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Flow boiling critical heat flux of FC-72 from flush-mounted and protruded simulated chips in a vertical rectangular channel

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Abstract

Experiments on flow boiling heat transfer and critical heat flux (CHF) of the dielectric coolant FC-72 are carried out for four in-line simulated electronic chips of 10 mm × 10 mm, for both flush-mounted and protruded chips on one wall of a vertical rectangular channel. The fluid velocity and subcooling are varied from 4.2 to 78 cm/s ($Re_L = 1.0 \times 10^3$ to 3.0×10^4), and from 15 to 33°C, respectively. The fully-developed nucleate boiling regime is not affected by changes in flow velocity and subcooling, whereas the surface temperatures decrease with increasing flow velocity and subcooling in the partial boiling regime. CHF generally increases with the degree of subcooling and with velocity at higher inlet velocities, but velocity has little effect at values less than 20 cm/s. The surface temperatures for the flush-mounted chips are lower than those for protruding chips, and the CHF data for the flush-mounted chips are higher than those for protruding chips; the differences between these two cases increase with increasing velocity. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Continued advances in the speed and performance of microelectronic devices necessitate the development of techniques to cope with the large heat removal requirements imposed by

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increased circuit concentration at the computer chip level and increased chip densities in multi-chip modules. The development of adequate cooling schemes is rendered particularly challenging by the requirement that heat flux approach 1 MW/m^2, while chip surface temperatures be maintained below 85°C to ensure reliable operation (Mudawar and Maddox, 1989). Direct liquid cooling offers much higher convection coefficients than air-cooling or indirect liquid cooling, with similar pumping power requirements. Boiling heat transfer exhibits even higher heat transfer coefficients than single-phase convection and provides an added advantage of dissipating large heat fluxes with only slight variations in the surface temperature of the heated elements. The dielectric liquid FC-72 is often used as a coolant because of its low boiling point and because it is a non-CFC agent (Bar-Cohen, 1993).

Subcooled boiling in uniformly heated channels typically results in established nucleate boiling curves that are independent of both velocity and subcooling. For a single heat source, the Lee and Simon (1989a) data for various velocities and subcoolings agreed with this behavior, with the boiling curves shifting to the left with increased pressure. On the other hand, Samant and Simon (1989) found that the slope of the boiling curve in the nucleate boiling regime increased with velocity. The established boiling data of Maddox and Mudawar (1989) and Mudawar and Maddox (1989) also indicate a pronounced shift in the established boiling curves as the velocity and subcooling are increased. For a linear array of nine discrete heat sources in a vertical rectangular channel with 5 mm height, the data of Willingham et al. (1991) and Willingham and Mudawar (1992) on nucleate boiling for all velocities fell along the same curve, with the velocity and subcooling showing little effect on the chip surface temperature. Heindel et al. (1992) studied an in-line 10 discrete heat sources, flush-mounted to protruding substrates located on the bottom wall of a horizontal channel, and found that varying the velocity had little effect on the surface temperature for a given heat flux, when the heat sources were undergoing nucleate boiling in a fluid near saturation conditions ($\Delta T_{sub} = 5°C$). However, partially developed nucleate boiling persisted over a wider range of heat fluxes and increasing the velocity could significantly reduce the surface temperature, when the fluid was highly subcooled. This phenomenon was not observed by earlier studies.

McGillis et al. (1991) investigated flow boiling curves for a linear array of 10 heat-dissipating elements in a vertical rectangular channel using R-113 as the coolant, and tested four different chip protrusions: 0.0, 0.8, 1.6 and 2.4 mm. They found that velocity had no effect on fully-developed nucleate boiling; and that the surface temperatures of protruding elements were higher than that of flush-mounted chips. However, they did not use independently powered chips, and thus their heat flux estimates for the individual chip may be of lesser accuracy.

The effect of chip protrusion on forced-convection boiling heat transfer of FC-72 was also investigated by Gersey and Mudawar (1993). Nine, in-line, 10 mm × 10 mm simulated microelectronics chips protruded 1 mm into a 20 mm wide side of a rectangular flow channel. The effects of velocity and subcooling on the boiling curve for the protruded chips were similar to the results obtained from flush-mounted chips. The nucleate boiling regimes for flush-mounted and protruded chips were similar, unlike the results of McGillis et al. (1991).

Critical heat flux (CHF) in flow boiling has been the focus of considerable research during the past three decades, due in part to application in the nuclear reactor. Reviewers on the subject include Marinelli (1977), Hewitt (1978); Katto (1994), and others. Most experiments on CHF were carried out in a simple tubular geometry, such as in a horizontal tube (Boyd, 1991), in a vertical tube (Nariai et al., 1989), or in an annulus tube (Rogers et al., 1982). Much less work has been done with discrete heat sources. The effect of velocity and subcooling on CHF had been studied by Samant and Simon (1989), Lee and Simon (1989b) and Mudawar and Maddox (1989) for a single heat source, and by Willingham and Mudawar (1992) and McGillis et al. (1991) for multi-chip modules. Most of these studies found that increasing the velocity or subcooling increased the CHF.

