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Theoretical analysis and modeling of flow instability in a mini-channel evaporator

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ABSTRACT

Pressure drop oscillations in micro/mini-channel evaporators and corresponding flow instabilities, temperature fluctuations have received copious of investigations during the last decade. This paper presents a transient lumped model and theoretical analysis for the pressure drop oscillation in a mini-channel evaporator. Based on the model, the effects of saturation temperature, heat and mass flux on the oscillation are investigated. Experimental studies of ammonia and water flow boiling instabilities are conducted. The mini-channel evaporator consists of 4 parallel 1×1.1 mm channels with a uniformly heated length of 250 mm. A nonlinear system stability analysis is presented. Apart from upstream compressibility, the inlet sub-cooling degree has a significant effect on the pressure drop oscillation. A maximum allowable inlet sub-cooling degree causing no pressure drop oscillation is proposed. The oscillation period is comprehensively studied, and it is found that the upstream compressible volume required sustaining the oscillation decreases with channel length/diameter ratio dramatically. Despite this, the internal compressibility of the long channel is insufficient to sustain the pressure drop oscillation. In addition, the mass flow rate of the upstream pump can greatly affect the oscillation and the flow boiling system may show different behaviors due to the variation of upstream mass flow rate.

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1. Introduction

Heat sinks with micro-channels have received numerous studies and been widely used in a variety of applications. In the next generation electronic systems, the heat dissipation rate in these electronics can be of the order of 100 W/cm^2 [1]. Besides, for most silicon-based electronics, the surface temperature must be maintained below 85 °C for safety [2]. With the merits of high heat transfer coefficients, small thermal resistance, compact physical size and low capital cost, reduced fluid inventory requirement, micro-channel heat sinks seem to be an ideal selection to meet the thermal challenges in the next generation electronic systems. However, the micro-channel heat sink is by no means a problem free technology to cool these high heat dissipation rate devices. Due to the reduced channel size, periodic reverse vapor flow and boiling instabilities with low-frequency pressure drop oscillations is a very noticeable problem in this kind of heat sinks [3].

In the last decade, extensive efforts have been made to understand the boiling instabilities. At first, flow boiling instabilities with low-frequency high amplitude pressure oscillations were identified in two-phase flow systems working at atmospheric pressure. Water and FC-72 were the commonly used coolants [4,5], some organic coolants, for example, pentane and were also investigated [6,7]. Wall temperature of the heat sink was found to be oscillating with the pressure synchronously [8] and pre-mature CHF was observed [9,10]. Flow pattern alternations and periodic reverse flow were also identified [11,12]. System pressure significantly affected the flow boiling instabilities in micro-channels [13], with system pressure increasing from 50 to 205 kPa, the boiling instabilities were significantly decayed and CHF was extended to high mass qualities. Besides, the oscillation amplitude of temperature reduced and the frequency increased with system pressure. Later, flow boiling instabilities in refrigeration and cryogenic systems were also identified. Szczukiewicz [14] observed significant flow instabilities with reverse flow using R245fa, R236fa, R1234ze as the coolant. The experimental results showed that the system can maintain a better heat transfer performance without the reverse flow. Tuo [3] investigated the boiling instabilities in an evaporator of the automotive air conditioning system with R134a. Three potential impacts of the reverse flow on the evaporator performance were identified: moderate liquid

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Nomenclature

A	area [m^2]
Cp	specific heat [J/(kg K)]
D_h	hydraulic diameter [m]
f	friction factor
G	mass flux [kg/(m^{2}s)]
h_{fg}	latent heat [J/kg]
Δh_{in}	inlet sub-cooling enthalpy [J/kg]
I	current [A]
K	liquid/vapor kinematic viscosity ratio [-]
L	channel length [m]
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
n	channel number [–]
Po	Poiseuille number [–]
Δp_a	accelerational pressure drop [Pa]
Δp_f	frictional pressure drop [Pa]
q	linear heat flux [W/m]
T	temperature [K]/oscillation period [s]
T_{AB}	time period of flow boiling stage [s]
T_{CD}	time period of liquid rewetting stage [s]
Tw	waiting stage [s]
t	time [s]
U	voltage [V]
u	velocity [m/s]
V	volume [m^3]
Wd	channel width [m]
Wh	channel depth [m]
x	vapor quality [–]
z	location [m]/mass oscillator [kg/s]

