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Effects of electric field on flow boiling heat transfer in a vertical minichannel heat sink

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ABSTRACT

Effects of applied DC electric field on flow boiling heat transfer in a vertical minichannel heat sink for two mass velocities and different heat fluxes are investigated experimentally. R141b is employed as working fluid. The heat sink contains eight rectangular minichannels, as well as both width and height of a single minichannel are 2 mm. Wire electrode is used and placed in the center of minichannel to create a non-uniform electric field. Flow visualization is performed using a high-speed video camera to analyze the interfacial features with and without electric field. Furthermore, the mechanism of two-phase flow boiling heat transfer enhancement under an electric field is explored. The results show that the onset of nucleation boiling slightly shifts towards downstream under electric field conditions. Electric field brings more vapor production, leading to early transition from bubbly flow to slug flow and early transition from slug flow to churn or annular flow. Electric field causes the bubbles to oscillate between the wall and the wire electrode, or renders the bubbles intermittently to touch the heated wall in the bubbly flow region. In the slug flow region, the surface of the elongated bubble intermittently touches the heated wall, and the interfacial shape irregularly changes with the bubble growing under electric field conditions. Overall, applying electric field can enhance the flow boiling heat transfer performance in the minichannel heat sink, and the enhancement effect is more significant in the bubbly and slug flow region. Moreover, the maximum enhancement ratio of 2.48 is obtained under present experimental conditions.

1. Introduction

With the power and electronic components across all industries trending towards higher power consumption and smaller sizes, the thermal management system designers pursued the higher heat transfer performance and more compact heat exchange devices to maintain acceptable temperatures for these components. For a heat exchange device containing multi-channels, the rate of heat transfer relies heavily on the heat transfer surface area and the flow velocity in the channels. Moreover, for a given volume of heat exchange device, smaller hydraulic diameter channels result in more channels and larger heat transfer area, and also cause greater flow velocity in the channels. This implies that using very small channel diameters will yield very high rates of heat transfer. Based on this principle, therefore, Tuckerman and Pease [1] firstly proposed the concept of micro/minichannel heat sink in 1981. This heat sink could dissipate a high heat flux of 7.9 MW/m^2 while the acceptable surface temperature was maintained. Aside from high heat dissipation efficiency, the micro/minichannel heat sink has many other merits, including small size and lightweight design, minimal coolant inventory, and low power consumption. These merits had attracted many researchers to engage in research on the micro/minichannel heat sink over the past decades. In general, these researches fall into two categories: single-phase and two-phase micro/minichannel heat sink researches. Compared single-phase micro/minichannel heat sink with two-phase counterpart, the latter achieves orders of magnitude heat transfer enhancement by using the latent heat of coolant, thereby reducing greatly the surface temperature gradients and maintaining the surface temperatures near to a fairly constant saturation temperature of coolant. These advantages motivated more researchers to shift their attention to the studies on the two-phase micro/minichannel heat sink recently.

Today, the gradual reducing in energy resources causes the energy conservation and management to attract a great deal of attention. Heat transfer equipment is main high-energy-consuming equipment in the industries. Therefore, applying the

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Nomenclature

A_{ch}	cross-section area of single minichannel, m^2
A_t	top planform area of heat sink, m^2
A_{we}	cross-section area of wire electrode, m^2
Co	confinement number
c_p	specific heat at constant pressure, J/kg K
D_h	hydraulic diameter of minichannel, m
d	diameter of wire electrode, m
$\boldsymbol{E}$	electric field strength, V/m
Eh	heat transfer enhancement ratio
F_a	lateral force, N
$\boldsymbol{F}_b$	force acting on bubble, N
$\boldsymbol{F}_e$	electrical body force, N/m^3
$\boldsymbol{F}_f$	liquid force on bubble, N
$\boldsymbol{F}_v$	vortex force on bubble, N
G	mass velocity, kg/m^2 s
g	gravitational acceleration, m/s^2
H_{ch}	height of minichannel, m
H_R	distance between resistance temperature detector (RTD) junction and minichannel bottom wall, m
h	local heat transfer coefficient, W/m^2 K
h_{fg}	latent heat of vaporization, J/kg
k_s	thermal conductivity of copper, W/m K
L_{ch}	length of minichannel, m
m	fin parameter
$\dot{m}$	mass flow rate, kg/s
N_{ch}	number of minichannels
$\dot{Q}$	total electrical power input, W
q	heat flux, W/m^2
T	temperature, °C
T_f	local bulk liquid temperature, °C
T_{in}	fluid temperature at inlet, °C
T_{out}	fluid temperature at outlet, °C
T_R	temperature measured by RTD, °C
T_{sat}	local saturation temperature, °C
T_w	temperature of minichannel bottom wall, °C
U	applied DC voltage, V
W_{ch}	width of minichannel, m
W_{fin}	between two adjacent minichannels, m
W_t	width of heat sink top planform, m
x_e	thermodynamic equilibrium quality
z	axial distance of minichannel

