International Journal of Heat and Mass Transfer 101 (2016) 341–353

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Porous-wall microchannels generate high frequency "eye-blinking" interface oscillation, yielding ultra-stable wall temperatures

Jinliang Xu *, Xiongjiang Yu, Wu Jin

The Beijing Key Laboratory of Multiphase Flow and Heat Transfer for Low Grade Energy Utilization, North China Electric Power University, Beijing 102206, PR China

ARTICLE INFO

Article history:
Received 6 March 2016
Received in revised form 8 May 2016
Accepted 9 May 2016

Keywords:
Microchannel
Flow instability
Heat transfer
Boiling/evaporating
Vapor–liquid interface

ABSTRACT

The proposed gradient–porous-wall microchannels consist of bare channels and pin–fin array regions, fabricated by MEMS (microelectricalmechanicalsystem) technique. Boiling experiments were performed with acetone as the working fluid. Ultra-stable wall temperatures are achieved with oscillation amplitudes in the range of 0.02–0.18 °C. Bubble nucleation is found to happen in the porous wall. The generated vapor flows towards bare channels due to surface tension driving flow. The vapor ejection direction is periodically switched between neighboring channels, called the "bubble emission switch". The bubble confinement ratio is newly defined. Bubbles become fat and slim in bare channels to generate high frequency "eye-blinking oscillation". Bubble confinement ratios display sine function, and out-of-phase characteristic between neighboring channels. We confirm the "eye-blinking" oscillation as a density wave oscillation, propagating in the channel width direction. Because the porous-wall width is much smaller than the channel length, the "eye-blinking" frequencies are 10–100 times higher than that of the axially propagated density wave oscillation. The "integration parameter model" establishes the connection between "eye-blinking" oscillation and wall temperatures. The convective heat transfer intensity in bare channels is assumed to follow the bubble confinement ratio variation. The wall temperature oscillation amplitude is inversely proportional to the "eye-blinking" frequency. The phase angle between bubble confinement ratios and wall temperatures are $3\pi/2$, being the negative feedback mechanism to inhibit wall temperature oscillations. The porous-wall microchannels open a new way to eliminate flow instabilities for heat exchangers and thermal energy systems.

1. Introduction

Historically, Ledinegg [1] is the pioneer work of two-phase flow instability. From 1960s to 1980s, the development of high power density boilers and pressurized water reactors attracted many researchers to investigate two-phase flow instabilities in tubes, heat exchangers and energy systems. It is not until late 1980s that the main instability mechanisms were understood. Now, the abundant articles or books recorded various phenomena and mechanisms. The detailed literature survey is beyond the scope of the present paper, but can be found in review articles [2,3].

The dynamic flow instability is more complicated compared with the static instability. Three typical types of flow instabilities may occur: pressure drop oscillation (PDO), density wave oscillation (DWO) and thermal oscillation (TO). They may be coupled with each other. PDO occurs if there is a large compressible volume upstream of the boiling channels. The pressure drop oscillation was analyzed by Stenning [4], Stenning and Veziroglu [5], etc. The increase of inlet flow resistance is an effective way to eliminate the pressure drop oscillation, with the penalty of increased pumping power. The density wave oscillation is widely studied in large size channels. It is related to the dynamic variation of the two-phase mixture densities. It is influenced by various factors such as flow patterns, void fractions, heat transfer and pressure drops. Oscillation cycle period relies on the propagation time of the disturbances of fluid particles, which is about 1.5–2 times of the fluid residence time in the channel [6].

Microchannel heat sink was proposed in 1980s for high power density electronic cooling, in which boiling/evaporation heat transfer in microchannels offers advantages compared with the single-phase heat transfer. However, experimental observations in the last decade showed apparent oscillations of pressure drops, flow rates and wall temperatures. Wu and Cheng [7] investigated boiling instabilities in silicon microchannels. They found large amplitude/long period oscillations. The oscillation cycle periods can be up to 10–100 s and the wall temperatures are oscillating with the amplitude of several tens of degrees. Xu et al. [8] measured

* Corresponding author. Tel./fax: +86 10 61772613.
E-mail address: xjl@ncepu.edu.cn (J. Xu).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.05.039
0017-9310/

