CHAPTER 1 INTRODUCTION

1.1 Rational

In recent years, there has been an increasing interest in flow boiling in micro-channels, due to their ability to dissipate very high heat fluxes per unit volume, which is encountered in the cooling of electronic components, especially when cooling high-performance electronic devices for the military and aerospace industries. In addition, when compared to conventional heat exchangers, using micro-channels provides other benefits, such as decreasing the required size, weight, pumping power, and amount of working fluid. All of these advantages motivate the researchers to study the heat transfer and pressure drop characteristics in micro-channels. However, in the open literature, there has been little study of heat transfer and fluid flow characteristics during flow boiling in micro-channels. Moreover, the experimental data available in the literature are rather controversial so that there is no general agreement about the effects of different variables on heat transfer characteristics. For this reason, the main aim of the present study is to investigate the effects of the relevant parameters of flow boiling, including mass flux, heat flux, saturation temperature, and vapor quality, on the heat transfer and fluid flowcharacteristics. The experiments were performed in a copper micro-channel heat sink that had 27 parallel rectangular channels with a channel depth of 470 µm and a channel width 382 µm. In this work, R134a was selected as the working fluid, due to its high performance as a coolant. Moreover, it is also suggested as one of the most suitable choices in cooling electronics devices.

1.2 Literature review

The concept of flow boiling in micro-channels was first proposed and used by Tuckerman and Pease (1981). They designed and tested a multi-micro-channel heat sink with 50×300 μm^2 cross-section to cool electronic components using deionized water as the working fluid. Their results demonstrated that high heat fluxes of 80 kW/m^2 could be removed using micro-channels. Since then, intensive studies on flow boiling in micro-channels have been conducted in order to study their heat transfer and pressure drop characteristics. Here, some of the most recent experiments concerning the flow boiling and pressure drop in micro-channels are reviewed.

1.2.1 Flow boiling heat transfer in micro-channel

Tran et al. (1996) conducted experiments with R-12 in 2.4 mm hydraulic diameter rectangular channels and 2.46 mm circular channels. Their results indicated that, at high vapor qualities, the heat transfer coefficient only depended on heat flux, while the mass flux and vapor quality had no influence on the heat transfer coefficients. This reveals that nucleate boiling heat transfer was the major mechanism in the experiments.

Lee and Mudawar (2005)performed an experimental study on the heat transfer and pressure drop characteristics of the refrigerant R134a flowing through micro-channels with a cross-section of 231×713 μm^2. The experiment was performed under conditions of mass fluxes, heat fluxes, and inlet quality ranging from 127–654 kg/m^2 s, 316–938 kW/m^2, and 0.001–0.25, respectively. Their results show that the two-phase heat transfer coefficient decreases as vapor quality increases. The influence of heat flux on the heat transfer coefficient is very strong—up to a quality value around 0.55, after which the heat flux effect is reduced. Moreover, they also presented three correlations to calculate the heat transfer coefficient based on three different thermodynamic equilibrium qualities of the working fluid.

A similar report was presented by Bertsch et al. (2009). They studied the flow boiling heat transfer of refrigerants R134a and 245fa in micro-channel cold plate evaporators with different hydraulic diameters of 1.09 and 0.54 mm, respectively. The heat transfer coefficient varied significantly with heat flux and vapor quality, but only slightly with saturation pressure and mass flux. They also reported that nucleate boiling dominated the heat transfer.

Saitoh et al. (2005) found that the heat transfer coefficient strongly increased with heat flux, but mass flux had no visible effect on it. This behavior indicated the presence of nucleate boiling for refrigerant R-134a in channels with diameters of 0.51, 1.12 mm, and 3.10 mm.

Agostini et al. (2008a, 2008b) conducted a series of experiments on flow boiling heat transfer in a silicon multi-micro-channel heat sink with a hydraulic diameter of 383 µm. They reported the heat transfer coefficients of R236fa and R245fa as functions of heat flux, mass flux, and quality. The results showed that the heat transfer coefficient increased with heat flux, while vapor quality and mass velocity had no effect on it.

In their experiments on the flow boiling of FC-72 refrigerant in micro-channels, Saraceno et al. (2012) concluded that, when increasing the heat flux applied to the micro-channel, the heat transfer coefficient increased, while the vapor quality had no significant effect on the heat transfer coefficient. In this work, the ranges of the mass fluxes and heat fluxes were between 1000 and 2000 kg /m^2 s and 10 and 150 kW/m^2, respectively.

