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# Flow patterns and heat transfer mechanisms during flow boiling over open microchannels in tapered manifold (OMM)

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ABSTRACT

The ever increasing demand of high heat removal from compact form factor devices has generated considerable interest in advanced thermal management techniques. Flow boiling in microchannels has the ability to provide high heat dissipation due to the utilization of the latent heat of vaporization, while maintaining a uniform coolant temperature. Recently, a number of studies have introduced variable flow cross-sectional area to augment the thermal performance of microchannels. The open microchannel with manifold (OMM) configuration provides stable high heat transfer performance with very low pressure drop. In the current work, high speed images are obtained to gain an insight into the nucleating bubble behavior and flow patterns at high heat fluxes including critical heat flux (CHF). The flow patterns are plotted as a function of superficial gas and liquid velocity. The resulting map indicates significant departure from the earlier work on macroscale tubes and confined microchannels. A mechanistic description of the heat transfer mechanism is also presented and the underlying differences between flow boiling in closed microchannels and open microchannels with tapered manifold configuration are highlighted. Furthermore, bubble ebullition cycle in pool boiling is compared with the tapered geometry utilizing plain and microchannel surfaces.



## 1. Introduction

Heat dissipation rate per unit device area has greatly increased due to the miniaturization of electronics [1]. As heat fluxes in medical, aerospace and defense related electronics equipment continue to increase, two-phase cooling is looked at as an attractive solution with a relatively small increase in the surface temperature. Flow boiling in microchannels has been studied as one of the cooling techniques to meet the current thermal requirements [2]. It is considered to be an attractive option due to its small hydraulic diameter, uniform temperature control, and compact design. However, the efficiency of the flow boiling technique in microchannels has been severely impacted due to early CHF [3] and flow instability [4]. For flow instabilities in microchannels, rapid/explosive bubble growth was seen as one of the main reasons. Hsu's criterion [5] provides the required surface cavity radius for bubble nucleation. The bubble growth rate in a microchannel depends on the local flow conditions and wall superheat, and the reasons for the explosive bubble growth were explained by Kandlikar [6]. The single-phase heat transfer coefficient in microchannel is high, and provides a superheated liquid state within the entire microchannel cross-sectional area. The bubble upon nucleating from the cavity experiences a highly superheated liquid environment causing it to rapidly expand in both upstream and downstream directions. For small channels, bubble nucleation causes local pressure variation along the flow path as seen from Fig. 1. The maximum pressure in the bubble can exceed the inlet pressure ($P_v > P_{in}$) due to the high wall temperature. This causes the bubble to overcome the incoming liquid inertia and travel in the upstream direction causing flow reversal.

When the bubble expands, the pressure decreases and enters a relaxation period as seen in Fig. 2 [7]. During this relaxation period, the pressure inside the bubble ($P_v$) reduces and drops below the inlet pressure ($P_{in}$), therein reversing the upstream movement of the bubble and flowing in the direction of the fluid flow.

This unstable flow causes severe pressure and temperature fluctuation and in some cases initiates an early CHF. Previous research efforts in this area have focused on overcoming these challenges by using various structures, such as inlet restrictors [8], artificial nucleation sites [9], reentrant cavities [10], vapor venting [11] and increasing flow cross-sectional area [12,13]. Further details

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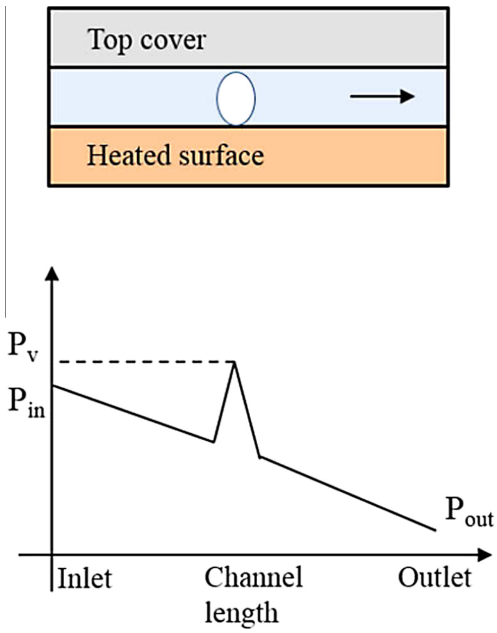