Greek symbols

ε	dielectric permittivity, F/m
η	fin efficiency
σ	surface tension, N/m
φ	heat transfer ratio
ρ	density, kg/m^3
ρ_e	charge density, C/m^3
ρ_f	liquid density, kg/m^3
ρ_g	vapor density, kg/m^3

Subscripts

ch	minichannel
e	electric field; equilibrium
f	liquid
fin	fin
in	inlet of minichannel
n	location number of resistance temperature detector
out	outlet of minichannel
R	resistance temperature detector (RTD)
s	solid
t	top planform
w	wall
we	wire electrode
x	*x*-direction

heat transfer enhancement techniques to this equipment can be helpful to save and manage the energy. Although the micro/minichannel heat sink, as a heat transfer equipment, has large potential to increase energy efficiency, it can't perfectly meet the requirements for the more stringent heat transfer owing to the rapid development in the modern high technologies. As a result, many researchers devote to developing innovative heat transfer enhancement techniques to further enhance heat transfer performance in the micro/minichannel heat sink, thereby improving the effective utilization of energy. There are various enhancement techniques for improving heat transfer performance in the micro/minichannel heat sink. But in general, these techniques can be grouped into two major categories: namely active and passive techniques [2]. The active techniques, as the name implies, require the external energy, e.g. electric field, magnetic field, injection or ultrasonic vibration; whereas the passive techniques are without utilizing external energy. Surface modification (such as rough or extended surfaces), applying longitudinal vortex generators, and using enhanced working fluid (such as nanofluid) are some examples of passive techniques. It is important to emphasize here that most researchers widely use the passive techniques to enhance heat transfer performance in the single-phase micro/minichannel heat sinks compared to the active technique, e.g. Refs. [3–6]. Certainly, passive techniques were also used to improve heat transfer performance in the two-phase micro/minichannel heat sinks, e.g. Refs. [7–11]. However, from these researches, it is found that more or less there are a few problems. For example, some surface structures (such as fins or ribs) in the channel readily hindered the vapor removing, resulting in pressure drop increasing, even causing critical heat flux (CHF) early to occur. Some surface modifications provided more activated nucleation sites, and these activated nucleation sites produced more bubbles on the heated wall at the high fluxes, rendering these bubbles effortlessly to coalesce into the vapor film around the heated wall, thereby leading to wall dryout. Rapid bubble growth instability often occurred due to bubble confinement in the micro/minichannel, leading to the system safety, stability and reliability decreasing. Surface deposition caused by nanofluid during boiling process blocked nucleation sites, bringing heat transfer deterioration. Here it is well to be reminded that don't use high concentration nanofluid to perform the flow boiling tests in the microchannel, because it will lead to catastrophic failures induced by large nanoparticle depositions [12]. To address above problems, some schemes were proposed and their details were summarized in Ref. [13]. Nonetheless, one problem is difficult to solve by using passive techniques. This problem is the controlling the heat transfer characteristics during flow boiling in the micro/minichannel heat sinks. Because the heat sinks have been constructed for steady state operation, and their operation parameters can't be changed easily, especially the two-phase flow can't be readily expanded or pumped when the system is working [14]. Thus, the problem for controlling the heat transfer characteristics is difficultly solved by using passive techniques. However, by using active techniques, this problem is relatively easy to be solved due to the fact that the effects of heat transfer enhancement are readily controlled by varying external energy used in active techniques. Among the numerous active techniques,