Even fewer studies were reported in the literature on the effect of protrusion on CHF. A decrease in CHF was observed for the protruded chips, as compared to the flush-mounted chips, by McGillis et al. The CHF data for the protruded chips increased with increasing velocity and subcooling as observed in the flush-mounted chips. On the other hand, the CHF data were higher for the protruded chips as compared to flush-mounted chips in the studies of Gersey and Mudawar (1993). When the adjustments for exposed surface and flow area were made, the CHF values became closer. These results were inconsistent with the results obtained by McGillis et al. Hence, the main motivation of the present work is to clarify the effect of protrusion on the CHF as well as on the boiling curve. And in view of the earlier finding by Heindel et al. of a partially-developed nucleate boiling region not found in other studies, it is also of interest to investigate this phenomena. In the present study, the effects of various

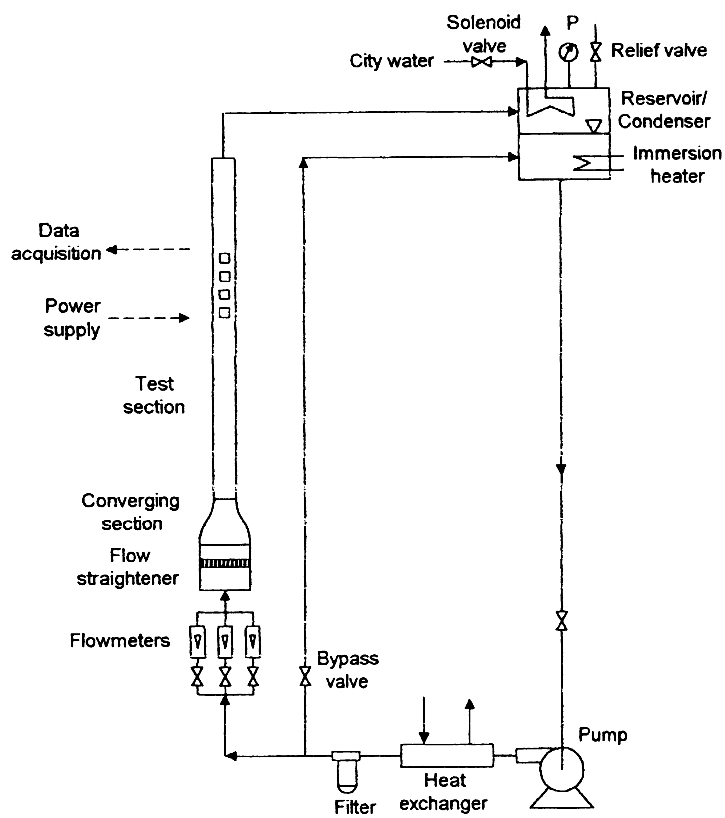

Fig. 1. Schematic of the liquid cooling test facility.

parameters on the subcooled flow boiling heat transfer for four in-line simulated chips in a vertical upflow channel are studied, with the chips being either flush-mounted or protruding on one wall of the channel.

2. Experimental set-up and procedure

The experiments are conducted in a closed-loop liquid flow facility with a vertical upflow, plexiglass test section, as shown in Fig. 1. The flow loop consists of a reservoir, pump, heat exchanger, filter, rotameters, flow channel and degassing facility. The temperature at the test-section inlet is maintained constant by means of the heat exchanger and the immersion heater in the reservoir, and is measured just prior to the test section by a K-type thermocouple. A converging section and a flow straightener, which has a series of screens and honeycombs, ensure a uniform flow upstream of the test section. FC-72 is used as the working fluid and is degassed for about 20 min prior to each experimental run, by simultaneously boiling and condensing the liquid in the reservoir, with almost all non-condensable gases being expelled through the relief valve. The multi-chip module is machined from high-temperature teflon block, and the simulated chips are flush-mounted or protruded on a vertical wall in the rectangular duct with a fixed 20 mm width and 10 mm height. The first chip is located 680 mm downstream of the channel inlet, providing a minimum hydrodynamic entry length of 50

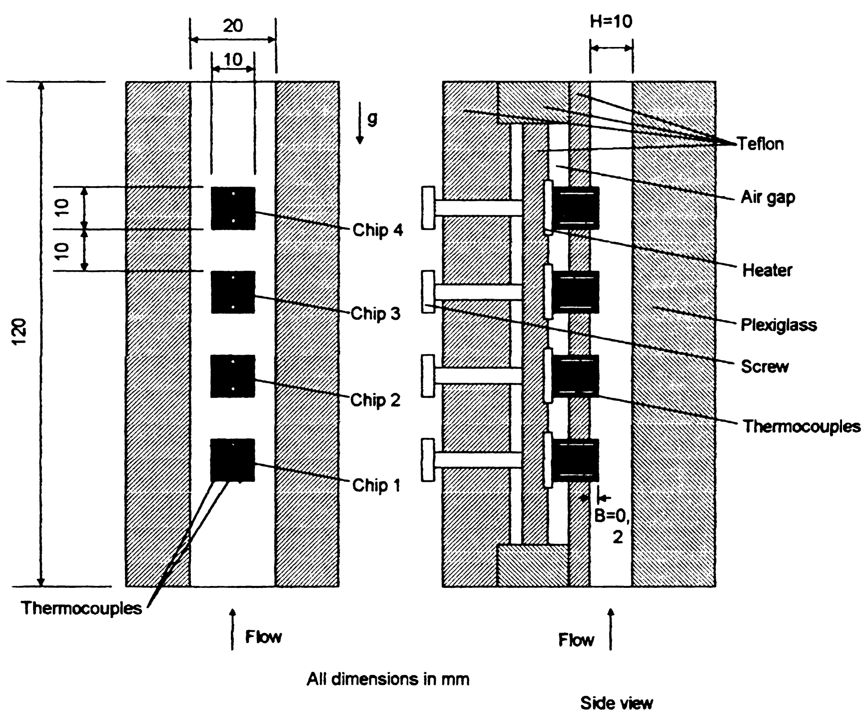

Fig. 2. Multi-chip model.

hydraulic diameters. To improve the accuracy of reading, three rotameters with different ranges are used to measure the flow rate.

