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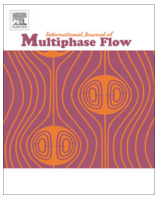

Review

Proposed models, ongoing experiments, and latest numerical simulations of microchannel two-phase flow boiling

S. Szczukiewicz, M. Magnini, J.R. Thome *

Laboratory of Heat and Mass Transfer (LTCM), Ecole Polytechnique Fédérale de Lausanne (EPFL), EPFL-STI-IGM-LTCM, Station 9, CH-1015 Lausanne, Switzerland

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ABSTRACT

A survey of the most recent work aimed at physically characterizing local heat transfer in flow boiling in microchannels is presented. This includes recent experimental work, new flow boiling prediction methods, and numerical simulations of microchannel slug flows with evaporation. Some significant developments in the measurement techniques provide simultaneous flow visualizations and measurements of 2D temperature fields of multi-microchannel evaporators. In particular, information on inlet micro-orifices has been gained as well as better ways to reduce such heat transfer and pressure drop data for very high resolution data (10,000 pixels at rate of 60 Hz). First of all, flow patterns are seen to have a significant influence on the heat transfer trends in microchannels (just like in macrochannels), and thus need to be accounted by visualization during experiments and during modeling. A clear distinction between steady, unsteady, well- and maldistributed flows needs to be made to avoid any confusion when presenting and comparing the heat transfer coefficient trends. In reducing the raw data to local heat transfer coefficients, the calculated values of several terms involved in the heat transfer coefficient determination are influenced by the data reduction procedure, especially the way to deduce the local saturation pressures/temperatures, and may lead to conflicting trends and errors approaching 100% in local heat transfer coefficients if done inappropriately. In addition to experiments, two-phase CFD simulations are emerging as a tenable tool to investigate the local heat transfer mechanisms, especially those details not accessible experimentally. In particular, a new prediction method based on numerical simulation results captures the heat transfer in the recirculating liquid flow between elongated bubbles. Thus, it is shown here that targeted computations can provide valuable insights on the local flow structures and heat transfer mechanisms, and thus be used to improve the mechanistic boiling heat transfer prediction methods.

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* Corresponding author. Tel.: +41 021 6935981.
E-mail address: john.thome@epfl.ch (J.R. Thome).

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1. Introduction

A noticeable global tendency towards miniaturization driven by the micro-electronics industry is bringing ever greater attention to multi-microchannel two-phase flow evaporation as the most advantageous cooling process, utilizing the latent heat of evaporation to extract the heat in an energy efficient manner. As a result of the enhanced thermal performance compared to other processes, better axial temperature uniformity (Agostini et al., 2008b), reduced coolant flow rates, and thus smaller pumping powers (Agostini et al., 2007) are obtained. Therefore, two-phase flow cooling provides an excellent opportunity to continue the progress relative to Moore's law (Moore, 1965) associated with a tremendous challenge of removing the continuously increasing heat fluxes dissipated by modern CPUs. The large amount of experimental work, theory and prediction methods have been reviewed in the past few years by Thome (2004, 2006), Cheng et al. (2008), Thome and Consolini (2010) and Baldassari and Marengo (2013). Consequently, the present review has a narrow scope to look at some new emerging issues regarding experimentation and the targeted use of numerical simulations to gain local, transient insight into the two-phase evaporation process and improvement of its heat transfer models.

Numerous micro-evaporators have been tested over the past few years. Their reported heat transfer performances, quantified in terms of local heat transfer coefficients, depend on the data reduction methods and assumptions each study used. Several aspects, such as determination of the local fluid saturation temperature, edge heat losses and heat spreading effects, and flow stability, need to be more carefully taken into account when comparing and modeling heat transfer coefficient results. Obviously, only the values calculated in the same manner, when merged together, will bring adequate conclusions on microchannel cooling capabilities. Moreover, the experimental techniques for measurements have some technical limitations due to the small length and time scales involved in flow boiling within microchannels. For instance, the time response for thermocouples in point-wise temperature measurements is usually larger than the characteristic time of the investigated phenomena, whilst experiments with Micro Particle Image Velocimetry (MicroPIV) still remain a challenging task at these high flow velocities.

