International Journal of Heat and Mass Transfer 110 (2017) 276–293

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

The effect of heating area orientation on flow boiling performance in microchannels heat sink under subcooled condition

R. Ajith Krishnan, K.R. Balasubramanian *, S. Suresh

Department of Mechanical Engineering, National Institute of Technology, Tiruchirappalli, Tamil Nadu 620015, India

A R T I C L E I N F O

Article history:
Received 10 November 2016
Received in revised form 9 February 2017
Accepted 10 March 2017

Keywords:
Subcooled flow boiling
Microchannels
Orientation
Heat transfer coefficient
Pressure drop

A B S T R A C T

Subcooled flow boiling heat transfer experiments were conducted in this work in order to investigate the effect of the heating area orientation of microchannels heat sink on flow boiling heat transfer and pressure drop characteristics. The flow boiling heat transfer experiments were conducted in a 31 parallel "U" shaped microchannels (width 305 μm and depth 290 μm) heat sink with deionized water as the working fluid. The tests were conducted for different orientations such as, Horizontal upward facing (HU), Horizontal with heating area vertically aligned (HV), Vertical with up flow (VUF), Vertical with downflow (VDF) and Horizontal downward facing (HD) in a forced convection loop with volume flow rate of 50 ml/min, 100 ml/min and 150 ml/min. From the experimental results, it was observed that the performances of the heat sink under all orientation conditions were found to be almost identical except the vertical downflow orientation (VDF). The critical heat flux values are found to be less in the case of vertical downflow orientation. In the case of vertical downflow orientation, the critical heat flux values corresponding to 50, 100 and 150 ml/min flow rate were 44.1 W/cm^2, 74 W/cm^2 and 99.3 W/cm^2 respectively. For VDF orientation the buoyancy force acts on bubbles against the flow direction. Consequently, the bubbles were built up and merge each other due to the difficulty in draining and reversed flow was created with less heat flux input. The total pressure drop observed to be more for vertical downflow orientation compared to other orientations. Significant pressure fluctuations were observed during flow boiling in microchannels with VDF and HD orientations at low flow rates. The percentage reduction in effective heat flux value at the incipience of critical heat flux (CHF) in VDF orientation for flow rate of 50, 100 and 150 ml/min were 13%, 10.30% and 7.40%, and the corresponding percentage reduction in maximum outlet heat transfer coefficient was 30%, 23% and 19% respectively.

1. Introduction

Heat flux from electronic devices is becoming a great challenge in the thermal management of electronic circuits. The heat removal is an important consideration in the design of many electronic systems such as microprocessors, IC chips, battery packs and inverters, laser diodes, avionic packages and several space systems. Flow boiling in mini/microchannels has been considered as the most promising cooling technique for a variety of high heat density applications. It was Tuckerman and Pease [1] demonstrated the importance of microchannels in cooling of electronic circuits. The first effective execution of microchannels in silicon devices was deemed by them. They were capable of removing the heat flux of 7.9 MW/m^2. Numerous researchers had evaluated and reported the performance of heat sinks based on flow boiling in microchannels. These include mainly the experimental observations characterising the steady state heat transfer and fluid flow behaviour, studies regarding numerical modelling and analysis of flow boiling, procedures for enhancing the critical heat flux and also the flow visualisation studies to understand the heat transfer mechanism of flow boiling in small channels.

Even though a large number of studies were reported regarding the flow boiling heat transfer and heat transfer enhancement in the microchannels heat sink, only limited studies are published to identify the effect of the heating area orientation of heat sink on flow boiling performance. In the application point of view, the microchannels heat sink may be placed in any orientations with heating area positioned vertically, horizontally, downward facing and also inclined at a specific angle. The variation in the flow direction due to the difference in orientation of the heating area of the heat sink plays an important role in flow boiling condition due to the influence of gravity. The influence of gravity on two-phase fluid flow and heat transfer is mainly due to the drastic density variation among vapour and liquid phase. Even if it is assumed that in

* Corresponding author.
E-mail addresses: ajithjec@gmail.com (R. Ajith Krishnan), krbala@nitt.edu (K.R. Balasubramanian), ssuresh@nitt.edu (S. Suresh).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.03.030
0017-9310/

microchannels flow boiling the surface tension force and shear force govern the thermal and momentum transport, we cannot completely neglect the effect of gravitational forces, especially in low mass flow rates. The best part of the available data regarding the influence of the orientation on boiling was mainly for macro scale size channels. To the best of the author's knowledge, only a few publications were carried out pertinent to the effect of heating area orientations on the performance of the microchannels heat sink [2–8].

Kandlikar et al. [2] investigated the influence of the orientation of the heat sink on flow boiling characteristics of water in a set of six parallel mini-channels each having a hydraulic diameter of 333 μm. The three different orientations such as horizontal, vertical downflow and vertical up flow experimented under matching operating conditions of heat and mass fluxes. The flow boiling performance of their mini-channel heat sink was found to be similar to the horizontal case where a gravity vector was absent. The authors conducted all experiments only at a single mass flux. The effect of mass flux on orientation effects was not reported. Moreover, the channel size used by them had a higher width and lower depth, which will provide sufficient room for the expanding bubble and reduces the pronounced effect of backflow.