A detailed view of the multi-chip module is provided in Fig. 2. The surfaces of the simulated chips with protrusion heights $B = 0$ or 2 mm, are mounted in a teflon substrate module, with the chips positioned in the center of the channel wall with a spacing of 5 mm between the edges of the chip and the channel side walls. The protrusion of the simulated chips is adjusted by screws, as shown in Fig. 2, and its error is estimated to be less than 2%. To identify specific chips within an array, a nomenclature is established that refers to Chip 1 as the most upstream chip in the array as shown in Fig. 2. Each chip is fabricated from oxygen-free copper such that the cross-sectional dimensions of the chip surface in contact with the liquid are 10 mm × 10 mm. Four film resistive heaters are installed in series within the respective chips, the variation in the heater power from heater to heater being negligible. A power meter is used to measure the power dissipation of the chips. The resistors are attached with thermally conducting epoxy to the underside of the copper blocks. As teflon is of low thermal conductivity, the heat loss for each chip has been estimated to be less than 3%, and is deemed effective in isolating the module from the surroundings. The teflon block is threaded to accommodate four set screws, for good thermal contact.

Prior to the experiments, the chip surfaces are polished with a silicon carbide paper, which has an average particle size of 10 μm, in order to create a uniform surface texture on each chip. Two K-type thermocouples are embedded along the chip centerline in the flow direction at a depth of 0.5 mm underneath the chip surface and aligned along the chip centerline at 2 mm upstream and downstream of the chip, respectively. Before measurements are recorded, the wall temperatures of the simulated chips are allowed to reach steady-state, typically achieved in 10 min after the power level, flow rate and subcooling are set. Temperature readings are sampled at 1 Hz and averaged over a period of approximately 5 min, and the average of the two surface temperatures yields the mean surface temperature. During each run, the flowrate and the inlet subcooling are held constant, while the power is increased by steps. Upon reaching steady state, the test section inlet pressure, temperatures, flowrate and power are recorded by the data acquisition system.

Data are collected for a velocity range of $U = 4.2$ to 78 cm/s, corresponding to an approximate range of Reynolds number Re_L, based on a single heat source length, from 1.0×10^3 to 3.0×10^4. The subcooling, ΔT_{sub}, is varied from 15 to 33°C based on inlet pressure. The heat losses are determined by measuring the surface temperatures of the teflon block exposed to the surroundings and the temperature of ambient air, and are based on the assumption that the heat losses by conduction in the multi-chip module are equal to the heat dissipation by natural convection from the surface of the multi-chip module to the surroundings, the contact resistance between the copper block and teflon insulation being negligible. The heat loss is estimated to be less than 5% of the total heat energy dissipated by the heater. Therefore, in light of the small heat losses, no correction is made for the power dissipated by the thick-film resistor in determining the chip heat flux. Generally, heat losses for liquid cooling of simulated chips are negligible, as reported in the studies of Incropera et al. (1986), Willingham and Mudawar (1992) and Heindel et al. (1992). An estimation of the uncertainty in the experimental data has been made using standard techniques for single-sample measurements (Kline and McClintock, 1953). The propagation of the uncertainties into the dimensionless parameters has been determined, revealing uncertainties in the excess temperature, heat flux and velocity to be less than 5, 7 and 4%, respectively.

3. Results and discussions

3.1. Boiling curve

Effects on boiling curves are shown in Fig. 3 for flush-mounted Chip 4 at two different degrees of subcooling and for protruded Chip 4 at three different degrees of subcooling, respectively. It should be noted that all chips in the array have about equal nucleate boiling convection coefficients, although the surface temperature of Chip 1 is lower than the other chips in the single-phase convection region. It can be seen from the figure that an increase in subcooling affects the boiling curve, by decreasing the surface temperature at a given heat flux. However, the subcooling effects diminish for heat fluxes q'' greater than about 2×10^5 W/m^2 for flush-mounted chips and 10^5 W/m^2 for protruded chips, respectively. Hence, the present study supports the observation that the nucleate boiling regime could be classified into two regions; one is partial boiling region, another fully-developed nucleate boiling region, as suggested by Heindel et al. (1992). In the fully-developed boiling region, subcooling, which has strong influence on single-phase heat transfer, has little or no effect on the surface temperature.