On the other hand, the recent advances on multiphase Computational Fluid Dynamics (CFD) techniques, together with the increasing processing power of computers, are making numerical simulations an ever more powerful and reliable tool to provide new and detailed insights into the local hydrodynamics and thermal features of flow boiling in microchannels. The accuracy of the gas–liquid interface tracking and modeling of interfacial effects is of primary importance for microscale-aimed computational methods, since the interface topology plays a fundamental role in flows within microdevices. Volume Of Fluid (VOF) (Hirt and Nichols, 1981) and Level Set (LS) (Sussman et al., 1994) methods are indeed the most widely used algorithms to model interfacial flows, due to their accuracy, robustness and easiness of implementation. In fact, the cited algorithms only add a "color function" equation (to identify each phase) to the single-phase flow equation set, which includes mass, momentum and energy equations, that are then solved in a fixed computational grid. However, it is important to remark that while numerical simulations provide an advanced tool to investigate two-phase flows which may also anticipate experimental findings, the development of such computational methods requires detailed experimental measurements to validate their new algorithms.

The present paper is organized as follows: first the most recent experimental findings on microscale two-phase flows are reviewed in Section 2, then Section 3 outlines the latest advances in multiphase numerical simulations in microchannels, next Section 4 discusses their mutual contribution and related issues of data reduction, stable and unstable flow, and hydrodynamics to the heat transfer coefficient trends, and finally Section 5 summarizes the main conclusions of this work.

2. State-of-the-art of microscale two-phase flow boiling

In spite of the large number of papers published in the flow boiling domain, many aspects still need to be better explained in order to provide a fuller understanding of local two-phase flow boiling characteristics. Such knowledge is essential to develop more reliable prediction methods that can be used for designing new high-performance microchannel heat spreaders for microelectronic and power electronic applications. This section presents the most recent experimental results in microscale two-phase flow research aiming to determine the contribution of geometrical parameters and other two-phase flow aspects on the heat transfer coefficient trends, which are then discussed in terms of two-phase flow patterns and flow transitions.

2.1. Microchannel flow boiling heat transfer

Geometrical parameters, such as the hydraulic diameter and the manifold's material and its shape, may significantly influence microscale two-phase flow results (Hetsroni et al., 2005). For example, several experimental studies reported significant heat transfer enhancement of flow boiling in small (Agostini and Bontemps, 2005; Karayiannis et al., 2010) and narrow channels (Su et al., 2005) compared to conventional macrochannels. On the other hand, the measurement reliability decreases with decreasing tube diameter, as pointed out by Mishima and Hibiki (1996). Additionally, numerous differences between micro- and macrochannels might be due to inaccurate dimensional measurements in the microscale (Agostini et al., 2006), where the surface roughness effect on heat transfer at low to medium vapor qualities in the slug flow regime is noticeable (Agostini et al., 2008d).

In particular, Agostini et al. (2003) showed that the flow boiling heat transfer coefficient of R134a increased by a factor of ~1.74 when decreasing the hydraulic diameter from 2.01 to 0.77 mm. The increase of heat transfer coefficient at low values of vapor quality with decreasing channel diameter is associated with the decrease in the initial film thickness between the elongated bubbles and the channel wall, as explained by Dupont and Thome (2005) based on the three-zone model of Thome et al. (2004). For example, Fig. 1 illustrates the local (width-averaged) heat transfer coefficient trend versus local vapor quality from inlet to outlet for a test section with 67 channels of $100 \times 100\ \mu m^2$ cross-section (Szczukiewicz et al., 2012b, 2013b), which were measured with a very fine resolution by means of a high-speed IR camera (for more details, refer to the following section). In the isolated bubble (IB) regime, in which bubbles might be smaller than the channel diameter or elongated, the heat transfer coefficient increases, and after the local maximum, it starts to decrease in the coalescing bubble (CB) regime. Then, when annular flow (AF) is formed, the heat transfer coefficient climbs considerably again, dramatically illustrating the importance of flow patterns on the heat transfer process. In the IB regime, heat transfer increases without formation of dry patches at the end of the elongated bubbles, while in the CB regime, the heat transfer coefficient decreases due to the onset of cyclical dryout as the vapor quality increases, which was observed visually by Borhani et al. (2010). The minimum coincides with the churn flow regime (see the corresponding snapshot in