International Journal of Heat and Mass Transfer 86 (2015) 165–173

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Subcooled flow boiling in a microchannel with a pin fin and a liquid jet in crossflow

Yingying Wang, Yoav Peles *

Department of Mechanical and Aerospace Engineering, University of Central Florida, 12760 Pegasus Drive, Orlando, FL 32816-2450, United States

ARTICLE INFO

Article history:
Received 26 June 2014
Received in revised form 26 February 2015
Accepted 27 February 2015
Available online 17 March 2015

Keywords:
Flow boiling
Pin fin
Microchannel
ONB
Nucleate boiling dominated
Jet in crossflow
Heat transfer enhancement

ABSTRACT

This experimental study presents subcooled flow boiling of an engineering fluid — *HFE*-7000 — downstream a single pin fin in a microchannel. A liquid secondary jet was introduced into the flow to examine its merits pertinent to heat transfer enhancement. It was found that for *HFE*-7000 high wall superheats ($\Delta T_{(sat,ONB)} \sim 40$ °C) were required for the onset of nucleate boiling (*ONB*). Once boiling started, nucleate boiling dominated. Heat transfer coefficient increased monotonically with heat flux, independent of mass flux and jet injections. Secondary flow injection, which was previously found to be an affective single phase heat transfer enhancement technique, showed limited potential for fully developed nucleate boiling.

1. Introduction

Flow boiling heat transfer in micro domains has been extensively studied and developed over the last two decades in pursuit of effective cooling solution for high power electronic systems. Various heat transfer enhancement techniques have been studied including engineered nucleation site [1–6], micro pin fins [7–11], micro jets [12,13], etc.

Krishnamurthy and Peles [7] experimentally studied flow boiling heat transfer of water across densely packed staggered micro pin fins; heat fluxes up to 350 W/cm^2 was reported. More recently, Krishnamurthy and Peles [8] investigated subcooled flow boiling of *HFE*-7000 in 222 μm hydraulic diameter channels containing a single row of pin fins; significant heat transfer enhancement was found. Qu and Siu-Ho [9] conducted a study of saturated flow boiling of water in an array of staggered square micropin–fins, and found that heat transfer was enhanced by inlet subcooling at low quality.

Besides microchannel surface modification, other techniques have been proposed. Wang and Peles [14,15] used previous micro scale mixing technique developed by Elcock et al. [16,17] to experimentally study a combined heat transfer enhancement scheme in microchannels by introducing a liquid jet from a pillar into the main channel flow. Improvement up to 80% of single phase heat transfer was demonstrated compared with a plain microchannel.

As an extension of previous single-phase studies, the current work presents flow boiling of *HFE*-7000 downstream a single pillar in a microchannel, and the effect of secondary liquid jets injected into the flow is examined. Heat transfer mechanisms are discussed and the enhancement potential of a secondary liquid jet injected into a microchannel is explored.

2. Experimental apparatus and method

2.1. The micro-device

The micro device, shown in Fig. 1, consisted of two substrates — Pyrex and silicon. The Pyrex substrate carried the heater and electrical vias, and a micro gap was etched in the silicon substrate. The external dimensions of the device were 23 mm long, 20 mm wide and 1.5 mm thick.

Fluid entered a 18.5 mm long, 1.5 mm wide, and 225 μm high channel (hydraulic diameter of $D_h = 391$ μm) and passed a 150 μm diameter pillar before reaching a 100 nm thick, 1 mm × 1 mm serpentine heater, positioned 225 μm away from the pillar's center (Fig. 2(c) and (d)). The fluid then left the channel through the exit manifold. A secondary jet flow was introduced from a 50 μm diameter orifice at the bottom of the pillar and then issued from two 25 μm wide slits into the main flow, which were

* Corresponding author.
E-mail address: Yoav.Peles@ucf.edu (Y. Peles).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.02.080

