International Communications in Heat and Mass Transfer 85 (2017) 131–138

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Visualization of flow patterns and bubble behavior during flow boiling in open microchannels

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ARTICLE INFO

Keywords:
Flow boiling
Open microchannels
Flow patterns
Bubble behavior
Flow instabilities

ABSTRACT

Flow boiling in microchannels is favored by the heat transfer community due to the high heat transfer rates that can be obtained with lower mass flow rates. However, the heat transfer rates for flow boiling in microchannels are impacted by flow reversals and flow instabilities. An open microchannel structure was recently proposed to reduce the impact of the flow boiling instabilities. Subcooled flow boiling experiments were conducted in open microchannels using deionized water. The open microchannels had 6 parallel channels with a 0.3 mm uniform thickness gap above them The channels were fabricated on a 6 mm × 40 mm copper block. The channels were 0.5 mm wide and 0.3 mm deep with 0.43 mm wide fins between them. Flow visualizations were performed with a high-speed CCD camera with the results showing that the flow regimes in the open microchannels differ from those in closed microchannels with stratified flow and no flow instability. Two types of confined bubbles were observed with characterizations of the effects of the bubbles on each other. The heat transfer mechanisms for flow boiling in open microchannels are also described.

1. Introduction

Heat fluxes in compact electronics are continuing to rise and are a major challenge for thermal management. Many electronics and energy applications, such as high-power defense electronics, high performance computers, and solid-state lasers, are dissipating 10^3–10^4 W/cm^2 and higher [1,2], so the cooling requirements of these high/ultra-high heat flux applications exceed the heat removal capability of conventional techniques like air cooling or single-phase liquid cooling. Micro/mini-channels with their very high heat transfer rates are being considered for such needs after the pioneering work of Tuckerman and Pease [3]. In particular, flow boiling in microchannels has received much attention and has been studied extensively over the past two decades because of the outstanding heat dissipation rates and the low liquid flow rates [4]. Numerous efforts have focused on improving the heat dissipation rates of two-phase devices, decreasing the effects of the flow boiling instabilities and improving the CHF.

Rapid bubble growth with expansion in both the upstream (flow reversal) and downstream direction in the channel is one of the main reasons for flow boiling instabilities in microchannels [5,6]. During the rapid bubble expansion, the liquid film surrounding the confined bubble is rapidly vaporized with the formation of a dry patch under the bubble, which is also responsible for the earlier CHF in microchannel flow boiling. Many efforts have focused on suppressing flow reversal, reducing the flow instability and improving the CHF by modifying the microchannel structure. Ali Koşar et al. [7] found that boiling flow instabilities in parallel microchannels were suppressed by introducing inlet restrictors. Kandlikar et al. [8] concluded that the use of pressure drop elements in conjunction with fabricated artificial nucleation sites eliminate the instabilities associated with reversed flow. Kuo et al. [9] found that structured reentrant cavities in microchannels reduced to an extent flow boiling instabilities and increased the CHF. Lu et al. [10,11] demonstrated that parallel microchannels with increasing flow cross-sectional areas significantly stabilized flow boiling in parallel microchannels. Recently, Kandlikar et al. [12,13] proposed an open microchannel with a manifold geometry to eliminate the flow instabilities with the additional flow area over the microchannel assisting removal of the generated vapor without an excessive pressure drop, which significantly reduced the downstream flow resistance and the backflow associated with such instabilities.

The heat transfer mechanisms during flow boiling in open microchannels are still not fully understood since they are strongly dependent on the flow patterns and bubble behavior. As seen in previous studies [14–17], high speed flow visualizations are a useful way to understand flow boiling in microchannels. This work uses high speed flow

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2017.05.008

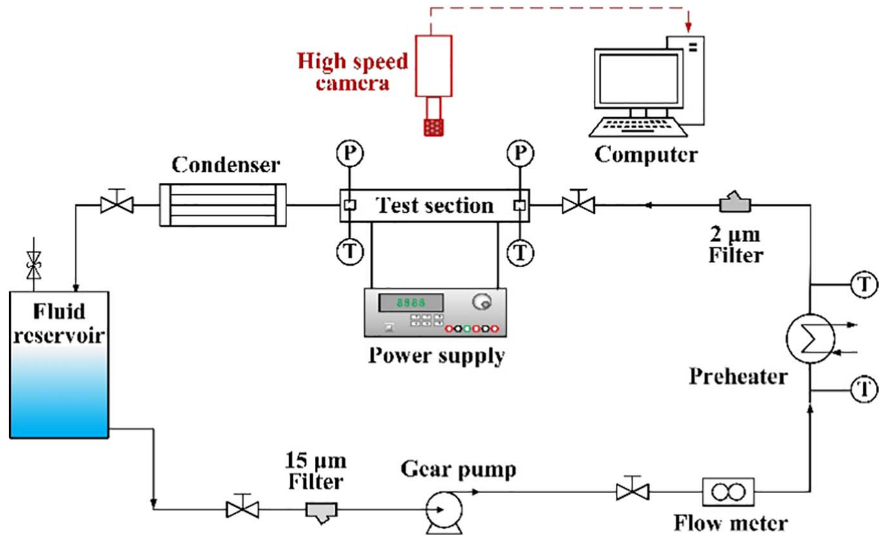

Fig. 1. Experimental setup.

