International Journal of Heat and Mass Transfer 121 (2018) 534–546

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Experimental and numerical study about local heat transfer in a microchannel with a pin fin

Yingying Wang [a], Jeong-Heon Shin [a,b], Corey Woodcock [c], Xiangfei Yu [c], Yoav Peles [a,*]

[a] Department of Mechanical and Aerospace Engineering, University of Central Florida, Orlando, FL 32828, USA
[b] Department of Thermal Systems, Korea Institute of Machinery & Materials (KIMM), Daejeon 34103, Republic of Korea
[c] Mechanical, Aerospace, and Nuclear Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180, USA

ARTICLE INFO

Article history:
Received 13 September 2017
Received in revised form 5 January 2018
Accepted 8 January 2018

Keywords:
Microchannel
Pin fin
Local temperature measurements
RTD
Local heat transfer coefficient
μPIV
Flow wake
CFD
Numerical simulation
Turbulence

ABSTRACT

Local single-phase flow heat transfer downstream a single pin fin in a microchannel was experimentally and numerically studied. Three distinct flow regimes, depending on the Reynolds number, were characterized, namely: laminar flow with steady wake, laminar flow with unsteady wake, and turbulent flow. Local temperature measurements with high spatial resolution were obtained by incorporating an array of micro resistance temperature detectors (RTDs) (~55 μm × 55 μm) on the internal microchannel surface. Local surface temperatures were related to the flow structures under different flow regimes. An enhanced local heat transfer coefficient at the trailing edge of the wake region downstream the pillar was observed. It is believed to be a result of vortex shedding and large-scale flow mixing triggered by flow instability at high Reynolds number. The numerical model enabled a full conduction/convection conjugate analysis of the entire system including heat conduction within the solid substrates and heat losses to the surrounding environment. Local heat transfer coefficient downstream the pin fin at each Reynolds number was obtained.

1. Introduction

Microchannel liquid cooling has been extensively studied in the last couple of decades because it enables system miniaturization, it has high heat transfer coefficient (*HTC*), and it brings the cooling channel closer to the electronic circuit (i.e., it reduces the number of thermal interface layers). Various heat transfer enhancement techniques have been explored to improve microchannel cooling systems. As part of this effort, micro scale pin fins have been studied [1–29]. Besides increased surface area, they promote flow mixing, which leads to enhance *HTC* [30–32].

A number of variables affect the heat transfer process, such as pin fin density, arrangement, pitch distances, etc. Different micro pin fin shapes and configurations, e.g., circular [1–4], square [5–7], hydrofoil-shaped [8–11], tip clearance [12,13], pin fin density [14], aspect ratio [15] and staggered/inline [13,16,17], were experimentally studied. Numerical models were developed to study conjugate heat transfer and to optimize the performance of micro pin fin heat sinks [18–29].

Wang et al. [30–33] studied a rudimentary configuration — fluid flow and heat transfer downstream a single pin fin in a microchannel. This study involved several phases of system development that resulted in two generations of micro devices. The initial micro device included a single pin fin and a micro heater downstream the pin fin. However, experiments provided only area-averaged temperature measurements over the heater area (~1 mm × 1 mm). Second-generation incorporated an array of resistance temperature detectors (*RTDs*) on top of a micro heater (1.5 mm × 5 mm). The *RTDs*, positioned around and downstream the pin fin, enabled the study of local heat transfer process at different regions of the heater (e.g., recirculation zone, flow acceleration zone, etc.).

With the first generation of micro device, Wang et al. [30–32] studied flow structure downstream a micro pin fin using a micro particle image velocimetry (*μPIV*) measurement system. By relating the flow field to the average heat transfer coefficient, it was found that increased fluid mixing and vortex shedding enhanced heat transfer. In the study of the second-generation micro device with local *RTDs*, Wang et al. [33] superimposed the local temperature distribution onto the velocity fields. Result indicated that the local surface temperatures in the wake region were lower than in

---

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

https://doi.org/10.1016/j.ijheatmasstransfer.2018.01.034
0017-9310/

Nomenclature

A_c	cross-section area of the microchannel
A_p	cross-sectional area of the pin fin
A_h	surface area of the heater
D	diameter of the pin fin
D_h	hydraulic diameter of microchannel
G	mass flux
H	height of the microchannel
I	electrical current in the heater
$h_{i,num}$	local heat transfer coefficient obtained numerically
$\dot{m}$	mass flow rate
$\dot{Q}$	total power rate supplied to the heater
q''	nominal heat flux
$q''_{i,num}$	local heat flux obtained numerically
Re_D	Reynolds number based on pin fin diameter
Re_{D_h}	Reynolds number based on based on hydraulic diameter of the microchannel
T_{in}	fluid inlet temperature
T_f	fluid bulk mean temperature
$T_{i,num}$	local surface temperature obtained numerically
U_l	mean velocity of the flow at the Y-Z plane where the pin fin was located
U	mean velocity of the flow in the microchannel
u	instantaneous velocity component along x direction
$\bar{u}$	time-averaged velocity component along x direction
u'	instantaneous velocity fluctuation component along x direction
V	voltage applied on the heater
v	instantaneous velocity component along y direction
$\bar{v}$	time-averaged velocity component along y direction
v'	instantaneous velocity fluctuation component along y direction
W	width of the microchannel
x/D	normalized x coordinate
y/D	normalized y coordinate

