TSF-1020

Two-Phase Heat Transfer Characteristics during Segmented Flow in Micro-Channels

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Abstract

Two-phase flow experiments are performed to explore flow and heat transfer characteristics in parallel rectangular micro-channels when segmented flow is established during the experiments. Flow patterns and Nusselt numbers are obtained, based on non-boiling air-water flow in 21 rectangular micro-channels with 40 mm long in the flow direction. Each channel has a width and a depth of 0.45 and 0.41 mm, respectively. The gas and liquid phases are mixed in the y-shape mixing chamber and, then, two-phase mixture is introduced, respectively, in the inlet plenum and micro-channels. Flow patterns are recorded by flow visualization system composing mainly of stereozoom microscope and camera. The results indicate the dependence of Nusselt number on liquid superficial Reynolds number. Segmented flow can provide a better heat transfer results when compared with the long gas core flow.

Keywords: Two-phase flow; Flow pattern; Micro-channels

1. Introduction

Two-phase flow researches have been carried out extensively over the years. However, there have been a relatively small amount of publications dealing with micro-channels when compared with those for ordinarily sized channels. Capillary force is likely to play an important role in two-phase flow and heat transfer characteristics, resulting in significant differences in the flow phenomena between ordinarily sized channels and micro-channels. A micro-channel heat sink, first introduced by Tuckerman and Pease [1], is a cooling device incorporating small channels in which fluid flows to cool a heated substrate. Micro-channel heat sinks are employed in various applications such as cooling systems in turbine blades, fusion reactor blankets, rocket engines, hybrid vehicle power electronics, computer chips, etc. Discussions for key applications of micro-channel heat sinks are given in details by Mudawar [2]. Due to the need for continuously increased power dissipation of microelectronic devices, the single-phase micro-channel flow seems to be no longer highly effective cooling method because they are limited by low Nusselt number in laminar flow. Two-phase flow in small channels has become another effective means for dissipating heat. Noting that the researches on the two-phase micro-channel heat sinks have been mainly reported for flow boiling characteristics and such drawbacks, difficult to control, as backflow and instabilities are generally addressed [3]. In contrast, non-boiling two-phase heat transfer data is still lacking.

Bao et al. [4] carried out experiments to explore heat transfer performance of air-water flow in a channel having a diameter of 1.95 mm. They reported that at a fixed liquid flow rate, heat transfer coefficient increased with the increase in air flow rate, which caused by the flow pattern transition. Heat transfer of air-water flow in parallel micro-channels of 0.1 mm in hydraulic diameter was experimentally investigated by Hetsroni et al. [5]. Their results showed the decrease in Nusselt number with increasing gas flow rate, which is opposite to the results obtained by Bao et al. [4].

Betz and Attinger [6] showed segmented flow, an intermittent pattern of gas bubbles and liquid slugs, resulting in the heat transfer enhancement up to 140% in a micro-channel heat sink when compared with single-phase liquid flow.

Heat transfer characteristics of non-boiling two-phase flow in micro-channels with different diameters were studied by Choo and Kim [7]. Air and water were used as working fluids to examine the dependence of Nusselt number on the channel diameter. They found that with channel diameters of 0.506 and 0.334 mm, the Nusselt number increased with the increment of gas flow rate, but decreased with increasing gas flow rate when the channel diameters of 0.222 and 0.140 were employed.

Marchitto et al. [8] studied two-phase flow distribution in parallel upward channels. They reported that the phase distribution was improved by using a special fitting, acting as distributor, which was installed inside the header.

According to the two-phase flow heat transfer reviewed by Saisorn and Wongwises [9], The two-phase heat transfer in micro-channels has been mainly investigated based on flow boiling. Nevertheless, only limited data is available for heat transfer of gas-liquid mixture in micro-channels and further research is needed to meet a general conclusion. The aim of the current research is to explore the heat transfer characteristics of gas-liquid segmented flow in parallel micro-channels with hydraulic diameter of 0.43 mm under low superficial Reynolds numbers (Re_{GS} = 50 – 150, Re_{LG} = 100 – 400), which has never been seen before. The heat transfer results are presented based on Nusselt number.

