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Heat transfer characteristics of gas–liquid flow in horizontal rectangular micro-channels

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ABSTRACT

An experimental study of heat transfer characteristics of air–water flow in horizontal micro-channels was carried out in this work. The gas–liquid mixture from a y-shaped mixing chamber was forced to pass through a plenum inlet and entered 21 parallel rectangular micro-channels 40 mm long in the direction of flow. Each channel had a width and a depth of 0.45 and 0.41 mm, respectively. The test runs were done at a heat load of 80 W, with superficial Reynolds numbers of gas and liquid ranging between 54–142 and 131–373, respectively. A Stereozoom microscope and camera system were employed to conduct flow visualization. To explore the dependence of a Nusselt number on the flow characteristics, two inlet sections with different designs were used in this work. The experiments revealed that the formation of small gas slugs instead of gas core flow involves an increase in Nusselt numbers. In this work, the gas–liquid flow gave heat transfer enhancement up to 80% over the liquid flow.

1. Introduction

Two-phase flow studies 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 for two-phase flow characteristics in micro-channels, resulting in flow phenomena significantly different from those observed in ordinarily sized channels. Serizawa et al. [1], for instance, investigated the visualization of the two-phase flow pattern in circular micro-channels. The flowing mixture of air and water in channels of 20, 25 and 100 μm in diameter and that of steam and water in a channel of 50 μm in diameter were conducted experimentally. The study confirmed that the surface wettability had a significant effect on the two-phase flow patterns in very small channels. The discrepancies between micro-scale and macro-scale flows have been reported in the literature [2–7].

Two-phase flow in micro-channels has gained significant attention in engineering due to wide application, extending to such fields as bioengineering, fuel cells, compact heat exchangers, heat sinks, and so on. For cooling purposes, various applications of micro-channels are discussed in detail by Mudawar [8]. Due to the rapid development of modern miniature devices generating large amounts of heat, the single-phase micro-channel flow seems no longer a highly effective cooling method.

Two-phase flow in small channels has become another effective means for dissipating heat. Flow boiling, for instance, involves very high heat transfer rate but backflow and instabilities, which are considered as drawbacks [9], have to be carefully controlled. According to the open literature, two-phase heat transfer in micro-channels have been mainly reported for flow boiling studies. The effects of such parameters as mass flux and heat flux on flow boiling phenomena have been reported in several publications [10–12]. Moreover, the up-to-date comprehensive discussions on flow boiling in micro-scale channels were given by Ribatski [13] and Tibirica and Ribatski [14]. In contrast, the data corresponding to heat transfer characteristics during non-boiling two-phase flow in micro-channels is still limited.

Bao et al. [15] carried out experiments to explore the 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, the heat transfer coefficient increased with the increase in air flow rate caused by the flow pattern transition. Hetsroni et al. [16] performed experiments to study two-phase flow regimes and bubble behavior in triangular parallel micro-channels made from $15 \times 15 \times 0.53\ \text{mm}^3$ square-shape silicon substrate. In this study, air–water and steam-water were chosen as working fluids and

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Nomenclature

A	area (m^2)
H	height (m)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
m	$(hP/kA_c)^{1/2}$
Nu	Nusselt number
P	perimeter (m)
Q	heat transfer rate (W)
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 (m)

Greek symbols

η	fin efficiency

Subscripts

b	base
c	cross-section
ch	channel
f	fin
L	liquid phase
TP	two-phase

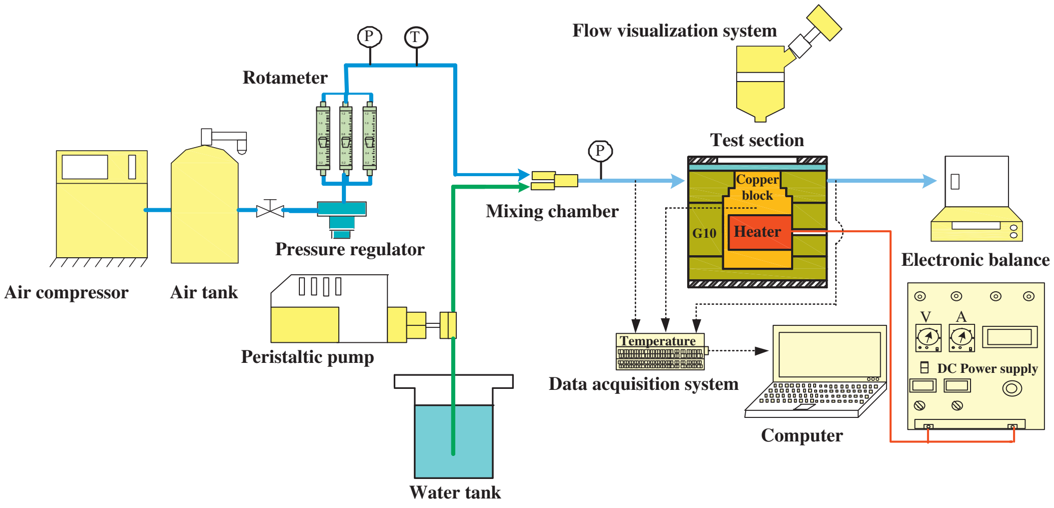

Fig. 1. Schematic diagram of experimental apparatus.

the differences between flow patterns of the two cases were addressed. It is noted from Triplett et al. [17,18] that based on different channel cross-sectional shapes, the adiabatic two-phase air–water flow characteristics in semi-triangular micro-channels were similar to those obtained from circular channels. The heat transfer of an air–water flow in parallel micro-channels of 0.1 mm in hydraulic diameter was experimentally investigated by Hetsroni et al. [19]. Their results showed a decrease in the Nusselt number with an increasing gas flow rate, which was opposite to the results obtained by Bao et al. [15]. Betz and Attinger [20] 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 a non-boiling two-phase flow in micro-channels with different diameters were studied by Choo and Kim [21]. 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. [22] studied two-phase flow distribution in parallel upward channels. They reported that the phase distribution

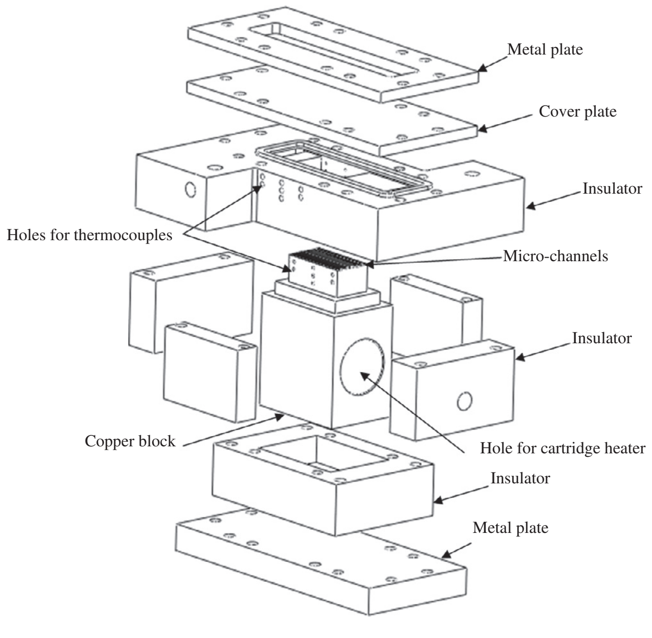

Fig. 2. Schematic diagram of test section assembly.