International Journal of Heat and Mass Transfer 108 (2017) 2346–2354

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Visualization and measurement of reverse flow in an actual channel of a microchannel evaporator

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ARTICLE INFO

Article history:
Received 7 November 2016
Received in revised form 15 January 2017
Accepted 21 January 2017

ABSTRACT

Two leading edge channels of a microchannel evaporator are made transparent to visualize the flow regimes inside. The evaporator is operated in an automotive air conditioning system under both two-phase refrigerant feeding and liquid refrigerant feeding modes. The flow regimes in the microchannels are different in these two operation modes. In two-phase feeding mode: churn, bubbly/slug, and annular flows occur alternatively, but the period of each flow regime is not constant. Flow reversal is only witnessed occasionally in bubbly/slug flow regime. In liquid feeding mode, only liquid and bubbly/slug flows are observed. Reverse flow occurs periodically. The duration of flow reversal is shorter in two-phase feeding mode than in liquid feeding mode. Most likely it is due to higher upstream resistance caused by two-phase refrigerant feeding.

1. Introduction

Microchannel heat exchangers are widely used in air conditioning and refrigeration systems because of their compactness and enhancement of heat transfer performance. However microchannel heat exchangers suffer from the problem of refrigerant maldistribution, especially for evaporator. Boiling instability and flow reversal is one cause of refrigerant maldistribution, since reversed vapor induces further quality maldistribution in the inlet header. According to Tuo and Hrnjak [28], flow reversal in microchannel evaporators deteriorates refrigerant distribution, increase pressure drop, although may increase local heat transfer coefficient. The focus of previous research on flow instability in microchannels has been on heat sinks for small scale cooling applications, such as electronic cooling. Brutin et al. [8] experimentally investigated the unsteady boiling of n-Pentane in heated minichannels. They found that the unsteady boiling region was determined by heat flux and mass velocity, and unsteady boiling created reverse flow and high amplitude fluctuation of pressure signal. Brutin and Tadrist [7] further studied the steady and unsteady boiling region determined by heat flux and mass velocity. They found that under each heat flux they examined, there is a critical mass velocity (or Re number) that delimit steady and unsteady boiling. Under each heat flux, unsteady boiling only happens at low mass velocity region, which can also be interpreted as high exit quality region. Wu and Cheng [32] studied water boiling in two silicon microchannels with diameters of 158.8 and 82.8 μm. They believed a new type of oscillation with long period was discovered in which single phase flow and two-phase flow appear alternatively. The oscillation period in the large channel was 31 s, and it was 141 s in the smaller tube. Wu and Cheng [33] continued their study about boiling instability in parallel microchannels. They first adjusted the water inlet pressure, then gradually increased heat flux. They discovered liquid/two-phase alternating flow at heat flux from 13.5 to 16.6 W/cm^2, then continuous two-phase flow at heat flux of 18.8 W/cm^2, and lastly liquid/two-phase/vapor alternating flow at heat flux of 22.6 W/cm^2. They found that liquid/two-phase/vapor alternating flow created the largest pressure oscillation, while continuous two-phase generated the least pressure oscillation. Qu and Mudawar [24] studied boiling instability of water in parallel microchannels under high heat fluxes. They were focusing on two types of dynamic instability: pressure drop oscillation and parallel channel instability. They found that pressure drop oscillation can be greatly suppressed by a throttling valve placed before microchannels. Parallel channel instability, which is much milder than pressure oscillation, can also be alleviated by more throttling. Hetsroni et al. [14] proposed detailed stages in one cycle of periodic boiling process. Soon after nucleation, a bubble grows very rapidly to the size comparable to the diameter of the channel (step a); then the bubble expands bidirectionally (step b); after the downstream edge of the bubble reaches channel outlet, the bubble begins to vent (step c); few liquid droplets are left on the wall after

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.01.085
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Nomenclature

Bo	Boiling number
Eo	Eotvos number
g	acceleration of gravity ($m\cdot s^{-2}$)
G	mass flux ($kg\cdot m^{-2}\cdot s^{-1}$)
h	heat transfer coefficient ($W\cdot m^{-2}\cdot K^{-1}$)
h_{fg}	latent heat of vaporization ($J\cdot kg^{-1}$)
k	thermal conductivity ($W\cdot m^{-1}\cdot K^{-1}$)
L	length (m)
Nu	Nusselt number
q	heat flux ($W\cdot m^{-2}$)
Greek	
Δ	difference
ρ	density ($kg\cdot m^{-3}$)
σ	surface tension ($N\cdot m^{-1}$)
τ	time (s)

