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Heat transfer of gas–liquid mixture in micro-channel heat sink

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ABSTRACT

The main objective of the present investigation is to study heat transfer in parallel micro-channels of 0.1 mm in size. Comparison of the results of this study to the ones obtained for two-phase flow in "conventional" size channels provides information on the complex phenomena associated with heat transfer in micro-channel heat sinks. Two-phase flow in parallel micro-channels, feeding from a common manifold shows that different flow patterns occur simultaneously in the different micro-channels: liquid alone (or single-phase flow), bubbly flow, slug flow, and annular flow (gas core with a thin liquid film, and a gas core with a thick liquid film). Although the gas core may occupy almost the entire cross-section of the triangular channel, making the side walls partially dry, the liquid phase always remained continuous due to the liquid, which is drawn into the triangular corners by surface tension. With increasing superficial gas velocity, a gas core with a thin liquid film is observed. The visual observation showed that as the air velocity increased, the liquid droplets entrained in the gas core disappeared such that the flow became annular. The probability of appearance of different flow patterns should be taken into account for developing flow pattern maps. The dependence of the Nusselt number, on liquid and gas Reynolds numbers, based on liquid and gas superficial velocity, respectively, was determined in the range of $Re_{LS} = 4–56$ and $Re_{GS} = 4.7–270$. It was shown that an increase in the superficial liquid velocity involves an increase in heat transfer (Nu_L). This effect is reduced with increasing superficial gas velocity, in contrast to the results reported on two-phase heat transfer in "conventional size" channels.

1. Introduction

Gas–liquid flows occur widely in both nature and industrial applications, including energy production (e.g., oil transportation, steam generators, cooling systems) and chemical engineering (e.g., bubble columns, reactors, aeration systems). Two-phase flows in micro-channels have attracted attention because their wide applicability to such advanced fields as MEMS, electronic cooling, medical and genetic engineering, bioengineering, etc. At present, additional knowledge of flow and heat transfer in micro-scale flow passages of a size less than 100 μm is required. Specifically, fundamental knowledge of two-phase flow characteristics in small flow passages, such as the flow pattern, void fraction, pressure drop, and heat transfer coefficient, is crucial for engineering design purposes as well as for evaluation of practical performance.

Papers by Ghiaasiaan and Abdel-Khalik [1], Serizawa et al. [2], Kawahara et al. [3], Garimella and Sobhan [4], Celata [5], and Cheng and Wu [6] extensively reviewed the literature on two-phase flow pattern in micro-channels. However, our current knowledge on two-phase flow characteristics and heat transfer in parallel micro-channels is still limited and in reality the literature sources are sparse. One of the questions is whether the two-phase heat transfer coefficient in micro-channels is different from that encountered in "conventional" size channels. Most of the heat transfer correlations are based on data obtained in flow boiling from relatively large diameter conduits and the predictions from these correlations show considerable variability. Effects of superficial liquid and gas velocity on heat transfer in gas–liquid flow and its connection to flow characteristics were studied by Hetsroni et al. [7–9], Kim et al. [10], Bao et al. [11], Ghajar et al. [12], and Zimmerman et al. [13]. These researches were carried out for "conventional size" tubes of $d = 1.95–42$ mm.

The main objective of the present investigation is to study the flow pattern, pressure drop and heat transfer in parallel micro-channels of a size about 0.1 mm. A comparison of results of this study with ones obtained for two-phase flow in "conventional" size channels provides information for understanding the complex phenomena associated with two-phase gas–liquid flow in micro-channel heat sinks.

2. Experimental set-up and procedure

2.1. Experimental facility

The experimental facility and flow loop were described in detail by Hetsroni et al. [14]. The loop consists of a liquid pump, piping, test module, entrance and exit tanks. Deionized water and air were

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Nomenclature

A	overall cross-section of micro-channels
C	constant of friction multiplier
d	diameter
F	area of heater
h	heat transfer coefficient
k	thermal conductivity
m	mass flux
N	electric power
Nu	Nusselt number
q	heat flux
Q	volumetric flow rate
Re	Reynolds number
T	temperature
U	velocity
X	Lockhart–Martinelli parameter

Greek symbols

α	void fraction
$\alpha(c)$	void fraction for bubble core and gas core with a thick liquid film
β	homogeneous void fraction
ΔP	pressure drop
ρ	fluid density
Φ	friction multiplier
τ	time
ν	kinematic viscosity

Subscripts

ac	acceleration
cal	calculated
con	contraction
ex	experimental
G	gas
GS	superficial gas
h	hydraulic, heated perimeter
in	inlet
L	liquid
LS	superficial liquid
Mean	mean
Mix	mixture
Out	outlet
TP	two-phase
w	wall

used in this study. The working mixture was pumped from the entrance tank through the inlet collector to the micro-channels in the test module, and from the micro-channels through the outlet collector to the exit tank. The two-phase flow was achieved by the introducing water and air into a mixer as shown in Fig. 1. The experiments were performed in an open loop, therefore the outlet pressure was close to atmospheric. Two types of pumps were used: peristaltic pump and mini gear pump.