2. Nomenclature

A = area (m^2)

H = height (m)

h = heat transfer coefficient (W/m^2K)

k = thermal conductivity ((W/mK)

m = $(hP/kA_c)^{1/2}$

Nu = Nusselt number

P = perimeter (m)

q = heat flux (W/m^2)

Re_{GS} = superficial Reynolds number of gas

Re_{LS} = superficial Reynolds number of liquid

T_f = fluid temperature (K)

T_w = wall temperature (K)

W = width

Greek symbols

η = fin efficiency

Subscripts

b = base

c = cross-section

ch = channel

f = fin

L = liquid phase

TP = two-phase

3. Experimental apparatus and procedure

A schematic diagram of the experimental apparatus is shown in Fig. 1. Peristaltic pump with adjustable flow rate is used to supply liquid flow through the micro-channel heat sink. The liquid mass flow rates are determined by using an electronic balance (320 $\pm$ 0.001 g) to measure weight of the liquid flowing from the test section outlet over a sufficient time whereas the flow rates of gas are measured by three sets of rotameters within the range of 5 – 50, 50 – 500, and 200 – 2500 sccm, respectively. An air-water y-shape mixer is served to introduce fluids smoothly along the test section. Instrumentation is installed at various positions to monitor the flow condition of the working fluids.

Fig. 2 illustrates an exploded view of the test section. The 21 parallel rectangular micro-channels of 0.45 $\times$ 0.41 mm (width $\times$ depth) with a 0.54 mm fin thickness are fabricated on the copper block in which a cartridge heater with adjustable input power is installed. The micro-channels are 40 mm long in the flow direction. On the top of the test section, the cover plate made of polycarbonate is placed to allow optical access for flow visualization. The copper block is well insulated by G10 epoxy. Metal plates and the insulators are bolted together with the copper block and the cover plate to firm the assembly.

To estimate the wall temperature needed for determining the heat transfer coefficient, 14 type K thermocouples are inserted in the copper block. Three thermocouples for each side of the test section are equally spaced along the axial direction, and located at a distance of 2.8 mm from the bottom of the micro-channels. The temperature measurements at equal distance of 4.3 mm along the direction perpendicular to the flow are also carried out for each side. Based on the mentioned installations, the wall temperature can be calculated using extrapolation. In addition to the wall temperature, the thermocouples are installed at the inlet and outlet of the test section to measure the fluid temperature. All thermocouples, pressure transducer and relevant instruments installed in the experimental apparatus are well calibrated.

The cover plate, which is transparent, serves as a viewing window for flow visualization. The detailed formation of flow pattern is registered by precise stereozoom microscope mounted together with a camera having shutter speeds of 1/15 – 1/10,000s. An adjustable LED light source is placed, perpendicular to the viewing section.

In this work, the experiments are conducted in such a way that the air flow rate is increased by small increments while the water flow rate and the heat applied to the test section are kept constant at the desired value. The system is allowed to approach a steady state before the flow pattern and relevant data are recorded. During the experiment, the temperature and pressure are continuously recorded by the data logger.

