CHAPTER 1

INTRODUCTION

1.1 Motive of the Present Study

Energy conservation is a major concern in many countries relying heavily on the imported oil. Thus improving the energy utilization efficiency is relatively important in designing most engineering systems. In the past decade the use of variable frequency compressors in air conditioning and refrigeration systems to meet the changing heat load is found to significantly improve their thermal efficiencies. It is important to note that two-phase flow in these systems is subject to time varying refrigerant flow rate and time varying imposed heat flux. It is also well known that the junction temperature of IC must be kept under 85°C to maintain its normal operation [1]. To solve the heat transfer problem of high power density in advanced CPU chips, methods employing boiling and condensation have been proposed and used recently. Moreover, the power dissipation in IC chips are also time dependent in practical operation. Therefore the coolant flow rate must be varied in time to meet the required time varying cooling load. Consequently, a detailed understanding of the phase-change processes subject to the time varying coolant flow rate and imposed heat flux is essential in thermal design for electronics cooling. Although considerable research has been carried out in the past for the two-phase flow and heat transfer under the condition of fixed flow rate and imposed heat flux, the corresponding research for the transient flow rate and imposed heat flux remains largely unexplored. In the present study an initial attempt is made to unravel how the characteristics of FC-72 flow boiling heat transfer and bubble motion in a channel are affected by the time varying refrigerant flow rate for a fixed imposed heat flux.

Due to thermally and chemically stable, the dielectric fluorocarbon liquid FC-72 is currently considered as a suitable coolant for electronics cooling. Hence FC-72 is chosen as the working fluid in the present experiment. Some thermophysical properties for FC-72 are given in Table 1.1.

1.2 Literature Review

In what follows the literature relevant to the present study is reviewed. Specifically, the literature on the use of boiling of dielectric liquids for cooling of electronic equipments will be examined.

1.2.1 Stable Single-Phase and Convective Boiling Heat Transfer

Boiling heat transfer from a small heated patch in the size of 0.25 × 2.0 mm (width × length) to R-113 and FC-72 was investigated by Samant and Simon [2]. They observed temperature excursions and boiling hysteresis at the onset of nucleate boiling, which were less pronounced at increasing velocity and/or liquid subcooling. They combined the experimental data for R-113 and FC-72 to develop an empirical correlation. Besides, in the nucleate boiling region the slope of the boiling curve increases with the coolant flow velocity. Garimella and Eibeck [3] analyzed the heat transfer characteristics of an array of protruding elements in single-phase forced convection of water for the channel Reynolds number ranging from 150 to 5,150. They noted that the heat transfer coefficient decreased with decreasing Reynolds number and the Nusselt number decreased with increasing ratio of the channel height to element height. Incropera et al. [4] experimentally investigated single-phase convective heat transfer from a single heat source and four-row arrays of 12 discrete heat sources flush-mounted in a horizontal rectangular channel. The working fluids they used were water and FC-77 for the channel Reynolds number ranging from 1,000 to 14,000. They developed a model to predict the relation between the Reynolds number and Nusselt number for the turbulent flow regime with 5,000 < Re_D < 14,000. Unfortunately, their measured data were significantly under-predicted in the laminar flow regime. Slightly later, Incropera et al. [5, 6] examined single-phase liquid convection and flow boiling of water and FC-72 in a horizontal rectangular channel with a 1 × 10 array flush mounted discrete heat sources. They found in the single-phase forced convection experiment that when the Reynolds number is raised from a very low value to a very high value, the resulting flow regimes included laminar mixed convection, transition from laminar mixed convection to laminar forced convection, laminar forced convection, transition from laminar forced convection to turbulent forced convection, and turbulent forced convection. Besides, they defined the wall temperature overshoot at the boiling inception as the constant heat flux temperature difference between the maximum temperature recorded under the single-phase convection condition and the corresponding theoretical temperature under boiling conditions. According to their experimental results, at increasing velocity the heat flux increases but the temperature overshoot decreases.

Mudawar and Maddox [7] investigated the critical heat flux for FC-72 boiling on a single heat source flush mounted on one wall of a vertical rectangular channel. They noted an increase in the channel pressure drop and a decrease in the critical heat flux at increasing void fraction. In a continuing study Mudawar et al. [8, 9] experimentally examined flow boiling of FC-72 over flush-mounted heat sources. The multi-heat sources in the vertical flow channel were arranged in an 1 × 9 array for the flow velocity ranging from 13 cm/s to 400 cm/s and for the liquid subcooling from 3 ^{o}C to 36 ^{o}C with the system pressure at 1.36 bar. They observed that increases in the flow velocity and subcooling resulted in a delay in the incipence of nucleate boiling and an increase in the critical heat flux. Besides, they proposed an empirical correlation for the heat transfer coefficient measured in the single-phase region. The chip surface temperature was noted to increase slightly at decreasing velocity, and the result was opposite to that of Tso et al. [10]. Yun et al. [11] investigated flow boiling heat transfer of carbon dioxide in mini tubes. They noted that the effects of the heat flux on the heat transfer coefficient before critical vapor quality were strong at all mass flux. Besides, when the mass flux is less than 500 kg/m^{2}s, the effects of the mass flux on the heat transfer coefficient before the critical quality are significant.