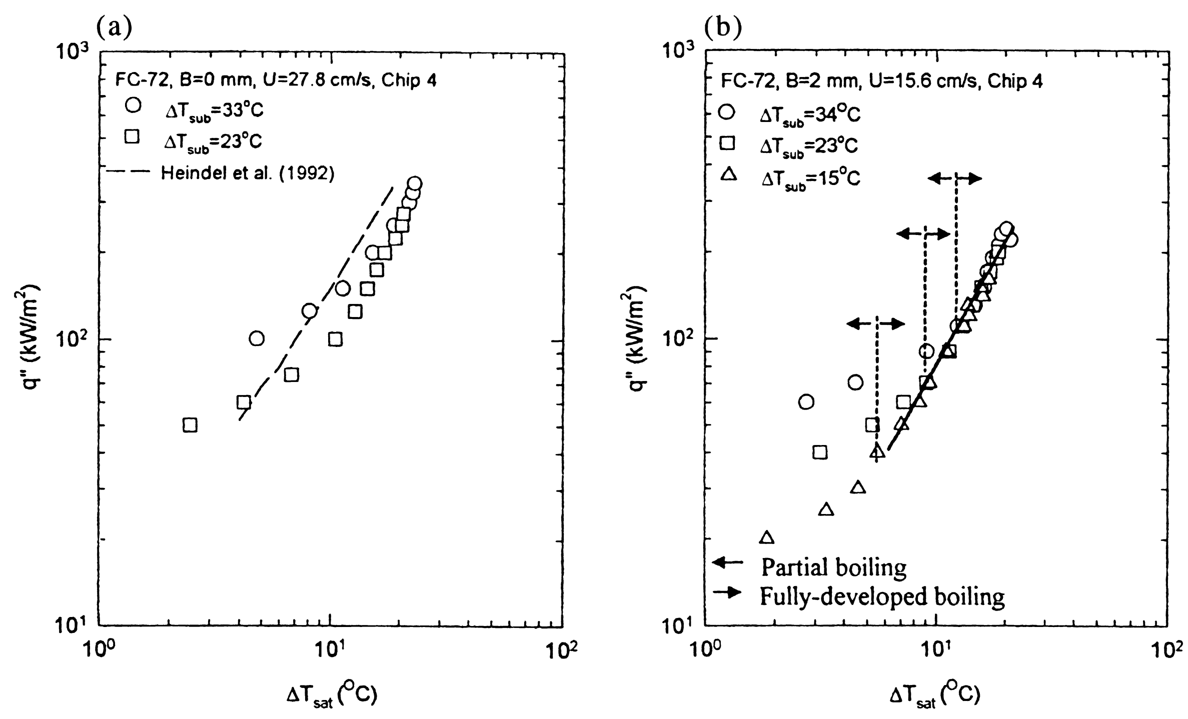

Fig. 3. Effects of subcooling on boiling curves.

It is also indicated in Fig. 3 that the transition heat flux from partial boiling to fully-developed boiling is increased as the degree of subcooling increases. The experiment confirms that boiling always begins at the downstream end of the chip.

Similar effects of subcooling on boiling curves also have been observed by Heindel et al. (1992), where, in their studies, an in-line 1 × 10 array of discrete heat sources is flush-mounted to protruding substrates located on the bottom wall of a horizontal flow channel. Comparing with their results in Fig. 3a, the present data agree well with their boiling curve at similar conditions with velocity 30.5 cm/s and subcooling 25.8°C, although the flow direction is different. It is suggested that the effects of flow direction (vertical upflow and horizontal flow) have little effect on nucleate boiling curve. This is consistent with the results observed by Gersey and Mudawar (1992) from studies of the effects of orientation on the boiling curves.

Figs. 4a and b display the effects of velocity on boiling curves for flush-mounted Chip 4 and protruded Chip 4. It is apparent from the figures that the boiling curves for different velocities can also be classified as the partial boiling region and fully-developed region. In the partial boiling region, for a given heat flux, the surface temperature decreased with increasing velocity, most probably as a result of the thinning thermal boundary layer, the enhanced turbulence and the increase in the component of single-phase heat transfer coefficient. Since the heat transfer coefficient is still influenced by single-phase convection for this condition, a substantial quantity of energy is required to maintain fully-developed nucleate boiling. As heat flux levels

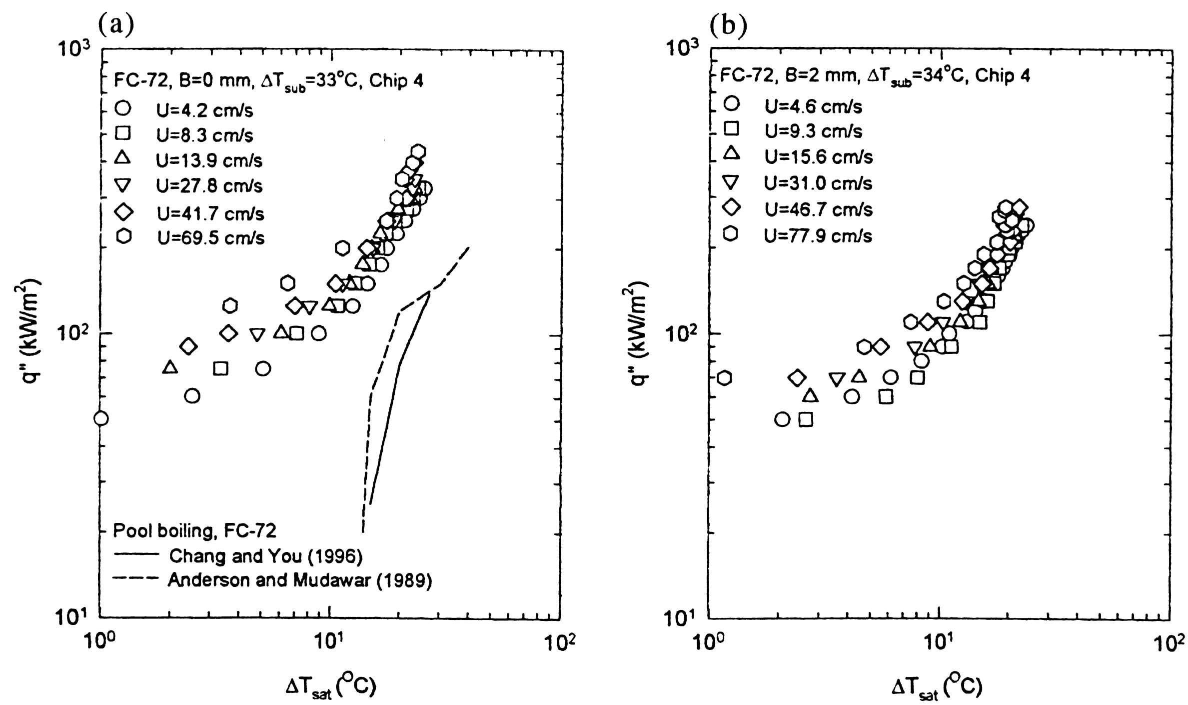

Fig. 4. Effects of velocity on boiling curves.

increase, the nucleate boiling data for different velocities are expected to be fully-developed, since the velocity seems to have a limited influence on the surface temperature.