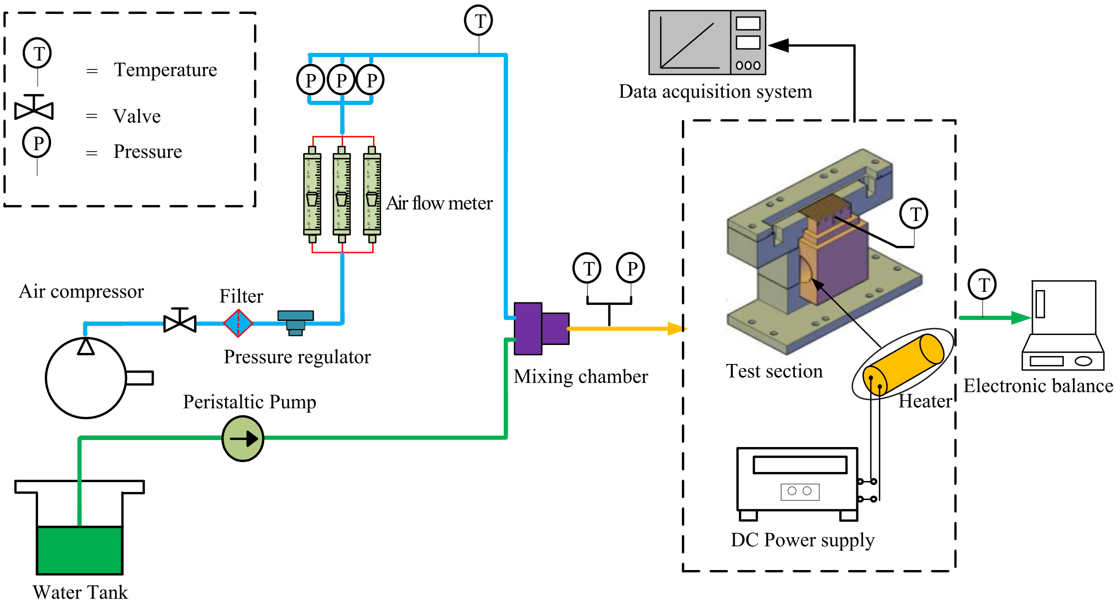

Fig. 1. Schematic diagram of experimental apparatus.

The single-phase flow experiments were the first to be conducted to confirm the validity of the experimental system. The conventional methods based on laminar developing flow are found to fairy predict the measured Nusselt number from single-phase flow experiments.

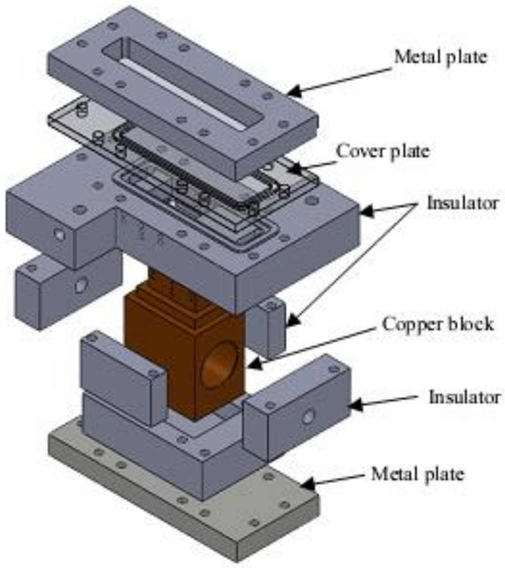

Fig. 2. Schematic diagram of test section.

4. Data reduction

Due to the cover plate which is made of polycarbonate, adiabatic fin tip is assumed to obtain the wall heat flux, q_w, calculated based on the effective area, which is given by

$$q_w = \frac{q_b\left(W_{ch} + W_f\right)}{\left(W_{ch} + 2\eta H_f\right)} \quad (1)$$

where q_b, W_{ch}, W_f, H_f and η represent, respectively, base heat flux, channel width, fin thickness, channel dept and fin efficiency.

The heat transfer coefficient is obtained from

$$h = \frac{q_w}{T_w - T_f} \quad (2)$$

where T_f is fluid temperature and T_w denotes the average wall temperature estimated by an extrapolation.

For one dimensional heat conduction with adiabatic fin tip, the fin efficiency is expressed by

$$\eta = \frac{\tanh(mH_f)}{mH_f} \quad (3)$$

where m is defined as

$$m^2 = \frac{hP}{kA_c} \quad (4)$$

In Eq. (4), P stands for fin perimeter, k for thermal conductivity and A_c for fin cross-sectional area.