visualizations to investigate the flow patterns and bubble behavior during flow boiling in open microchannels with a uniform thickness gap above the channels. Various flow patterns and bubble behavior are observed for various heat fluxes and mass fluxes. These are used to analyze the underlying heat transfer mechanisms for flow boiling in open microchannels.

2. Experimental setup

The experimental setup is shown in Fig. 1. Deionized water was boiled violently for about half an hour and was then stored in the sealed liquid tank. A magnetic micro gear pump drove the fully degassed water into the flow loop with a 15 μm filter placed before the pump to remove any possible particles. A preheater was installed upstream of the test section to heat the liquid to the desired subcooling with a condenser downstream of the test section to cool the working fluid before it flowed back into the liquid tank. A 2 μm filter was placed before the test section to prevent solid particles from entering the microchannel. The mass flow rate was measured using a Coriolis mass flow meter. The working fluid pressures and temperatures at the test section inlet and outlet were measured by two pressure transducers and two K-type thermocouples. The flow patterns and bubble behavior during flow boiling in the open microchannel were visualized and recorded by a high speed CCD camera at 500 fps above the test section.

The open microchannel test section consisted of 6 parts as shown in Fig. 2. The test section contained six parallel 0.5 (width) × 0.3 (depth) mm^2 channels with 0.43 mm wide fins between the channels. The channels had a 0.3 mm thick open space above them. The cover plate was made of Polycarbonate, while the microchannels were formed on the top surface of an oxygen-free copper block. The Cu block was heated by a ceramic heater from below with the whole setup held together by the PTFE housing and the epoxy resin board. The PTFE housing had inlet and outlet plenums with four holes drilled into these plenums for the thermocouple probes and the pressure transducers. A sealing groove was cut into the top of the PTFE housing for an O-ring to seal the assembly. The polycarbonate cover, PTFE housing and epoxy resin board were clamped together by screws. Thermal insulation (not shown in the figure) was placed between the ceramic heater and the epoxy board, the fiber glass was coated on the sides of the Cu heating block and test assembly to reduce the heat losses from the test section.

The tests used mass fluxes of $G = 115–641\ kg/(m^2\ s)$ and heat fluxes of $q = 175–701\ kW/m^2$ with an constant inlet temperature of 65 °C. The combined effects of the heat flux and the mass flux on the flow boiling phenomena were characterized by the Boiling number ($Bo = q/Gh_{fg}$, where h_{fg} is the latent heat of vaporization) which ranged from 2.7×10^{-4} to 2.7×10^{-3}.

3. High speed visualizations

3.1. Flow pattern transitions

The flow patterns observed during subcooled flow boiling in the

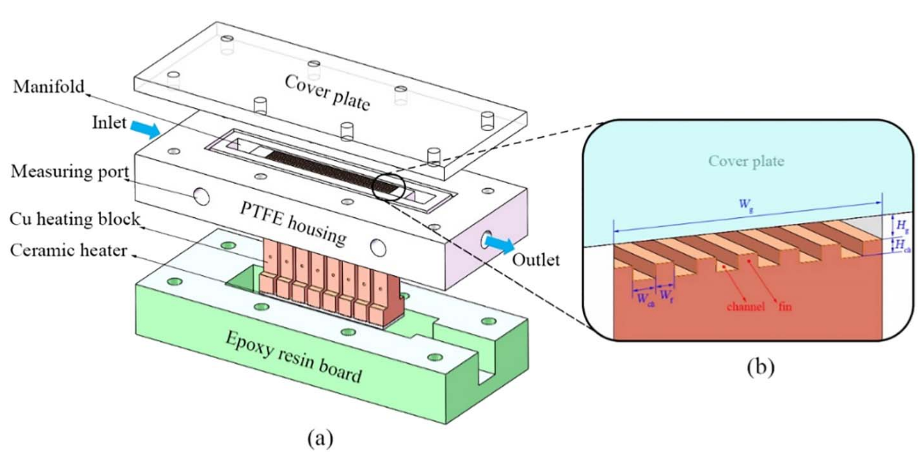

Fig. 2. (a) Open microchannel test section and (b) expanded view of the flow cross section.