It is also of interest to compare the flow boiling curves for flush-mounted chips with previous work on pool boiling. The boiling curve of Anderson and Mudawar (1989) for saturated pool boiling of FC-72 from a vertical simulated chip made of oxygen-free copper with heated surface area of 12.7 mm × 12.7 mm is shown in Fig. 4a. Results obtained by Chang and You (1996) for saturated pool boiling of FC-72 from a vertical copper surface with heated area 10 mm × 10 mm are also shown. It is found that the saturated pool boiling curve cannot be extrapolated to accurately represent the established subcooled flow boiling. The surface temperature of flow boiling is much lower than that of pool boiling for a given heat flux. The difference between pool boiling and flow boiling is decreased as the velocity and subcooling decrease. Both pool boiling curves are in close agreement with each other.

Fig. 5 compares the boiling curve for Chip 4 in the flush-mounted and protruding configurations for subcooling of 23°C and at velocities of 13.9 and 15.6 cm/s, respectively. For protruded chips, the heat flux is calculated based on the total exposed area. At lower heat fluxes, the regime is partial boiling, and the surface temperature of the protruding chip is higher than that of the flush-mounted chip. In the fully-developed boiling region, the surface temperature of the protruding chip is nearly same as that of the flush-mounted chip, for heat fluxes higher than 10^6 kW/m^2. Similar effects of protrusion have been observed by McGillis et al. (1991). However, Gersey and Mudawar (1993) find that there is no clear trend of relative

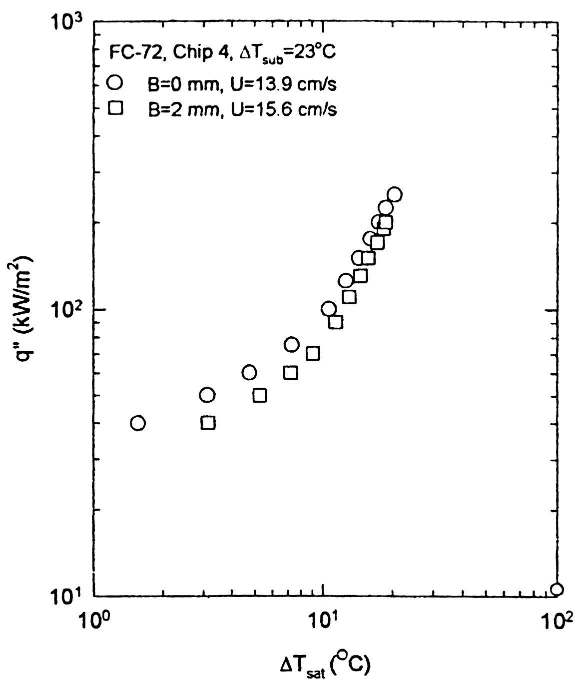

Fig. 5. Effects of protrusion on boiling curves.