Nomenclature

A_c	cross-section area of the microchannel
A_{heater}	surface area of the heater
A_j	pillar slits open area along the channel
B_o	boiling number
Cp	fluid specific heat at constant pressure
$C\mu$	jet-to-crossflow momentum coefficient
D_h	hydraulic diameter of microchannel
F	enhancement Factor for boiling heat transfer coefficient
G	mass flux
$\bar{h}$	area-averaged convective heat transfer coefficient
h_{cv}	heat transfer coefficient for the convective contribution
h_{nb}	heat transfer coefficient for the nucleate boiling contribution
h_{sp}	single phase heat transfer coefficient
h_{tp}	two-phase heat transfer coefficient
J_a	Jacob number
$\dot{m}$	mass flow rate
M	molecular mass
P_f	saturation pressure
P_r	Prandtl number
q''	heat flux applied on the heater surface
$\dot{Q}_{heater}$	power rate supplied to the heater
$\dot{Q}_{loss}$	heat loss rate from heater other than convection directly to fluid
r_{cr}	critical cavity radius for the onset of nucleate boiling (*ONB*)
R	gas constant
T_{in}	fluid inlet temperature
T_m	fluid bulk mean temperature
$\bar{T}_s$	area-averaged surface temperature
T_{sat}	saturation temperature
T_w	channel wall temperature
U_∞	mean velocity of the main flow
U_j	mean velocity of the jet flow

Greek symbols

ρ_∞/ρ_f	density of the liquid in main flow
ρ_j	density of the liquid in jet flow
ρ_g	density of the vapor
σ	fluid surface tension
ΔT_{sat}	wall superheat
$\Delta T_{sat,ONB}$	wall superheat at *ONB*
Δh_{fg}	enthalpy of vaporization

located at an angle of 110° in respect to the stagnation point (Fig. 2(b)).

The fixture (Fig. 3), precision machined from Delrin, was designed to contain the micro-device and provide fluidic connections to and from external fittings. For electrical connections, two spring-loaded contact probes were fit into the fixture and protruded above a mating surface, contacting the two aluminum pads on the micro-devices. O-rings were used to achieve fluidic seals with the micro-devices. The devices were held in the fixture by a 4 mm thick aluminum cover plate.

2.2. Apparatus

To measure the heat transfer coefficient in the microchannel, a closed fluid loop with coolant (*HFE*-7000) was constructed (Fig. 4). Driven by a micropump, the fluid, which was contained in a sealed tank, flowed into the microchannel, dissipated the heat from the heater, and exited into the fluid tank. A calibrated rotameter was used to measure flow rates; a thermocouple was used to measure inlet temperature; and two pressure transducers were installed upstream and downstream of the package to measure fluid inlet and outlet pressures. The flow rate was controlled by varying the output power of the micropump, and a needle valve was used for fine adjustment. Concurrently, the same fluid (*HFE*-7000) was propelled by a syringe pump into the main flow in the microchannel through the fixture and the pillar's slits.

Power was supplied to the thin-film heater by a *GW* Instek® *DC* power supply. The voltage across and the current through the heater were measured simultaneously using two Agilent® digital multimeters. The LabVIEW program and National Instruments™ data acquisition hardware were used with a personal computer (*PC*) to acquire and record the experimental measurements.

The fixture, which contained the micro-device, was placed accordingly under an inverted microscope for two-phase flow visualization. A high speed camera was connected to the microscope and captured images and videos that were transferred to the *PC* for storage. To minimize the noise generated by vibration and leveling effects, the experiments were conducted on an optical table with an anti-vibration system.

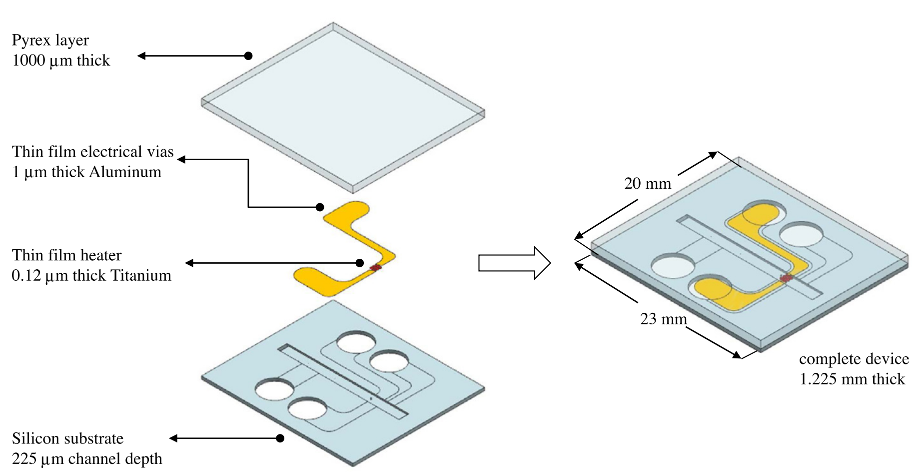

Fig. 1. Micro-device schematics.