bubble depletion (step d); along with bubble depletion, pressure inside of the channel decreases and fresh liquid starts to move in (step e); finally, a new cycle starts (step f). Through experiments, they also found that pressure oscillation caused by boiling instability increases with increasing quality. Hetsroni et al. [15] tried to describe boiling instability by dimensionless groups. They picked Nusselt number ($Eo = \frac{hL}{k}$), Eotvos number ($Eo = \frac{\Delta\rho g L^2}{\sigma}$) and Boiling number ($Bo = \frac{q}{G h_{fg}}$). They correlated initial film thickness and Nu/Eo with Bo and believed Bo (q/mh_{fg}) is the bond between momentum and energy equations. Chen and Garimella [10] visualized FC-77 flow in parallel silicon microchannels. They found that under high heat fluxes (>427 kW/m^2), flow reversal occurs near the inlet of the microchannels, causing oscillation of pressure drop. They also concluded that flow reversal, which creates changes of mass flow rate, causes the alternation of flow regime near the outlet of the microchannel. From their results, it can be seen that higher heat flux leads to greater chance of reverse flow, but this comparison is made under the same mass flux and changing outlet quality (under same mass flux, higher heat flux will create higher exit quality). Harirchian and Garimella [13] visualized FC-77 flow in parallel silicon microchannels with different geometries. They located a throttling valve before the heat sink to suppress instability, but flow reversal was still observed at their highest heat flux examined. Huh et al. [16] studied boiling instability in one microchannel. They discovered that there is a phase shift between pressure drop oscillation and mass flow oscillation. A sudden increase of mass flow rate occurred at the peak of pressure drop. They also found that an increase of mass flow rate lead to smaller oscillation amplitude and shorter period. Under the same mass flux, increasing heat flux (equivalent to higher exit quality) created higher oscillation amplitude and longer period. Zhang et al. [34] investigated excursive instability in parallel microchannels. They found that increasing operation pressure, channel diameter, and channel length and adding an inlet restrictor could alleviate instability. Compared with experimental work, few simulative studies about boiling instability and flow reversal are found in the literature. Kenning et al. [18] developed a 1D model to simulate single bubble growth in a microchannel. They defined bubble growth into two stages: unconfined and confined. In the unconfined stage, the radius of the spherical bubble is governed by an analytical correlation proposed by Plesset and Zwick [22]. In confined growth stage, the bubble growth is governed by mass, momentum and energy conservation equations. Comparison between experimental data and optimized simulation results shows that this model predicted accurately the exponential growth of a bubble and predicted fairly well the fluctuation of the inlet pressure. The drawback of this model is that it assigned uniform velocity to the vapor slug which is not true based on our visualization. Gedupudi et al. [12] developed a 1D model for single bubble growth inside of one microchannel. They divided the whole growth process into 3 stages (1) Partially confined growth, (2) Fully confined growth, (3) Vapor venting. Bubble growth was governed by the energy input. The growth rate of the bubble determined the velocity difference of the upstream liquid slug and the downstream liquid slug. The velocities of both liquid slugs were also governed by pressure. Momentum conservation equation was solved with the knowledge of heat input. When the outlet pressure was fixed, oscillation of the inlet pressure can be simulated by their model. The highest pressure was found to be somewhere along the tube instead of the inlet. Belmares and Park [4] simplified the flow inside of a microchannel into two elements: liquid and vapor. They modeled the pressure drop of each element and applied mass balances on the liquid and vapor interfaces. Through simulation, they found that flow reversal occurs more easily if liquid front interface lies closer to the inlet and inlet flow restriction can alleviate flow reversal. Revellin et al. [25] modeled the collisions between a series of bubbles. They used the model developed in Agostini et al. [1] to link the velocity and length of elongated bubbles. Coupled with heat input, which determines the growth rate of a bubble, bubble collision can be simulated when the liquid slug between bubbles vanishes. Most of the aforementioned models are only capable of simulating single bubble dynamics in one microchannel. The only model employing multiple bubbles (Revellin et al. [25]) was used to simulate bubble collisions, which is not suitable for predicting pressure oscillation and change of bulk fluid directions.

To the best of the authors' knowledge, flow reversal in air conditioning application was first observed at Creative Thermal Solutions (CTS) in 2006 and later published by Bowers et al. [5]. Tuo and Hrnjak [28] reported periodic reverse flow in a Flash Gas Bypass (FGB) system. The FGB system was first used for systems with microchannel evaporators by Beaver et al. [3], later Elbel and Hrnjak [11]. It can improve the refrigerant distribution inside of microchannel evaporators compared with direct expansion (DX) operation mode. Periodic oscillation of pressure at the evaporator inlet was discovered and the dominant frequency was identified to be 0.53 Hz by fast Fourier transform. Through visualization of the flow regime in the inlet header, they divided one oscillation cycle into three parts: (1) reverse vapor flow; (2) vapor re-entraining in forward flow; (3) liquid refilling in forward flow. The vapor re-entraining significantly deteriorated the refrigerant distribution. Tuo and Hrnjak [29] invented a new system configuration: revised flash gas bypass (FGBR) to vent the reversed vapor in the evaporator. They found that the reverse vapor accounted for 2–8% of the total supplied liquid into the evaporator. By venting the reverse vapor, 5% of capacity and 3% of COP improvement could be achieved compared with the FGB system baseline. Tuo and Hrnjak [30] further reported that the liquid level in the inlet header was stabilized and elevated above inlets of every tube by venting the revered vapor, thus refrigerant distribution was improved. In addition, the pressure drop across the evaporator was further reduced compared with the FGB baseline. Tuo and Hrnjak [31]