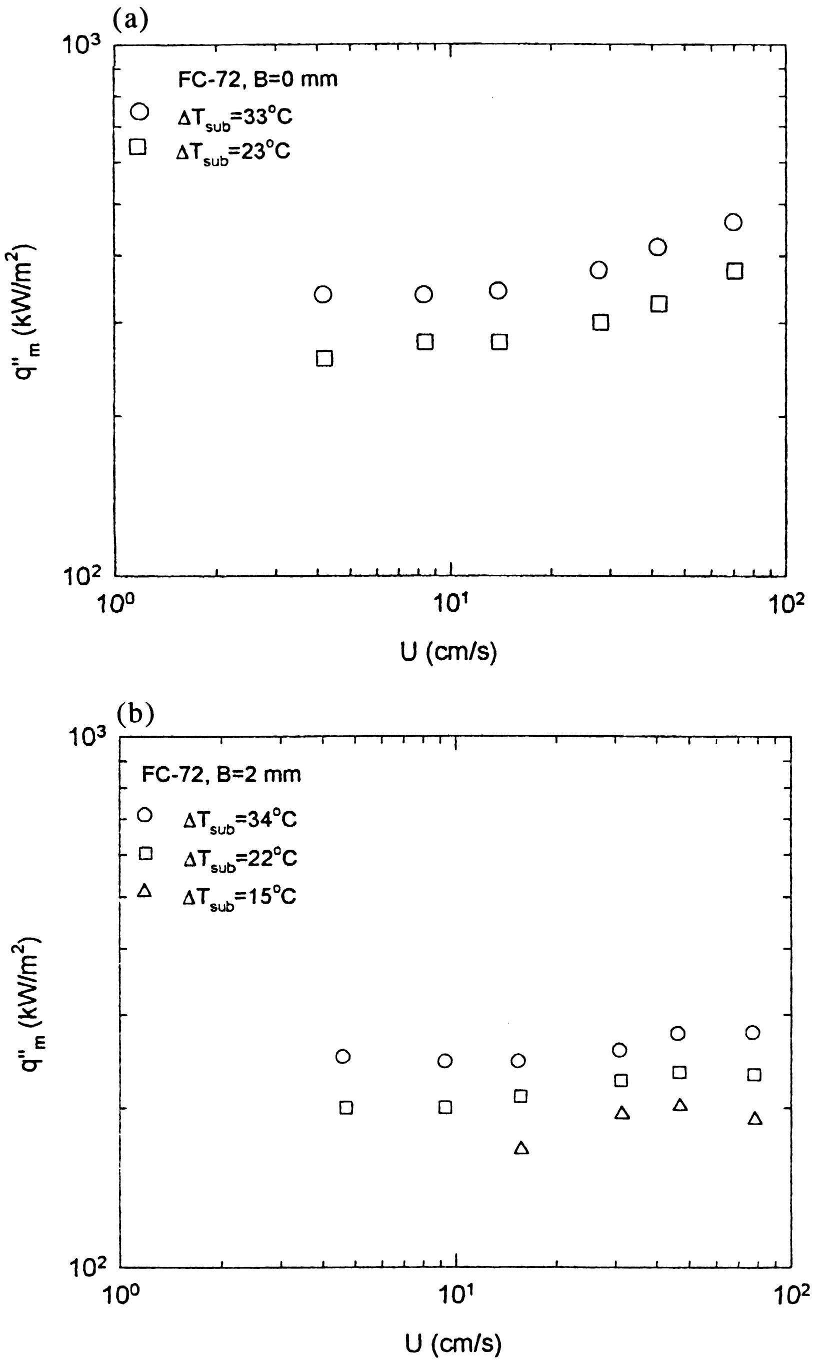

Fig. 6. Effects of velocity and subcooling on CHF data.

change in the surface temperature throughout the nucleate boiling data base, from flush-mounted and protruding chips, with a protrusion of 1 mm.

3.2. Critical heat flux trends

For the majority of the experiments, the most downstream Chip 4 attains CHF first. It is probably due to the fact that some of the vapor generated in the upstream cannot be condensed over the unheated region by the liquid and this causes vapor quality and void fraction to increase in the liquid adjacent to the downstream chip. Another reason may be that the thermal boundary layer that develops as the fluid passes over the array of heated chips causes a stream-wise increase in the fluid temperature and a decrease in the subcooling. The effects of a larger void fraction and a lower subcooling in a downstream chip would tend to produce the CHF condition on the downstream chips at a lower heat flux than that at which it occurs on the downstream chip.

The effects of flow velocity and subcooling on the CHF are illustrated by the representative data in Figs. 6a and b for flush-mounted chips and protruded chips, respectively. The CHF condition usually occurs at Chip 4 first, and sometimes at Chip 3. For any given velocity, CHF increases with increasing subcooling. The CHF mechanism has been incorporated into the sub-layer dryout model of Mudawar and Maddox (1989). In that model, the transition to film boiling is dictated by the evaporation of the liquid sublayer between a large bubble and the wall. Thus, cooling of the heat source just prior to CHF is dependent on boiling and evaporation of liquid entering the sublayer from the subcooled core region of the channel. Subcooled liquid entering the sublayer has a greater capacity for heat absorption. Therefore, the heat flux necessary to achieve a transition to film boiling increases as the degree of subcooling increases. The positive effect of subcooling on CHF has been reported by Samant and Simon (1989), Lee and Simon (1989b), Mudawar and Maddox (1989), Heindel et al. (1992) and Willingham and Mudawar (1992).

Increasing the velocity can significantly increase the CHF, for value higher than 20 cm/s. However, the velocity has little effect on the CHF when it is lower than 20 cm/s. This trend indicates a marked change in the CHF mechanism with increased velocity. In the low velocity regime, it has been proposed that the CHF remains constant as velocity decreases, as a result of the effect of vapor buoyancy on the flow field. The buoyancy acting on the vapor bubbles, generated and released from the element surfaces, strongly augments the upward flow near the elements. Hence, at low velocities in the channel, the buoyancy-induced local velocity enhancement near the elements may act to augment the CHF. When velocity increases, the influence of buoyancy gradually diminishes, since the shear and drag force on individual bubbles growing at the element surfaces increase. So bubbles depart rapidly within a very short period following nucleation. Entrained bubbles are also observed to be smaller than those in lower velocity flow and the thin vapor layer covering the boiling surface and appearing as a continuous blanket is also much smaller in size than the chip surface.

Comparing the CHF data in Fig. 6a for flush-mounted chips with those in Fig. 6b for protruded chips, it can be seen that the former data are about 40% higher than those for protruding chips. It also appears that the difference in values between the flush-mounted chips and protruding chip increases as the velocity increases. This can be explained by noting that