The single-phase heat transfer correlations proposed in the above studies are listed in Table 1.2

1.2.2 Unstable Convective Boiling Heat Transfer

Two-phase flow instabilities in flow boiling of various liquids in long heated channels have been recognized for several decades [12, 13]. Under certain operating condition significant temporal oscillations in pressure, temperature, mass flux and boiling onset appear. Recently, some detailed characteristics associated with these instabilities were explored through experimental measurement and theoretical modeling. Specifically in flow boiling of refrigerant R-11 in a vertical channel, the pressure drop and thermal oscillations were observed by Kakac et al. [14]. Meanwhile, a two-phase homogeneous model along with the thermodynamic equilibrium assumption was used to predict the conditions leading to the thermal oscillation. Besides, they also predicted the periods and amplitudes of the oscillations, which were in good agreement with their measured data. Slightly later, Kakac and his colleagues [15] further noted the presence of density-wave oscillation superimposed on the pressure-drop oscillations. Moreover, the drift-flux model was employed in their numerical prediction. In a continuing study for R-11 in a horizontal tube of 106 cm long [16], the research group led by Kakac examined the dependence of the oscillation amplitude and period on the system parameters and located the boundaries of various oscillations on the steady-state pressure drop vs. mass flux characteristic curves. A similar experimental study was carried out by Comakli et al. [17] for a longer tube (L=319.5 cm). They showed that the channel length has an important effect on the two-phase flow dynamic instabilities.

Analysis of the dynamic behavior of a horizontal boiling channel connected with a surge tank for liquid supply also receives some attention. Mawasha and Gross [18] used a constitutive model containing a cubic nonlinearity combined with the homogeneous two-phase flow model to simulate the pressure-drop oscillation. The prediction is in qualitative agreement with the measured data. Later, the effects of the channel wall heat capacity are included in the analysis [19] to allow the wall temperature and heat transfer coefficient to vary with time.

The boiling onset in a upward flow of subcooled water in a vertical tube of 7.8 m long with a liquid surge tank was noted by Wang et al. [20] to cause substantial flow pressure and density-wave oscillations. These boiling onset oscillations were attributed to a sudden increase of pressure drop across the channel and a large change in the water flow rate at the onset of nucleate boiling, which resulted in the feedback of the pressure drop and flow rate by the system and caused the location of the boiling onset to move in and out of the channel. Therefore, large flow oscillations appear in the channel.

Aside from the boiling instabilities in conventional channels, pressure-drop oscillations of n-pentane liquid in a vertical small rectangular channel (D_h=0.889 mm and L=50 & 200 mm) were reported recently by Brutin et al. [21]. Besides, a non-stationary state of two-phase flow was observed. The effects of the inlet flow conditions on the boiling instabilities were found to be relatively significant [22]. A similar study for subcooled flow boiling of deionized water was conducted by Shuai et al. [23] and the pressure-drop oscillations were also noted.

1.2.3 Bubble Characteristics

Experiments conducted by Chang et al. [24] for water focused on the behavior of near-wall bubbles in subcooled flow boiling. The number of near-wall bubbles increases with the increase in the heat flux and in the superheated liquid layer with very small bubbles attach on the heated wall. In addition, the size of coalesced bubbles decreases with the increase in the mass flux of the flow. In a recent experiment Bang et al. [25] examined boiling of R-134a in a vertical rectangular channel focusing on the characteristic structures in the near-wall region. They noted the presence of the vapor remants below the discrete bubbles and coalesced bubbles and the presence of an interleaved liquid layer between the vapor remants and bubbles. Besides, the bubble layer was divided into two types, a near wall-bubble layer dominated by small bubbles and a following bubble layer prevailed by large coalesced bubbles. Kandlikar [26] examined the subcooled flow boiling for water in a rectangular horizontal channel. They concluded that the bubble growth was slow at high subcooling and the departure diameter decreased as the flow rate increased.