The temperature of the working fluid was measured at the inlet and outlet collectors of the test module, by 0.3 mm type-T thermocouples. The thermocouples were calibrated in 0.1 K increments. The flow rate of the working fluid was measured by a weighting method. Pressures were measured at the inlet and the outlet manifolds of the test module by silicon pressure sensors, with sensitivity of 3.3 mV/kPa, and response time 1.0 ms. Data were collected by a data acquisition system.

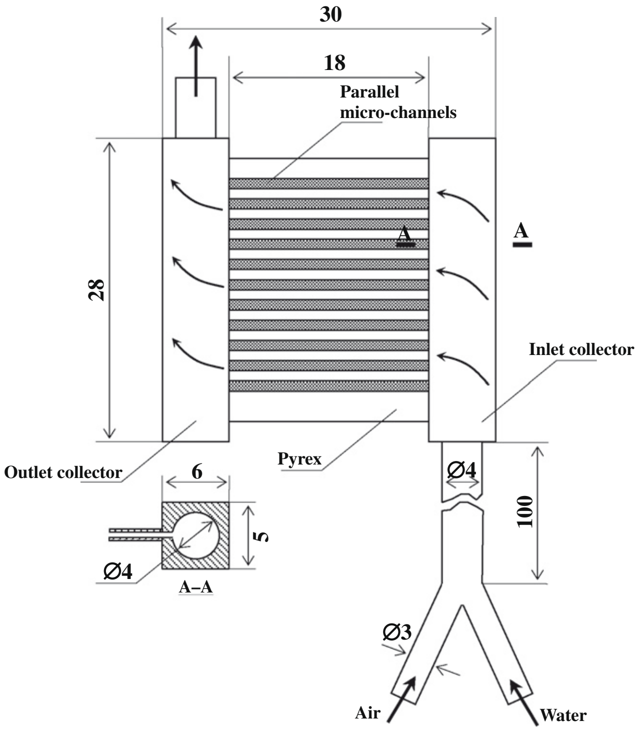

Fig. 1. Experimental facility. All dimensions in [mm].

The test module is shown in Fig. 2. It was fabricated of a square-shape silicon substrate 15 × 15 mm, 530 μm thick, covered by a Pyrex cover, 500 μm thick, which served both an insulator and a transparent cover through which flow in the micro-channels could be observed. The Pyrex cover was anodicaly bonded to the silicon chip, in order to seal the channels. In the silicon substrate, parallel micro-channels were etched, the cross-section of each channel was an isosceles triangle. The angles at the base were 55°. We used the test module having 21 micro-channels with hydraulic diameter of 130 μm. An electrical heater of 10 × 10 mm^2, was deposited on the back surface of the silicon, and served to simulate the heat source. The heater was coated with a thin layer of black diffusive paint, with emissivity $\varepsilon \approx 0.96$. The heater had a serpentine pattern and a dimension of 0.001 mm in thickness, 0.2 mm in width and 250 mm in length. This design allowed a uniform heating of the surface and reduces the contact resistance between the heater and the wafer. The input voltage and current were controlled by a power supply.

2.2. Flow and thermal visualization

A microscope with an additional camera joint was assembled to connect a high-speed camera to the microscope. A high-speed camera with a maximum frame rate of 10,000 fps, was used to visualize the two-phase flow regimes in the micro-channels. To study the temperature field of the resistor a high-speed focal plane array radiometer containing 75 kpixels was utilized. The measurement resolution was 0.03 °C with a standard measurement accuracy of ±2 °C for the range of 0–100 °C and ±2% above 100 °C. In an isolated laboratory environment using an appropriate black body, improved calibration and non-uniformity-correction are possible, therefore an accuracy of ±1 K can be achieved. Using microscopic lens and reduced array size, IR measurements can be taken at up to 800 Hz with a 30 μm spatial resolution.