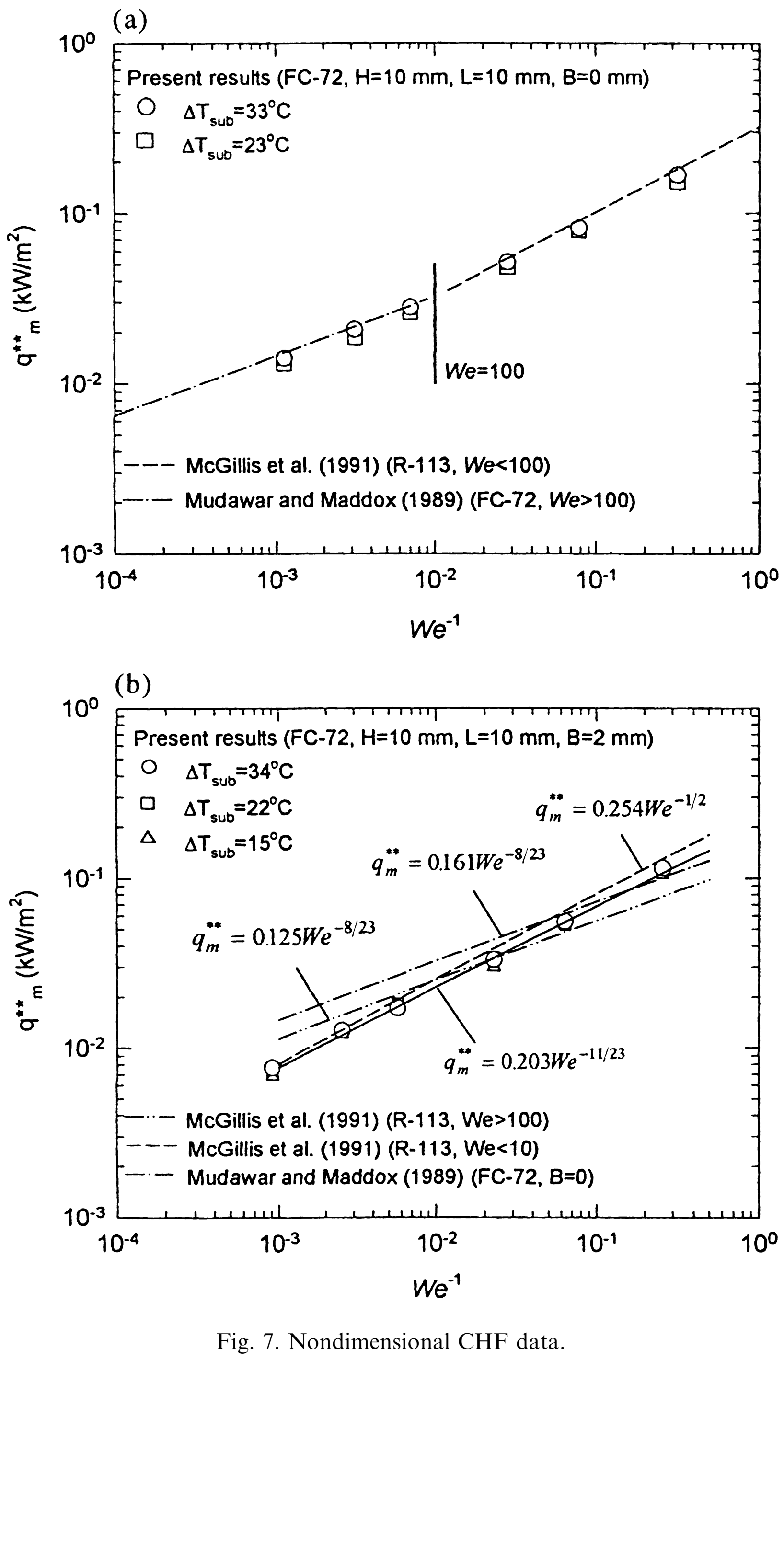

Fig. 7. Nondimensional CHF data.

the forced-convection effect in the wake of the protruding chip is relatively less effective in maintaining adequate liquid flow to the downstream face of the heated chip. Since the liquid motion in the recirculating flow downstream of the chip is relatively weak, it is expected that dryout on the rear face of the chip may be dictated by mechanisms similar to those for pool boiling in a motionless pool of liquid. If the rear surface of the chip trips to film boiling first, the heat normally transferred from this surface by nucleate boiling would be diverted to the other surfaces of the chip. The resulting higher effective heat flux applied to the other surfaces could promote the onset of CHF.

That the CHF data from protruding elements are less than those from flush-mounted elements has been reported by McGillis et al. On the other hand, the CHF data of Gersey and Mudawar (1992) from protruding chips are very close to the data from flush-mounted chips. It may be due to the fact that the ratio of protrusion to the length of heat element is different; the effect of recirculating flow decreases as the ratio decreases. In McGillis et al.'s studies, B/L ranges from 1/8 to 3/8, in Gersey and Mudawar, the ratio is 1/10. The present results are for B/L of 1/5.

3.3. Critical heat flux correlations

Several existing correlations for flow boiling from electronic chips are reviewed to test their suitability for the present data. The following model-based correlation of Mudawar and Maddox (1989) has been developed from FC-72 flow boiling result in a rectangular channel with a single 12.7 mm × 12.7 mm heater, where the exponents are from theory and the two constants are based on experimental data:

$$q_{\mathrm{m}}^{**} = \frac{q_{\mathrm{m}}/(\rho_{\mathrm{g}} U h_{\mathrm{fg}})}{\left(\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}}\right)^{15/23}\left(\frac{L}{D_{\mathrm{h}}}\right)^{1/23}\left(1+\frac{c_{\mathrm{pf}}\Delta T_{\mathrm{sub}}}{h_{\mathrm{fg}}}\right)^{7/23}\left(1+0.021\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}}\frac{c_{\mathrm{pf}}\Delta T_{\mathrm{sub}}}{h_{\mathrm{fg}}}\right)^{16/23}} = 0.161\, We^{-8/23}, \tag{1}$$

where q_{m}^{**} is nondimensional CHF, q_{m} is CHF, L is heat source length in flow direction, H is height of channel, D_{h} is hydraulic diameter of channel; c_{pf} is liquid specific heat at constant pressure, ρ_{g} and ρ_{f} are density of gas and liquid, respectively, h_{fg} is latent heat of vaporization and We is Weber number, defined as

$$We = \frac{\rho_{\mathrm{f}} U^2 L}{\sigma}. \tag{2}$$

Here, σ is surface tension and U is the mean flow velocity in the channel. Eqs. (1) and (2) imply that CHF q_{m} is proportional to $U^{7/23}$. For the higher velocities ($We > 100$) investigated in this study, the trend of the experimental data is in good agreement with this predicted trend as shown in Fig. 7a for flush-mounted chips. It is noted that the data of Mudawar and Maddox (1989) have not been obtained for $We < 100$. Similar results have been verified by Willingham and Mudawar (1992) for FC-72 and McGillis et al. (1991), for R-113 as $We > 100$.