By using optical measurement techniques, Maurus et al. [27, 28] examined the bubble distribution and local void fraction in subcooling flow boiling of water at atmospheric pressure. They reported that the bubble size increased with an increase in the heat flux but reduced with an increase in the mass flux. The total bubble life time, the remaining lifetime after the detachment process and the waiting time between two bubble cycles decreased significantly as the mass flux increased. In a recent study Maurus and Sattelmayer [29] further defined the bubbly region by the ratio of the averaged phase boundary velocity to the averaged fluid velocity. On the other hand, an experimental analysis was carried out by Thorncroft et al. [30] to investigate the vapor bubble growth and departure in vertical upflow and downflow boiling of FC-87. They found that the bubble growth rate and bubble departure diameter increased with the Jacob number (increasing ΔT_{sat}) and decreased at increasing mass flux in both upflow and downflow. Bubble rise characteristics after the bubble departure from a nucleation site in vertical upflow tube boiling were investigated by Okawa et al. [31-33]. They noted that the inertia force had a significant influence on the onset of detachment but the influence was gradually reduced with time. They also observed three different bubble rise paths after the departure from nucleation sites. Specifically, some bubbles slide upward along the vertical wall, some bubbles detach from the wall after sliding, and other bubbles remain close to the wall and reattach to the wall. Forced convection boiling experiments conducted by Situ et al. [34, 35] for water in a vertical annular channel revealed that the bubble departure frequency increased as the heat flux increased. Moreover, the experimental results indicate that bubble lift-off diameter increases at increasing inlet temperature and heat flux. In addition, Yin et al. [36] examined the subcooled flow boiling of R-134a in a horizontal annular duct and noted that both the bubble departure size and frequency reduced at increasing liquid subcooling. They found that only the liquid subcooling showed a large effect on the bubble size.

1.3 Objective of This Study

The above literature review clearly indicates that the two-phase instabilities in the flow boiling of liquids in a long heated channel has received considerable attention. However, the unstable characteristics of flow boiling heat transfer and associated bubble behavior in a channel subject to imposed time varying liquid flow rate and heat flux remain largely unexplored. In this study, an experimental study will be carried out to investigate how the imposed inlet flow rate oscillation affects the transient flow boiling heat transfer of FC-72 and associated bubble characteristics on a heated flat plate flush mounted on the bottom of a horizontal rectangular channel with a constant imposed heat flux. The use of this flat heater intends to simulate the power dissipating chip in an electronic system. In the experiment both the transient saturated and subcooled flow boiling will be examined. Effects of the period and amplitude of the flow rate oscillation on the boiling characteristics will be inspected in detail for various average mass fluxes of FC-72 and imposed heat fluxes at different degrees of inlet liquid subcooling.

Table 1.1 Thermodynamic properties for FC-72.

Properties	**FC-72**
Appearance	Clear, colorless
Average Molecular Weight	338
Boiling Point (1 atm)	55.7°C
Pour Point	-90°C
Estimated Critical Temperature	449K
Estimated Critical Pressure	1.83×10^{6} pascals
Vapor Pressure	30.9×10^{3} pascals
Latent Heat of Vaporization (at normal boiling point)	88 J/g
Liquid Density	1680 kg/m^{3}
Kinematic Viscosity	0.38 centistokes
Absolute Viscosity	0.64 centipoise
Liquid Specific Heat	1100 J kg^{-1} C^{-1}
Liquid Thermal Conductivity	0.057 W m^{-1} °C^{-1}
Coefficient of Expansion	0.00156 °C^{-1}
Surface Tension	10 dynes/cm
Refractive Index	1.251
Water Solubility	10 ppmw
Solubility in Water	<5 ppmw
Ozone Depletion Potential	0

Table 1.2 Some single-phase convection heat transfer correlations for electronics cooling.

Reference	**Working Fluid**	**Heat Transfer Correlation**	**Conditions**
Samant and Simon [2]	R-113 & FC-72	$\mathrm{Nu_H} = 0.47\mathrm{Re_H}^{0.58}\mathrm{Pr}^{0.5}$	Test patch size: 0.25mm × 2.0mm Bulk velocity: 2.05 ~ 16.86 m/s Pressure at the patch: 118.8 ~ 338.1 kPa
Garimella and Eibeck [3]	Water	$\mathrm{Nu} = 1.31\mathrm{Re_a}^{0.48}(\mathrm{LS} / \mathrm{B})^{0.15}$	Heat sources size: 1.9 cm × 1.9 cm $150 < \mathrm{Re_H} < 5150$ Arrays: 5 row × 6 line
Incropera et al. [5]	Water & FC-77	$\mathrm{Nu_L} = 0.13\mathrm{Re_D}^{0.64}\mathrm{Pr}^{0.38}(\mu_o / \mu_h)^{0.25}$	Heat sources size: 12.7mm ×12.7mm Arrays: 4 row × 3 line Inlet temperature: 14 &30 $^{\circ}$C $5000 < \mathrm{Re_D} < 14000$
Gersey and Mudawar [8]	FC-72	$\mathrm{Nu_L} = 0.362\mathrm{Re_L}^{0.614}\mathrm{Pr}^{1/3}$	Heat sources size: 10mm ×10mm Arrays: 9 row × 1 line Flow velocity: 13 ~400 cm/s