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Subcooled flow boiling heat transfer and associated bubble characteristics of FC-72 on a heated micro-pin-finned silicon chip

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ABSTRACT

Experiments are conducted here to investigate subcooled flow boiling heat transfer and associated bubble characteristics of FC-72 on a heated micro-pin-finned silicon chip flush-mounted on the bottom of a horizontal rectangular channel. In the experiments the mass flux is varied from 287 to 431 kg/m^2 s, coolant inlet subcooling from 2.3 to 4.3 °C, and imposed heat flux from 1 to 10 W/cm^2. Besides, the silicon chips contain three different geometries of micro-structures, namely, the smooth, pin-finned 200 and pin-finned 100 surfaces. The pin-finned 200 and 100 surfaces, respectively, contain micro-pin-fins of size 200 μm × 200 μm × 70 μm (width × length × height) and 100 μm × 100 μm × 70 μm. The measured data show that the subcooled flow boiling heat transfer coefficient is reduced at increasing inlet liquid subcooling but is little affected by the coolant mass flux. Besides, adding the micro-pin-fin structures to the chip surface can effectively raise the single-phase convection and flow boiling heat transfer coefficients. Moreover, the mean bubble departure diameter and active nucleation site density are reduced for rises in the FC-72 mass flux and inlet liquid subcooling. Increasing coolant mass flux or reducing inlet liquid subcooling results in a higher mean bubble departure frequency. Furthermore, larger bubble departure diameter, higher bubble departure frequency, and higher active nucleation site density are observed as the imposed heat flux is increased. Finally, empirical correlations for the present data for the heat transfer and bubble characteristics in the FC-72 subcooled flow boiling are proposed.

1. Introduction

In recent quick development of the IC (Integrated Circuits) technology, novel design in many electronic devices increases their power density and hence results in more heat dissipation for the same device size, especially for the advanced microprocessors and high power modules. As denoted by Simons [1], the IC junction temperature must be kept under 85 °C to avoid being damaged. The heat removal methods based on the traditional air-cooling are normally insufficient for these high power density requirements. Due to high ability in the heat transfer rate, two-phase flow boiling is considered as one of the most effective methods in electronics cooling. To ensure safety and stability of the cooling, dielectric coolant FC-72 made by 3M Company satisfies the above essentials and has been studying for the electronics cooling in recent years. Besides, the use of surface micro-structure to enhance the heat transfer performance is expected to be beneficial. Thus, it becomes increasingly important to understand the flow boiling processes of the dielectric liquid on micro-structure enhanced surfaces and the associated heat transfer. Moreover, boiling heat transfer in subcooled liquid flow is known to be better than in saturated liquid. However, heat transfer and associated bubble characteristics in subcooled flow boiling of FC-72 on various micro-structure surfaces remain largely unexplored.

In the following the literature relevant to the present study is reviewed. Mudawar and his colleague [2] experimentally studied the subcooled flow boiling of FC-72 on a linear array of discrete heat sources in a vertical channel for the flow velocity ranging from 13 to 400 cm/s. They found that the boiling incipience was delayed to higher heat flux values for a higher flow velocity. Similar experiments for a horizontal heat source array were conducted by Heindel et al. [3]. They noted that an increase in the flow velocity caused reduction of temperature overshoot at onset of nucleation boiling (ONB) but exhibited little effect on the boiling curves in the fully developed nucleate boiling region. As the liquid subcooling increases, the temperature overshoot at ONB decreases and the surface heat flux increases. Similarly, Tso et al. [4] found that the chip surface temperature decreased with the increases of the flow velocity and liquid subcooling only in the partial boiling region. Samant and Simon [5] analyzed the heat transfer from a small region to refrigerants R-113 and FC-72 and noted that as the flow velocity and subcooling increased, the temperature excursion and boiling hysteresis appeared less pronounced.

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Nomenclature

A_f	surface area of a single fin (m^2)
A_s	surface area of a bare chip (m^2)
Bo	Boiling number, $\mathrm{Bo} = \frac{q''}{G \cdot i_{lv}}$, dimensionless
c_p	specific heat (J/kg °C)
D_h	hydraulic diameter of rectangular channel (m)
E	enhancement factor
$f, \bar{f}$	mean dimensional and dimesionless bubble departure frequency (s^{-1})
F	pin-fin factor for the effects of fin geometries, dimensionless
Fr_l	Froude number, $\mathrm{Fr}_l = \frac{G^2}{\rho_l^2 \cdot g \cdot D_h}$, dimensionless
g	acceleration due to gravity (m^2/s)
G	mass flux (kg/m^2 s)
h	heat transfer coefficient (W/m^2 K)
H	height (m)
I	measured current from DC power supply (A)
i_{lv}	enthalpy of vaporization (J/kg K)
Ja'	Jacob number based on ΔT_{sub}, $\mathrm{Ja}' = \frac{\rho_l \cdot c_{pl} \cdot \Delta T_{sub}}{\rho_v \cdot i_{lv}}$, dimensionless
k	thermal conductivity (W/m K)
L	length (m)
N	number of micro-pin-fins
N_{ac}	Active nucleation site density (n/m^2)
N_{conf}	Confinement number, $N_{conf} = \frac{(\sigma/(g \cdot \Delta\rho))^{0.5}}{D_h}$, dimensionless
Nu	Nusselt number, $\mathrm{Nu} = \frac{h \cdot L}{k}$, dimensionless
P	system pressure (kPa)
Pr	Prandtl number, $\mathrm{Pr} = \frac{\mu \cdot c_p}{k}$, dimensionless
Q	heat transfer rate (W)
q''	average imposed heat flux (W/cm^2)
Re_l	liquid Reynolds number, $\mathrm{Re}_l = \frac{G \cdot D_h}{\mu_l}$, dimensionless
T	temperature (K)
$u_{l,in}$	liquid FC-72 velocity at the inlet (m/s)
V	measured voltage from DC power supply (V)
Greek symbols	
ΔT	temperature difference (K)
ρ	density, kg/m^3
μ	dynamic viscosity ($N\,s/m^2$)
ε	relative heat loss, dimensionless
σ	surface tension (N/m)