Greek symbols

α	void fraction
μ	viscosity
v	specific volume
γ	kinematic viscosity
φ	Heat transfer efficiency
ρ	density [kg/m^3]

Subscripts

0	initial state
b	buffer tank/location B
ch	channel
e	evaporator
g	vapor phase
in	inlet
l	liquid phase
OFI	Onset of Flow Instability
out	outlet
sp	single phase
tp	two-phase

maldistribution, reduced heat transfer coefficient and increased pressure drop. Qi [15] studied the flow boiling instabilities of liquid nitrogen in micro-tubes. The phase difference between the pressure drop and mass flux oscillations was about 180°. Yu et al. [16] investigated the flow instability in a mini-rectangular channel. They thought that the flow excursion and surge tank compressibility were the requirements for the flow instability. And this compressibility comes from the pressurizer used in their experiment. The pressurizer can provide a large compressible volume. Besides, the flow instability occurred at the outlet vapor quality region between −0.001 and 0.012 [17]. Wang et al. [18] studied the specific points on demand curves with the method of visualization measurement. It was found that the onset of flow instability was very close to the saturated boiling point.

These low-frequency flow boiling instabilities can cause uneven distribution of evaporator surface temperature, mechanical vibrations and system safety problems [19]. Celata [20] investigated the flow boiling of FC-72 in single micro-channel, and the result showed that the system heat transfer performance deteriorated due to flow instabilities. Qu [21] found that the flow instabilities negated the advantages of inlet sub-cooling, resulting in a CHF virtually independent of inlet temperature. Bergles and Kandlikar [22] concluded that CHF in micro-channels resulted from the instabilities rather than the conventional dryout mechanism. They suggested that all the CHF in their tests were affected by instabilities, and the CHF suffered severe reduction due to flow instabilities [23]. Therefore, flow instabilities are a concern in the design of evaporators with micro-channels [24].

The abovementioned studies provide variable insight into the low-frequency flow instability in micro-channel evaporators. However, most of the existing work focused on experimental demonstrations and visualization. Qu [25] classified this instability as pressure drop oscillation, which can be triggered by flow excursion and sustained by interactions between the vapor generation and the upstream compressible volume. Tadrist [26] thought the instability resulted from the feedback between the flow rate; the vapor generation rate and the pressure drop in a boiling channel. Bergles et al. [19] noted that the pressure drop instability can be sustained when there existed an upstream compressible volume and the demand curve of pressure drop versus flow rate must have a negative-slope region. The upstream compressibility can be caused by an entrained non-condensable bubble, a flexible hose, a large volume of degassed liquid [22] or a buffer tank. In micro-channels system, the upstream compressible volume may result from the internal compressibility of very long channels [19]. In addition, Tuo [3] noted that for evaporator with parallel channels, the inlet header can also serve as a buffer tank which provides significant compressible volume. Zhang et al. [27] studied the Ledinegg instability in micro-channels experimentally and numerically. The demand curve with a negative-slope region was obtained in subcooled boiling cases. Later, they developed a lumped oscillator model to quantify the upstream compressibility [28]. However, parameters in their model were identified according to the experimental results with the method of least square fitting. Hence, the effects of compressible volume and flow conditions were not investigated. Barber et al. [29] investigated flow boiling and fluctuations in a rectangular microchannel using n-Pentane as the working fluid. Oscillations of channel wall temperature, local heat transfer coefficients and pressure are all studied. A time step model with two periods is proposed. The numerical result of wall temperature fits well with the experimental data at the rising edge of the temperature oscillation wave. However, no more information about the comparison at the falling edge and the pressure was provided. Wang et al. [30] investigated two-phase flow instabilities in single high-aspect-ratio rectangular microchannel with FC-72. According to their experimental data, a non-dimensional parameter is employed to analysis the flow instability. But the physical interpretation is insufficient. Mawasha and Gross [31] analyzed the pressure drop in a horizontal boiling. The periods of numerical simulations agree with the experimental data

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