A number of other studies in the literature have reported conflicting trends. Lee and Lee (2001) performed flow boiling experiments with refrigerant R-113 using rectangular low-aspect-ratio channels. The plate heat exchanger used had channel heights of 0.4 to 2.0 mm with a fixed channel width of 20 mm. The heat transfer coefficient increased with mass flux and quality, however, the effect of heat flux appeared to be minor. Whereas the heat transfer coefficient in this case increased with vapor quality, Steinke and Kandlikar (2003) found the exact opposite trend in their measurements on six parallel rectangular micro-channels of hydraulic diameter 207 μm. They also found the full range of flow patterns seen in conventional-sized channels: nucleate boiling, bubbly flow, slug flow, annular flow, annular flow with nucleation in the thin film, churn flow, and dry-out. In addition, flow reversal and flow instabilities were observed in the micro-channel array under certain conditions.

Nascimento et al. (2013) recently reported on the flow boiling of R134a through a micro-channel heat sink . Their results showed that, for a fixed average vapor quality, the heat transfer coefficient increased when increasing the mass flux and fluid subcooling at the test section inlet. Similar behavior was observed and reported by Bertsch et al. (2008).

1.2.2 Two-phase pressure drop during flow boiling in micro-channel

Although there are several advantages arising in micro-channel applications, a considerable penalty is relatively high pressure drop, due to the increased wall friction, when compared with the conventional channels. It is therefore important to understand pressure drop characteristics in addition to heat transfer phenomena in micro-channel, which is of necessity for operating and evaluating the system performance.

Two-phase pressure drop across micro-channels were measured by Lee and Mudawar (2005). Flow boiling of R-134a in rectangular channels was established in their study. The measured pressure drops were not well predicted by the existing correlations. To improve the accuracy of the prediction, the parameters including liquid viscosity and surface tension were incorporated in their correlation and expressed as follows.

For laminar-liquid laminar-vapor:

$$C = 2.16\,\mathrm{Re}_{lo}^{0.047}\,We_{lo}^{0.6} \qquad (1.1)$$

For laminar-liquid laminar-vapor:

$$C = 1.45\,\mathrm{Re}_{lo}^{0.25}\,We_{lo}^{0.23} \qquad (1.2)$$

Pehlivan et al. (2006) also investigated two-phase pressure drops in a single channel with diameters of 0.80, 1.00 and 3.00 mm. Their pressure drop data were compared to prediction methods available in literature and the authors concluded that the homogeneous and Chisholm (1967) method best predicted their 0.80 and 1.00 mm data. The authors explained that their measurement errors increased as the channel diameter decreased, leading to the conclusion that comparisons with the homogeneous model lose its accuracy. This view is supported by Kandlikar (2002) who proposed that more accurate flow boiling pressure drop data as a function of quality, heat flux, mass flux and various channel dimensions are required to establish a clear indication of two-phase pressure drops in microscale channels.

Lee and Garimella (2008) experimentally investigated two-phase pressure drop in rectangular micro-channels. The measured pressure drop strongly depended on heat flux. The comparisons between the experimental data and the existing correlations were discussed. They also proposed a correlation for pressure drop prediction based on the method by Mishima and Hibiki (1996) as follows.

$$C = 2566G^{0.5466}D_h^{0.8819}\left(1 - e^{-319D_h}\right) \qquad (1.3)$$

Choi et al. (2008) performed flow boiling pressure drop experiments. R-410A was used as working fluid flowing in stainless steel tubes with diameters of 1.5 and 3 mm. The results indicated that the two-phase pressure drop increased with mass flux and vapor quality. The pressure drop was also strongly dependent on the channel diameter.

Agostini et al. (2008) carried out experiments to investigate pressure drop of R245fa and R236fa during flow boiling in micro-channel. They reported that flow boiling of R245fa induced higher pressure drop than R236fa.The prediction method on the basis of homogeneous flow model predicted well their measured results.

Lie et al. (2008) studied experimentally flow boiling of refrigerants in micro-channels. The frictional pressure drop characteristics of R134a and R407C were reported in their work.The results showed the increase in pressure drop with increasing vapor quality and mass flux. The reduction in pressure drop was observed as the saturation temperature was increased. In their study, the pressure drop to be was less dependent with heat flux.

The use of R134a as a working fluid caused a pressure drop relatively high in comparison to R470C.

Soupremanien et al. (2011) indicated that aspect ratio had an influence on pressure drop characteristics during flow boiling in rectangular channels. The pressure drop became lower as aspect ratio was decreased. In their work, the test sections with the same hydraulic diameter of 1.4 mm were examined.

1.3 Objectives of study

To study the effect of operational parameters composed of heat flux, mass flux, saturation temperature and inlet vapor quality on heat transfer and flow characteristics during boiling inside a multi-microchannel heat sink.

1.4 Scopes

The scopes of this study can be given as presented below.

1. A rectangular multi-microchannel heat sink is constructed and used as a test section.
2. R134a refrigerant is used as a working fluid.

1.5 Significance and Usefulness

The resuls and findings from this are expected to be guideline for applying the other systems using flow boiling in micro-channel heat exchangers with similar geometry. Ultimately, the results of this study will aid the design and optimization of new generation of compact heat exchangers by providing a better understanding of flow boiling and convective heat transfer in microscale two-phase flow.