the nucleate boiling regime. This trend was also confirmed visually.

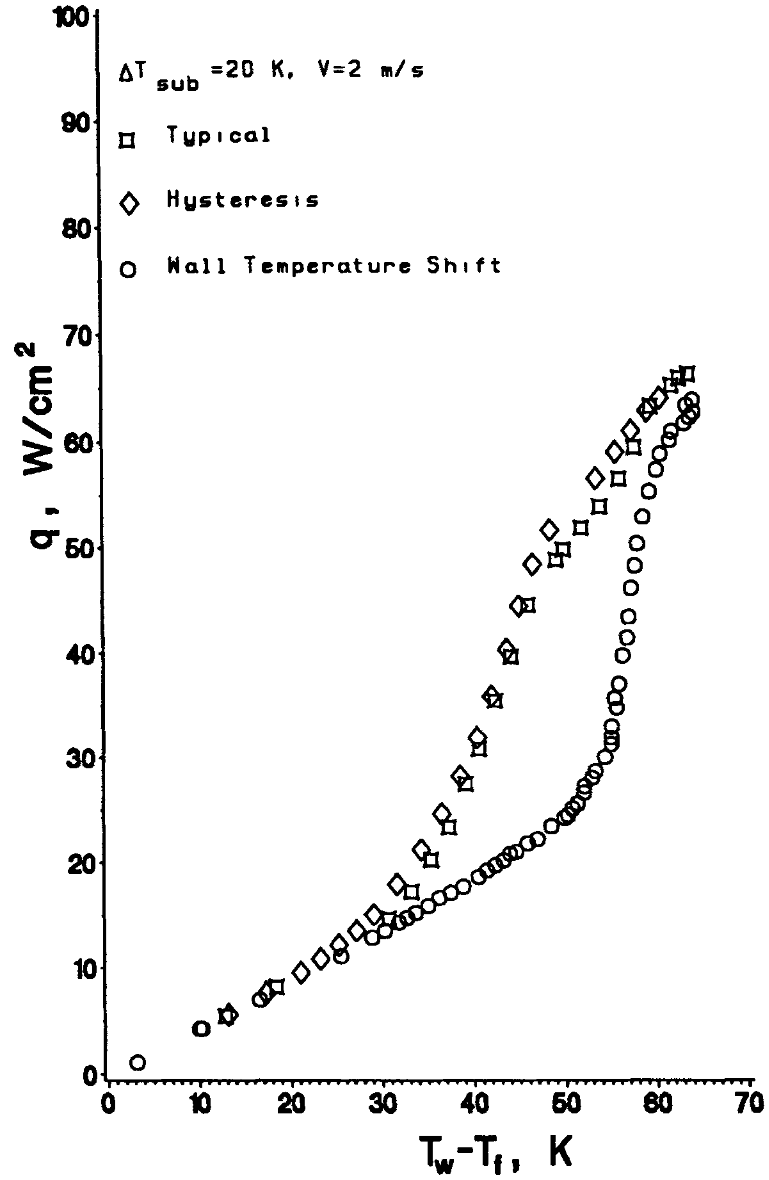

FIGURE 3. Effect of Hysteresis and Temperature Shift of Nucleate Boiling Regime.

Incipience overshoot is generally most pronounced when the surface has remained wetted under non–boiling conditions for more than one day. This is because the fluid has forced gas out of the nucleation sites. The presence of non–condensable gas lowers the amount of wall superheat ($T_w - T_f$) required for nucleation. The most extreme case of the overshoot phenomenon occurred during the first test after the heater surface was exposed to air for about 48 hours. This is counter intuitive to what is known about boiling and remains to be explained. All other cases of the overshoot phenomenon also occurred during the first test of the day and showed offsets of less than 5 K. Subsequent tests showed no signs of this phenomenon and are very repeatable throughout the entire boiling regime.

Figure 3 also shows the effect of boiling hysteresis encountered by reducing heat flux from near CHF conditions. As can be seen, the effect is small, but predictable. This should not be confused with the more common boiling hysteresis encountered during a transition from film to nucleate boiling. Film boiling tests have not been run because of the temperature limitations of the test apparatus.

CONCLUSIONS AND PLANS

It has been found that at low velocities, CHF varies roughly as $(a/g)^{0.3}$ as opposed to $(a/g)^{0.25}$ for pool boiling. CHF is predictable in all cases, however the point of nucleate boiling incipience may change significantly if boiling has not occurred for over six hours.

The large offset of the nucleate boiling regime for some initial tests poses the biggest problem to using this method in application. More tests will be run to gain an understanding of the temperature shift phenomenon. Tests will also be run to characterize this process over a larger range of velocity and subcooling.

Acknowledgments

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