Fig. 6a shows that the critical flux data are independent of the flow velocity when the latter is smaller than 20 cm/s, so the correlation of Mudawar and Maddox (1989) may not be suitable for data at the lower velocities. McGillis et al. (1991) correlated the CHF data for R-113 in the low velocity regime ($We < 10$) by using the form of Mudawar and Maddox (1989) as the following:

$$q_{\mathrm{m}}^{**} = \frac{q_{\mathrm{m}}/\left(\rho_{\mathrm{g}} U h_{\mathrm{fg}}\right)}{\left(\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}}\right)^{15/23}\left(\frac{L}{D_{\mathrm{h}}}\right)^{1/23}\left(1+\frac{c_{\mathrm{pf}}\Delta T_{\mathrm{sub}}}{h_{\mathrm{fg}}}\right)^{7/23}\left(1+0.021\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}}\frac{c_{\mathrm{pg}}\Delta T_{\mathrm{sub}}}{h_{\mathrm{fg}}}\right)^{16/23}} = 0.321\,We^{-1/2} \tag{3}$$

The above equation implies that q_{m} is independent of flow velocity. Although the range of We is limited to less than 10 for their experimental data, it appears that the correlation of McGillis et al. is applicable for the present FC-72 data in the range of Weber number between 10 and 100, as shown in Fig. 7a.

The foregoing discussion implies that the correlation proposed by Mudawar and Maddox for predicting the subcooled flow boiling CHF on a single isolated flush element can be successfully applied to an array of flush elements for $We > 100$. It also implies that the correlation developed by McGillis et al. for R-113 in multi-chip channel can be applied to predict FC-72 flow boiling CHF from flush-mounted chips for $We < 100$.

It appears from Fig. 7b that the correlation of Mudawar and Maddox from a single flush-mounted chip overpredicted the present data from protruding chips when $We > 100$. Although the CHF data of Gersey and Mudawar (1993) for protruding chips agree well with the correlation of Mudawar and Maddox, it should be noted that, for the protruding data, the increase in the exposed chip surface area and flow velocity above the chip have not been adjusted in Gersey and Mudawar's studies. Therefore, if the heat flux data were adjusted by using the total exposed surface chip area, the CHF data of Gersey and Mudawar would be below the prediction of Mudawar and Maddox.

Fig. 7b also compares the present data to the curve-fits of McGillis et al. from protruding chips for $We > 100$ and $We < 10$ with R-113. It is found that the present data fall along the curve predicted by their correlation for $We < 10$. Extending the same correlation to compare with our data for higher Weber numbers ($We > 10$) shows that the correlation still has good agreement. On the other hand, the correlation of McGillis et al. for $We > 100$ overpredicts the present data for $We > 100$ and underpredicts when $We < 10$.

The present data from protruded chips for Weber number ranging from 1 to 10^3, can be correlated by a form of Eq. 1 as follows:

$$q_{\mathrm{m}}^{**} = \frac{q_{\mathrm{m}}/\left(\rho_{\mathrm{g}} U h_{\mathrm{fg}}\right)}{\left(\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}}\right)^{15/23}\left(\frac{L}{D_{\mathrm{h}}}\right)^{1/23}\left(1+\frac{c_{\mathrm{pf}}\Delta T_{sub}}{h_{\mathrm{fg}}}\right)^{7/23}\left(1+0.021\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}}\frac{c_{\mathrm{pf}}\Delta T_{\mathrm{sub}}}{h_{\mathrm{fg}}}\right)^{16/23}} = 0.203\,We^{-11/23}. \tag{4}$$

The exponent of We is near to $-1/2$ in the above equation, implying that the velocity has little effect on the CHF, since q_m is proportional to $U^{1/23}$.

4. Conclusions

The results of our experimental study of the flow boiling heat transfer and CHF with subcooled FC-72 from four in-line, flush-mounted and protruding heat sources in a rectangular channel give rise to the following conclusions.

1. For both of the flush-mounted chips and protruding chips, in the partial boiling region, the chip surface temperatures decrease as velocity and subcooling increase, for a given heat flux. In fully-developed nucleate boiling, varying of subcooling and velocity has little effect on the surface temperature.
2. CHF data increases with increasing subcooling for any given velocity. For the flush-mounted chips, velocity has little effect on the CHF at flow velocities less than 20 cm/s. On the other hand, increasing the velocity can significantly increase the CHF. The CHF data at the lower flow velocities are slightly higher than the prediction from pool boiling of a vertical chip-size element obtained by Anderson and Mudawar (1989). Nondimensional CHF data agree well with the correlations of Mudawar and Maddox (1989) and McGillis et al. (1991) for $We > 100$ and $We < 100$, respectively.
3. The CHF data for the protruding chips are well-correlated by using the form of Mudawar and Maddox, but the present data do not agree well with their correlation. The present data within the experimental range $3.86 < We < 1101$ are in fair agreement with the prediction of McGillis et al. correlation for $We < 10$.
4. Surface temperatures of the flush-mounted chips are lower than those of protruding chips in the partial boiling regime under the same conditions. Surface temperatures of the flush-mounted chips are closed to the surface temperatures of the protruding chips in the fully-developed nucleate boiling.
5. The critical heat flux data for the flush-mounted chips are higher than those for the protruding chips, and the difference between these two cases increases with increasing velocity. The reduction of the CHF associated with the protrusion of chips is a matter of concern in electronics cooling design.

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