Greek symbols

ρ	density of HFE-7000
μ	viscosity of HFE-7000

regions outside the wake. The result was verified by a 3D numerical simulation showing a strong conjugate convection/conduction interplay. This local conjugated process needs to be considered in order to properly resolve the local heat transfer coefficient, especially in the vicinity of the pin fin.

The current work expands our previous studies about local heat transfer downstream a single pin fin by addressing local heat transfer processes as a function of the Reynolds number. Experiments were conducted at Reynolds numbers ranging from laminar to turbulent. Numerical models were developed to supplement experiments providing insights about the heat transfer coefficient, heat flux distributions, and their relation to the flow field.

2. Methodology

The micro-device consisted of two substrates, one made of Pyrex and one made of silicon (Fig. 1). The Pyrex substrate carried a heater layer and an *RTD* array layer. The silicon substrate was deep etched to form a single microchannel (18.5 mm long, 1.5 mm wide, and 200 μm high). The closed rectangular channel was formed by bonding the Pyrex substrate to the silicon substrate.

A single circular pin fin made of silicon with a diameter of 150 μm and a height of 200 μm was placed 14.5 mm downstream from the fluid inlet. The heater on the Pyrex substrate, made from a 30 nm thick Platinum film, was 1.5 mm wide and 5 mm long and was positioned to cover the area around the pin fin on the top channel wall (indicated by the red[1] rectangle in Fig. 1c). The heater had a 170 μm-diameter hole concentric with the corresponding pin fin at the silicon substrate. Since the pin fin had the same height as the microchannel, an intimate contact between the pin fin tip and the Pyrex was formed. An array of RTDs was deposited over the heater layer to measure local surface temperatures.

Two sets of micro devices with two different *RTD* array configurations were used — inline (I) and staggered (II). By applying the same conditions to the two micro-devices, and superimposing the results, temperature distribution downstream the single pin fin was obtained at locations shown in Fig. 2a; their relative coordinates corresponding to the center of the pin fin are specified in Table 1. As depicted in Fig. 2c, the overall size of each *RTD* was ~55 μm × 55 μm. For simplicity, the distances were all normalized by the diameter of the pin fin. Among the eight locations, RTD3 and RTD8 were both included in the inline and the staggered configurations. Obtaining measurements and comparing temperature data at the same location in two different devices helped verify the results.

2.1. Apparatus and experimental procedure

A block package was machined to house the micro-device and to provide the fluid connection between the microchannel and the external fluid loop. A custom made printed circuit board (*PCB*) with an array of spring-loaded probes was pressed against the micro-device to provide electrical connections between the RTDs and external circuits.

A closed fluid loop (Fig. 3) was constructed to conduct the experimental study. The loop included a fluid tank, a gear pump (Micropump), a filter (Swagelock), a rotameter (Omega), a control valve (Swagelock), and the package housing the micro-device. T-type thermocouples (Omega) and pressure transducers (Omega) were used to measure the fluid temperature and pressure in the loop. The thermocouples and pressure transducers were connected to a data acquisition unit (National instrument, *c-DAQ*). Through the *PCB* and ribbon cables, the micro heater was wired to a power supply (Keysight) and two Digital Multi-meters (Keysight) to measure the current and voltage across the heater. The RTDs were wired to a signal conditioning extension for instrumentation (*SCXI*) data acquisition (*DAQ*) unit (National Instrument, *SCXI*) that was dedicated to measure the resistance of each RTD. Detailed description of the device packaging and the experimental setup can be found in a previous study [33] that used the same micro-device and test platform.

Before running experiments, the heater and the RTDs were calibrated in a temperature controlled oven and a linear relationship between the resistance and the temperature was observed for all RTDs and the heater. The resistance ranges from 390 to 420 Ω for the RTDs and around 35 Ω for the heater at room temperature. The average sensitivity of the RTDs was 2.2 °C/Ω.

Engineered fluid HFE-7000 (3M™ Novec™) was used as the working fluid. The system pressure was maintained at atmospheric

---

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.