**Fig. 1.** Pressure variation inside a microchannel during bubble nucleation, adapted from [6].

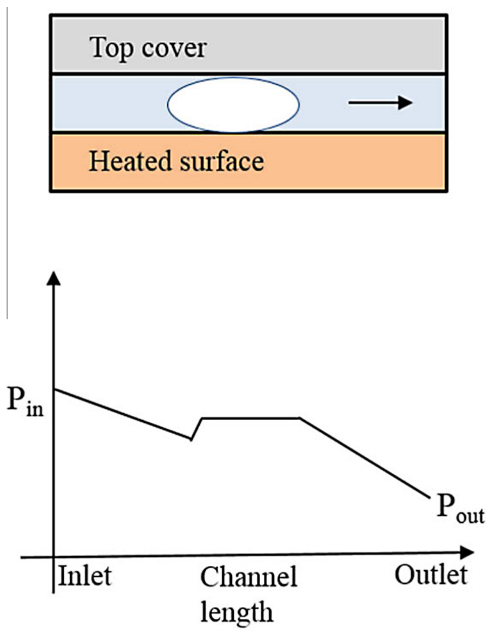


**Fig. 2.** Pressure variation inside a microchannel during bubble expansion, adapted from [7].

on these techniques that provide enhanced heat transfer and reduced flow instability have been addressed in a previous publication by the authors [14]. The open microchannel with manifold (OMM) geometry was introduced by Kandlikar et al. [15] to provide a stable, low pressure drop and high performance system. This geometry provides additional flow area over the microchannel (manifold region) which assists in removing the generated vapor without an excessive pressure drop. Tapered manifold was used to provide gradual area increase downstream thereby reducing flow resistance and increasing flow stability.

High speed flow visualizations have been conducted by various researchers under different parameters to study various flow patterns in their systems. For example, Hetsroni et al. [16] observed two types of flow patterns, namely annular and dryout in their study. Kandlikar [17] studied the heat transfer mechanisms in microchannels, focusing on flow instability and two-phase flow patterns (slug flow, annular flow, churn flow and dryout condition). Zhang et al. [18] observed nucleate boiling and eruption boiling in their single microchannel study. They also found the boiling mechanism to be strongly dependent on the wall surface roughness. Chen and Garimella [19] observed bubbly and slug flow at low heat fluxes. At higher heat fluxes, the authors observed annular and churn flow in the downstream section and flow reversal near the microchannel inlet. Harirchian and Garimella [20] studied the effect of various parameters on flow boiling regimes. The authors reported that the flow regimes for microchannels with 400 μm (width) and greater were similar, while microchannels with width less than 400 μm showed different flow regimes. Balasubramanian et al. [12] used a stepped microchannel in their investigation and observed bubbly, intermittent, and annular flow regimes. Recently, Tamanna and Lee [21] used expanding silicon microgap heat sink to study the bubble mechanism in their geometry through high speed visualization. Excellent reviews discussing the flow patterns for different flow conditions and other aspects of microchannel flow boiling are available in literature [22–24].

In this work, flow patterns and heat transfer mechanisms of an open microchannel with tapered manifold are investigated. Various flow patterns are observed and their transitions with increasing heat flux are described. The underlying mechanisms of bubble nucleation, growth and departure are explored through high speed visualization. Furthermore, closed microchannel and open microchannel geometries are compared via bubble dynamics through high speed image sequences. Plain surface bubble ebullition cycle and flow conditions leading to CHF in the OMM geometry are also discussed.

## 2. Experimental setup

Fig. 3 shows the schematic representation of the test loop used in the flow boiling study with OMM geometry. The experimental setup was designed and fabricated to study flow boiling with OMM geometry with high speed visualization capabilities. The setup details can be obtained from a previous publication [9]. Briefly, distilled water was degassed in a pressure canner using a hot plate to remove dissolved gases following the procedure recommended by Steinke and Kandlikar [25]. A Micropump® was used to circulate the liquid. The flow rate for a given test run was set using a rotameter. An inline heater with a PID controller was used to provide the desired inlet temperature for the system. The exit liquid–vapor mixture from the test section was returned to the pressure canner. The test section consisted of a microchannel chip with a channel depth of 205 μm, width of 250 μm, and fin width of 145 μm. A fixed inlet height of 127 μm above the microchannel surface was used for all test runs along with a taper gradient of 4%, resulting in an increase in the manifold height by 400 μm over a flow length of 10,000 μm at the exit section. Three mass fluxes of 196, 393 and 688 $kg/m^2s$ were studied. Further details regarding the tapered manifold, heat flux and pressure drop calculations can be obtained from an earlier publication [9].

## 3. High speed visualization

High speed visualization was accomplished with a Photron 1024 Fastcam CMOS camera and a 150 mm Nikon lens. Additional light required for imaging was provided using a Dolan-Jenner Fiber-lite MH-100 metal halide Machine Vision illuminator lamp. The polysulfone manifold block was polished to a transparent finish to facilitate visualization. The images were taken