Iteration process for Eqs. (1) – (4) is needed to determine the wall heat flux and heat transfer coefficient. The process is carried out until the fin efficiency converges to a fixed value.

5. Results and discussion

Flow visualization is carried out by using stereozoom microscope and camera system. In this work, segmented flow, corresponding to the alternating appearance of liquid slug and gas slug, is induced by installing the foamed plastic polymers in the inlet plenum. Fig. 3 illustrates the segmented flow in rectangular micro-channels.

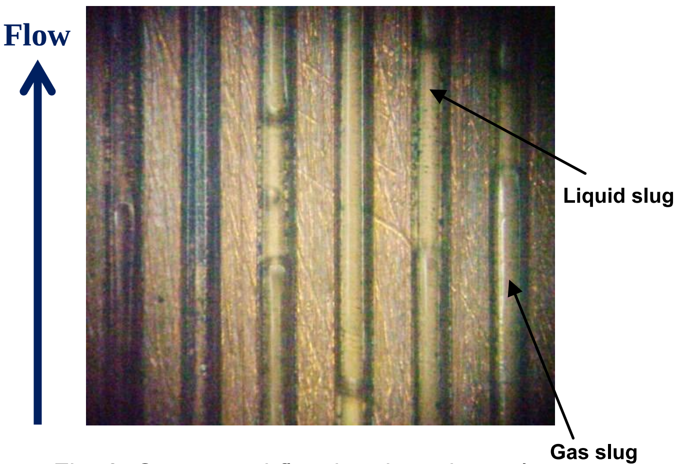

Fig. 3. Segmented flow in micro-channels.

For heat transfer considerations as presented in Fig. 4, the Nusselt number increases with liquid superficial Reynolds number. It is noted from the experiments that there is no remarkable change in the flow pattern over a range of gas flow rate and, hence, the Nusselt number is less dependent on the gas superficial Reynolds number. The small gas slugs in segmented flow contribute to agitation in the liquid film on the wall, leading to the improvement of heat transfer up to 80% over the single-phase liquid flow.

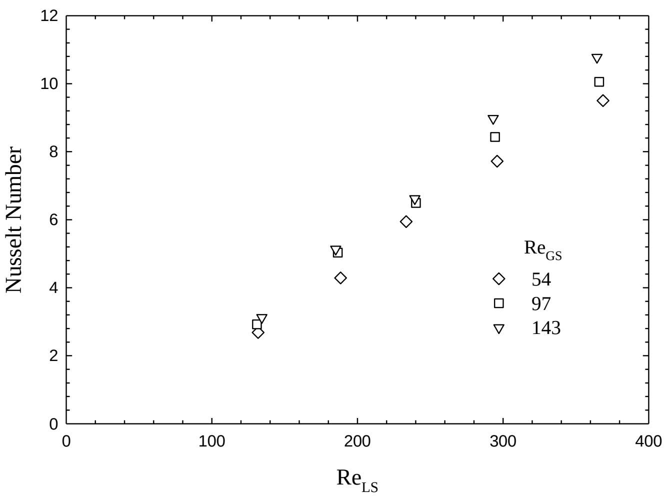

Fig. 4. Heat transfer data for different superficial Reynolds number.

6. Conclusion

Heat transfer and fluid flow characteristics of non-boiling air-water flow through micro-channels are reported in this work. Both single-phase and two-phase flows are carried out in 21 parallel rectangular micro-channels. Each channel has a width and a depth of 0.45 and 0.41 mm, respectively. The operating conditions under low flow rates are carried out during the experiments. Flow visualization is carried out using stereozoom microscope mounted together with the camera.

Gas-liquid heat transfer during segmented flow gives better results when compared with the single-phase liquid flow. The experimental results indicate the dependence of Nusselt number on liquid superficial Reynolds number.

7. Acknowledgement

The authors would like to express their appreciation to the Thailand Research Fund (TRF), KMITL Research Fund and the National Research University Project of Thailand's Office of the Higher Education Commission for providing financial support for this study.

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