Miyata et al. [3] conducted flow boiling studies in a single copper tube of hydraulic diameter 1 mm using R410A refrigerant as the working fluid. The 320 mm length tube was tested vertically in both downward and upward flow directions. They observed an early changeover from the slug flow to the annular flow at the low mass flux situation in the vertical downward flow case. No noticeable difference in heat transfer between upward flow and downward flow was observed. The authors also reported that the pressure drop in the vertical downward flow direction was considerably larger than in the vertical upward flow direction. Their experiments were in the channel diameter range of 1 mm and with refrigerant, where the bubble departure diameter was very small. This small bubble departure diameter helps in the easy bubble removal and thus imparts fewer effects on the performance of heat sink under different orientation. Furthermore, the authors considered only upward and downward orientation.

The effect of inclination of microchannels heats sinks on flow boiling using HFE-7100 as a coolant was studied by Wang et al. [4]. Multiple parallel rectangular microchannels with 0.825 mm hydraulic diameter were considered in the study and it was tested in orientations spans from vertically upward to vertically downward flow. The authors observed that for the vertically upward and horizontal flow the heat transfer coefficient was comparable at low mass velocities. The results also signify that the vertical downward orientations always depreciate the heat transfer performance. From their flow visualisation studies, they inferred that the vapour slug velocity was improved in the upward flow path due to buoyancy effect. In the first part of a two-part study related to microchannel evaporator for space applications, Lee et al. [5] addressed the effectiveness of two-phase micro-channels in negating the body force effects. For this, they conducted flow boiling experiments with FC-72 as working fluid with three different flow orientations such as horizontal, vertical up flow and vertical downflow. From the experimental studies conducted over broad ranges of mass velocity and heat flux, they summarised that the influence of the orientation on two-phase heat transfer was significant for low mass velocities. Beyond this, they demonstrate that by using a sufficiently high mass velocity, the flow boiling in microchannels was highly effectual in negating the influence of body force/buoyancy force in space system.

The flow boiling heat transfer performance comparison of HFE-7100 at a different inclination of the test surface was investigated experimentally by Hsu et al. [6]. The multiport micro-channel tested by them had a hydraulic diameter of 440 μm. Different inclinations include −90, −45, 0, 45, and 90° with respect to the horizontal. Heat transfer coefficient for upward arrangements in their study is superior to that of downward arrangement which shows the effect of orientation on boiling performance in microchannels. Leao et al. [7] experimented the flow boiling of R245fa in 50 parallel rectangular microchannels heat sink with different orientations. The experimental trial with heating area horizontally positioned provides the higher overall heat transfer coefficient in their studies when compared to other orientations. The vertically positioned orientation with upward flow through the microchannels recorded the highest pressure drop. For most of the experimental conditions with different orientations bubbly and elongated bubble flow patterns was observed by the researchers. According to the author's view, the vertically positioned upward flow orientation provides uniform flow pattern distribution among the channel. Moreover, the presence of reverse flow is rare for this orientation.

Recently, Tamanna et al. [8] performed both heat transfer and flow visualisation studies in order to identify the effect of orientation of heat sink on flow boiling in silicon nanowire microchannels. They conducted experiments in a forced convection loop with deionized water as the working fluid. Flow boiling test was conducted in heat sink consisting of five parallel straight microchannels with silicon nanowire and heat sink without nanowire (plain channels). Only two orientations were chosen in their studies: upward facing (0° Orientation) and downward facing (180° Orientation). The authors reported that a strong influence of orientation was observed in boiling curves of plain wall microchannels heat sink, with a very meagre heat transfer performance showed by downward facing orientation. Meanwhile, the nanowire microchannel heat sink shows insensitivity to orientations at medium to high mass fluxes. For both nanowire and plain channel case, the pressure drop was found to be very little sensitive to orientation.

As seen from the above-discussed literature, the presented results concerning the effect of orientation of the boiling surface on the performance of microchannels heat sink are not decisive. Besides, the previously published research papers were relevant only to vertical and horizontal orientations of the microchannels heat sinks, where the working fluid selection in most of the literature was either the refrigerant or the dielectric fluid. The bubble departure diameters in the case of the dielectric liquid and refrigerant flow boiling were much smaller when compared to water flow boiling [9]. The blockage caused by the bubbles departed from the surface in the case of water flow boiling was much intense when compared to the refrigerant and dielectric flow boiling. Hence it is very much needed for evaluating the flow boiling performance of microchannels heat sink with different orientations and flow rates with water as the working fluid, so as to study the effect of gravity on heat transfer, pressure drop and flow instabilities. Additionally, there was no organised information about the influence of mass flow rates and all possible orientations including horizontal upward facing, horizontal downward facing, vertical up flow, vertical downflow and horizontal with vertically aligned channels on the performance of microchannels heat sink. In this context, it is the main objective of our study to investigate the impact of heating area orientation on the heat transfer and total pressure drop of microchannels heat sink with different flow rates during subcooled flow boiling, with deionized water as the coolant.

2. Experimental methods and data reduction

2.1. Experimental facility

The schematic diagram and the actual photograph of the experimental facility of the present study are shown in the Figs. 1 and 2.