Experimental Thermal and Fluid Science 62 (2015) 29–39

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

An experimental study of two-phase air–water flow and heat transfer characteristics of segmented flow in a microchannel

Pansunee Suwankamnerd, Somchai Wongwises *

Fluid Mechanics, Thermal Engineering and Multiphase Flow Research Lab (FUTURE), Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangmod, Bangkok 10140, Thailand

ARTICLE INFO

Article history:
Received 8 May 2014
Received in revised form 13 November 2014
Accepted 16 November 2014
Available online 21 November 2014

Keywords:
Two-phase flow
Segmented flow
Micro channel
Flow patterns
Flow regime map

ABSTRACT

Cooling systems are needed for electronic devices in order to operate efficiently. Whereas the size of the equipment has decreased to the micro scale, research on the heat transfer characteristics in a microchannel heat sink is needed. In this work, we suggest that the segmented air–water flow can enhance the heat transfer rate in a microchannel heat sink as compared to using single-phase water cooling. The experiment was conducted with two-phase air–water flow in a single rectangular microchannel with a hydraulic diameter of 267 μm. The test section was made from copper. For a clear understanding, two-phase flow pattern, pressure drop, and heat transfer characteristics in the low Reynolds number of air–water flow were identified. The results show that segmented, throat-annular, throat-annular/liquid, and annular flow were observed within the test section. A flow pattern map was created and compared with the previous maps. The pressure drop can be predicted by the homogeneous flow model and the Friedel correlation separated flow model. The Nusselt number of segmented flow increases up to 1.2 times over the single-phase flow.

1. Introduction

The two-phase flow of gas and liquid is not only usually found in nature but is also widely used in energy and chemical applications. There are many related applications, such as oil transport and processing, steam generators, cooling systems, and reactors. Presently, the two-phase flow in microchannels has found applications in micro-electro-mechanical systems (MEMS), cooling of electronics devices, medical systems, and bioengineering systems. Hence, the knowledge of fluid mechanics and heat transfer in micro-scale devices is necessary. It leads to the study of the two-phase flow in microchannels with an emphasis on pressure drop, void fraction, flow pattern, and the heat transfer coefficient. These are important elements for the design and development of devices in order to provide the best performance.

Over the past decades, the single-phase flow of liquids or gases has been a topic of interest and many questions about single-phase flow in small channels have been effectively solved. On the other hand, the two-phase gas–liquid flow in microchannels has received comparatively little attention in the literature [1].

The criteria for the classification of different – sized channels have been proposed by several reasearchers.

For example, the confinement number (Co) recommended by Kew and Cornwell [2] is defined as

$$Co = \frac{\sqrt{\frac{\sigma}{g(\rho_L - \rho_G)}}}{D_h} \tag{1}$$

Where D_h is hydraulic diameter, σ is surface tension, g is gravitational acceleration, ρ_L and ρ_G are liquid and gas densities. The channel can be classified as "micro-channel" if Co is greater than 0.5.

Mehendale et al. [3] employed the hydraulic diameter as an important parameter to classify the heat exchangers.

1.1. Adiabatic two-phase flow patterns

During the past decade, there have been a number of studies pertaining to the two-phase flow pattern in microchannels. Researchers conducted experiments by varying the shape, size, and working fluids of the microchannels for the purposes of observing the flow patterns and generating the flow-regime maps.

Triplett et al. [4] studied horizontal channels as circular microchannels with 1.1 and 1.45 mm diameter and semi-triangular microchannels with hydraulic diameters of 1.09 and 1.49 mm,

* Corresponding author. Tel.: +66 2 470 9115.
E-mail address: somchai.won@kmutt.ac.th (S. Wongwises).

http://dx.doi.org/10.1016/j.expthermflusci.2014.11.010
0894-1777/

Nomenclatures

A_{ch}	surface area of the test section, m^2
AR	aspect ratio of channel
C	coefficient C value
C_c	coefficient of contraction
Co	confinement number
C_p	specific heat (J/kg K)
D_h	hydraulic diameter of channel, m
Fr_H	the dimensionless factor
f	friction factor
G	mass flux, kg/m^2 s
g	gravitational acceleration, m/s^2
H	channel height, m
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	channel length, m
Nu	Nusselt number
P	pressure, Pa
Q_{bulk}	heat transfer, W
q''	heat flux, W/m^2
Re	Reynolds number
T	Temperature, °C, K
U	velocity, m/s
V	volume flow rate, m^3/s
W	channel width, m
We	Weber number
X_{vv}	Martinelli parameter for larminar–larminar flow
x	mass quality