Nomenclature

A	vapor–liquid interface area per unit flow length (m^2)
A_{film}	thin film heating area (m^2)
A_c	effective cross section area of the microchannel (m^2)
Bi	*Biot* number
Co	bubble confinement number
C_p	specific heat (J/kg K)
D	hydraulic diameter (m)
f	frequency (Hz)
G	mass flux (kg/m^2 s)
g	gravity force (m/s^2)
h	specific enthalpy (J/K)
h_{fg}	latent heat of evaporation (J/K)
i	number of bare channel
K	non-dimensional K number
L	bubble slug length (m)
l	length (m)
l_c	capillary length
l_{mc}	microchannel length (m)
l_{unit}	length of unit (m)
m	mass flow rate (kg/s); mass (kg)
m_e	evaporation rate (kg/s)
n	number of samples
n_p	number of pixels
P	pressure (Pa)
ΔP	pressure drop across the microchannel (Pa)
Δp	pressure drop (Pa)
Q	effective heating power (W)
Q_h	heat source (W)
Q_t	heat power (W)
q	effective heat flux (W/m^2)
R	gas constant for vapor (J/mol K)
R_s	standard resistance (Ω)
S	slip ratio
S_n	non-dimensional oscillation amplitude
S_{tp}	ratio of vapor velocity to liquid velocity
T	temperature (°C)
ΔT_{sub}	inlet liquid subcooling temperature (°C)
$T_{X,Y}(t)$	wall temperature at the location (X,Y) at time t (°C)
$\bar{T}_{X,Y}$	time averaged temperature at (X,Y) (°C)
V_1	voltage on film heater (V)
V_2	voltage on standard resistance and film heater (V)
V_{vacuum}	vacuum volume in the microchannel region (m^3)
v_r	radial velocity
W	bare channel width (m)
W_{porous}	porous wall width (m)
w	bubble width (m)
w_s	characteristic sizes for smaller space (m)
w_l	characteristic sizes for larger space (m)
X	length along flow direction (mm)
x	vapor mass quality
Y	length along width direction (mm)

Greek symbols

α	void fraction; convective heat transfer coefficient (W/m^2 K)
αA	film convective heat transfer intensity (W/K)
δ_c	etched channel depth (m)
η	bubble confinement ratio
μ	dynamic viscosity (kg/m s)
$\Delta\rho$	density difference between vapor and liquid (kg/m^3)
ρ	density (kg/m^3)
σ	surface tension force (N/m)
$\sigma(X,Y)$	standard deviation at position (X,Y)
τ	fluid residence time (s)
φ	thermal efficiency

Subscripts

ave	average
eff	effective
f	liquid
g	vapor
i	number of channel
in	inlet
m	average
max	maximum
out	outlet
r	residence
s	solid
sat	saturated
sp	liquid phase
w	wall
1	upstream; small space
2	downstream; large space

onset of flow instability (OFI) (static flow instability) and dynamic flow instability using 26 rectangular microchannels each with a width of 300 μm and a depth of 800 μm, using deionized water as the working fluid. The onset of flow instabilities was identified as occurring at the outlet temperature of 93–96 °C, which is several degrees lower than the saturation temperature corresponding to the exit pressure. In conditions that the mass flux is lower than that at the OFI condition, three types of flow instability were identified: large amplitude/long period oscillation, small amplitude/short period oscillation, and thermal oscillation. The reported cycle periods are also very long. Other studies related to boiling instabilities can be found in Refs. [9–15].

In order to understand instability mechanisms in microchannels, Lyu et al. [16] used the wavelet decomposition method to remove the nose signal from the mother signal and decouple the oscillation signal at different timescales. Silicon microchannels were used and water was the working fluid. The bottom wall temperatures were measured by a high spatial-time resolution IR (infrared radiation) image system, having a temperature sensitivity of 0.02 °C. The recording rate was 500 simples per second. All the parameters (pressures, flow rates, temperatures, and flow patterns) are synchronously measured. By decomposition of the signal at different timescales, it is found that the so-called large amplitude/long period oscillation is the pressure drop oscillation (~10 s cycle period), while the density wave oscillation displays the cycle period of ~10 ms (corresponding to the frequency of ~100 Hz). The mechanisms of the two oscillations are similar to those happened in large size channels. However, the varied liquid film evaporation induced oscillation is specific to microchannels.

Even though many studies are reported in the literature, flow instabilities in microchannels are not fully understood. The flow instabilities induce wall temperature oscillations to cause the varied thermal stress across the microfluidic chip. Many engineering applications need to suppress the temperature oscillations significantly. The wall temperatures should be stable enough for precise thermal management [17–19]. Various methods such as the introduction of pressure resistance element at the microchannel upstream [20], artificial nucleation cavities on channel walls [21] and injection of seed bubbles in microchannels [22] were used to eliminate the flow instabilities.