Ma and Chung [6] examined bubble dynamics in reduced gravity flow boiling of FC-72 over a thin gold film semi-transparent heater. The bubble departure size was found to be bigger in the micro-gravity environment. At increasing flow rate, the bubble departure time and departure size decrease. This was also found by Situ et al. [7] later. Besides, they also noted that the bubble growth rate dropped sharply after lift-off. In addition, Yin et al. [8] examined the subcooled flow boiling of R-134a in an annular duct and found that both the bubble departure size and frequency reduced at increasing liquid subcooling. Experiments conducted by Chang et al. [9] for R-134a and water focused on the behavior of near-wall bubbles in subcooled flow boiling. They identified four different two-phase flow patterns including the discrete attached bubbles, sliding bubbles, small coalesced bubbles and large coalesced bubbles or vapor clots at increasing heat flux. For a higher mass flux of the flow, the coalesced bubbles are smaller. Bang et al. [10] further noticed the presence of the R-134a vapor remnants below the discrete bubbles and coalesced bubbles, and the presence of an interleaved liquid layer between the vapor remnants and bubbles. Besides, the bubble layer could be divided into two types – a near-wall bubble layer dominated by small bubbles and a following bubble layer prevailed by large coalesced bubbles. Using digital imaging and analyzing techniques, Maurus et al. [11] investigated subcooled flow boiling and noted that the bubble population increased with the heat flux and the bubble density reduced drastically at increasing mass flux. Besides, the bubble size increases at increasing heat flux and decreasing mass flux. In a continuing study [12] they further showed that the effects of the heat flux and mass flux on the bubble size distribution were weak for small bubbles but became more pronounced for bigger bubbles. The total bubble life time, the remaining lifetime after the detachment process, and the waiting time between two bubble cycles decrease significantly as the mass flux increases.

Flow boiling of FC-72 over microstud, microgroove, and cylindrical micro-pin-fin enhanced surfaces flush-mounted on a vertical rectangular-channel wall was examined by Maddox and Mudawar [13]. The presence of the surface micro-structures was found to significantly enhance the heat transfer performance and reduce the boiling hysteresis. Heat transfer in pool boiling of FC-72 on silicon chips with the surface micro-structures of micro-pin-fins was recently investigated by Honda et al. [14,15]. They noted that both the nucleate boiling heat transfer and the critical heat flux were effectively enhanced by the micro-pin-fins. The observed boiling phenomena revealed that a small amount of vapor was left within the gap between the pin-fins when a growing bubble left the surface. On the other hand, Honda and Wei [16] conducted a critical review on the boiling heat transfer enhanced by the surface-structures. They indicated that all the surface micro-structures including the microroughness, micro-reentrant, and micro-porous structures were helpful in reducing the boiling incipience superheat. Generally, the micro-pin-fins were most effective in augmenting CHF and micro-porous structures were most effective in enhancing nucleate boiling heat transfer. Recently, Ramaswamy et al. [17] examined the effects of varying geometrical parameters on boiling from microfabricated enhanced structures. They showed that increasing pore size caused higher heat dissipation and the pore pitch had more significant effect on the heat transfer performance. Finally, nucleate boiling heat transfer from the micro-porous finned surface was found to be better than the plain finned surface [18].

The above literature review clearly indicates that the pool boiling heat transfer from micro-structure surface and the associated bubble dynamics have received some attention. But heat transfer and bubble characteristics in flow boiling of dielectric coolants on micro-structure surfaces have been less explored. In a recent study [19], we conducted an experiment to investigate the saturated flow boiling of FC-72 over a micro-pin-fin surface flushed-mounted on the bottom of a horizontal rectangular channel. Here in the present study we move further to examine the subcooled flow boiling heat transfer and the associated bubble characteristics of FC-72 on the same micro-pin-fin surfaces.

2. Experimental apparatus and procedures

The present experimental system consists of a degassing unit, a coolant loop, a hot-water loop, and a cold-water loop, as schematically depicted in Fig. 1. The degassing unit is a tank of 8 l in capacity with an electric-heater in it to expel the dissolved air or non-condensable gas in the FC-72 coolant before every run. Then we remove any non-condensable gases or moisture possibly present in the coolant loop by using a vacuum pump and fill the loop with the degassed liquid FC-72. The coolant loop includes a