Greek symbols

β	gas volumetric ratio
ρ	density, kg/m^3
α	void fraction
μ	dynamic viscosity, kg/m s
σ	surface tension, N/m
γ	ratio of the cross-sectional flow area in the flow passage connected to the channel test section to that in the channel test section
ϕ	two-phase frictional multiplier
ΔP	pressure drop, kPa/m

Subscripts

ch	channel
c/e	contraction/expansion
exp	experimental value
f	fluid
G	gas
GS	gas superficial velocity
H	homogeneous flow
L	liquid
LS	liquid superficial velocity
$pred$	predicted value
s	surface
TP	two-phase

which presented bubbly, churn, slug, slug-annular, and annular flow patterns. They found that the experimental data was comparable to the similar data of Suo and Griffith [5] and Damianides and Westwater [6].

For the vertical channels, Satitchaicharoen and Wongwises [7] conducted the experiment to observe the two-phase flow of air–water, air–20 wt.% glycerol solution, and air–40 wt.% glycerol solution. They used 5 variously sized rectangular test sections of mini-gap transparent acrylic glass channels and reported that the flow patterns of cap-bubbly, slug, churn, and annular flow were observed in every size of the channel, whereas the bubbly flow pattern was only found in the 40 mm $\times$ 3 mm rectangular channel. The effects of channel sizes and working fluids were also discussed and were found to be consistent with the study of Zhao and Bi [8]. They reported that the bubbly flow was not found in the small channel.

There are various names of the same flow pattern that have been defined by many researchers, which results in the difficulty in distinguishing the same or different flow pattern. For example, slug [4,9], and bubble train flow [10] have been designated to indicate the same flow pattern.

1.2. Two-phase pressure drop

Many researchers [11–13] have applied the separated flow model with the modified two-phase frictional multiplier to predict a two-phase frictional pressure drop. Additionally, Sur and Liu [14] discovered that the use of a flow pattern-based model can predict the frictional pressure drop better than the separated or homogeneous flow model.

1.3. Heat transfer characteristics

Nowadays, electronic devices and microprocessors are available in smaller sizes. The optimized cooling system design is necessary for heat transfer enhancement. Most researchers focus on the study of using flow boiling to enhance heat transfer in the system instead of on the single-phase flow that occurs in low Nusselt numbers in the laminar flow condition. However, using flow boiling may be ineffective due to backflow, flashing, and instability phenomena. Moreover, it is not suitable to use air and water as the working fluids in flow boiling because of the high boiling temperature of the water. Thus, the segmented air–water flow in microchannels is proposed by Betz and Atinger [15], Lim et al. [16], Majumder et al. [17], and Saisorn et al. [18]. They concluded that segmented air–water flow can enhance the Nusselt number in the channels up to 1.76 times over the single-phase flow of water. The factors that make the heat transfer enhancement are the mixer velocity from the air injection and the internal circulation of liquid slug induced by the gas bubbles, which enhances the mixing of the hot liquid film near the channel wall with cooler liquid from the center.

As mentioned above, relatively little information is currently available on the two-phase flow and heat transfer characteristics of segmented flow in a microchannel, especially for diameters of less than 500 μm. In this work, we performed the experimental study of two-phase flow patterns, the pressure drop, and heat transfer characteristics of segmented flow in a rectangular microchannel, which has a unique shape and size. The flow conditions needed to fulfill and improve the fundamental understanding of two-phase flow in the microchannel is studied (Fig. 1).

2. Experimental apparatus

The schematic diagram of the test apparatus is shown in Fig. 2. Water and air were mixed by the Valco Tee connecter (SS, 0.25 mm bore, 1/16″, 10–32), where the water was pumped from a peristaltic pump (Masterflex L/S, easy-load model 7518-00). The mass flow rate of water was found by measuring it at the outlet with a digital