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Experimental investigation of flow boiling in single minichannels with low mass velocities

Burak Markal[a], Ayse Candan[b], Orhan Aydin[b,*], Mete Avci[b]

[a] Department of Energy Systems Engineering, Recep Tayyip Erdogan University, 53100 Rize, Turkey
[b] Department of Mechanical Engineering, Karadeniz Technical University, 61080 Trabzon, Turkey

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ABSTRACT

Flow boiling characteristics in a single minichannel with the aspect ratio of 2 (1.8 mm width and 0.9 mm height) are studied experimentally. Experiments are conducted for different values of the wall heat flux (in the range of 204.7–431.3 kW/m^2) and low mass fluxes (G = 20, 40 and 60 $kg\,m^{-2}\,s^{-1}$) at a constant inlet temperature of deionized water (approximately 70 °C). Effects of the heat and mass fluxes on the local two phase heat transfer coefficient and the total pressure drop are examined. A considerable attention is also paid to performing high speed flow visualization study to have qualitative information about the flow physics. The heat transfer coefficient shows an irregular trend with increasing heat flux or the vapor quality, while it increases with increasing mass flux. On the other hand, the pressure drop increases with an increase in the heat flux or in the exit vapor quality. For the lowest mass flux value considered, temperature jump or the critical heat flux (CHF) condition is shown to occur at higher heating powers.

1. Introduction

Removing high heat fluxes from the small scale surfaces in electronics (and other relevant industries) is one of the major problems for thermal engineers and designers. Recently, some passive and active novel cooling options have appeared such as heat pipes, jet impingement and multiphase flow techniques. Among the mentioned ones, flow boiling in small scale channels is promising due to the higher heat dissipation capacities. Therefore, a great deal of research attention has been devoted to it. An excellent and comprehensive review of the studies existing in the literature can be found in recent studies of Kandlikar et al. [1], Szczukiewicz et al. [2] and Karayiannis and Mahmoud [3]. Here, it is focused mainly on the studies include similar scope, geometrical aspects or experimental conditions.

Some researchers studied flow boiling in small scale channels and reported contradictions regarding the effect of heat and mass fluxes. Tran et al. [4] performed an experimental study on flow boiling of R12 in a rectangular channel with the hydraulic diameter of 2.40 mm. They stated that heat transfer coefficient increased with increasing heat flux, while it was independent of mass flux and vapor quality. Lee and Lee [5] studied flow boiling of R113 in three different single channels with the hydraulic diameters of 0.784 mm, 1.9 mm and 3.63 mm, respectively. Contrary to the results of Tran et al. [4], they concluded that heat transfer coefficient increased with increasing mass flux and vapor quality while it was nearly independent of heat flux. Steinke and Kandlikar [6] studied boiling of water in six parallel slightly trapezoidal micro-ducts with the hydraulic diameter of 207 µm. They stated that heat transfer coefficient decreased with an increase in the vapor quality, and nucleate boiling was shown to be the dominant heat transfer mechanism. Balasubramanian and Kandlikar [7] investigated flow patterns, pressure drop fluctuations and flow boiling instabilities of deionized water in a parallel microchannel heat sink included six rectangular channels (each has the hydraulic diameter of 333 µm). They declared that the dominant frequency of the pressure drop fluctuations increased with an increase in the surface temperature, and back flow could enter the inlet manifold, which caused flow maldistribution in the channels. Bertsch et al. [8] experimentally investigated boiling phenomenon of R134a in a parallel channel heat sink. The channels had a hydraulic diameter of 1.09 mm. They stated that the heat transfer coefficient increased with increasing heat and mass fluxes, while it was nearly not influenced by saturation pressure. Harirchian and Garimella [9–11] experimentally studied effects of geometrical aspects on flow boiling of FC-77 in different parallel channel heat sinks. The widths and heights of the channels in the heat sinks ranged from 0.1 mm to 5.85 mm, and from 0.1 mm to 0.4 mm, respectively. They emphasized the critical role of the cross sectional area on boiling characteristics. Liu et al. [12] investigated boiling characteristics of deionized water flow. The rectangular channels used in the experiments had 0.293 mm and

* Corresponding author at: Karadeniz Technical University, Department of Mechanical Engineering, 61080 Trabzon, Turkey.
E-mail address: oaydin@ktu.edu.tr (O. Aydin).

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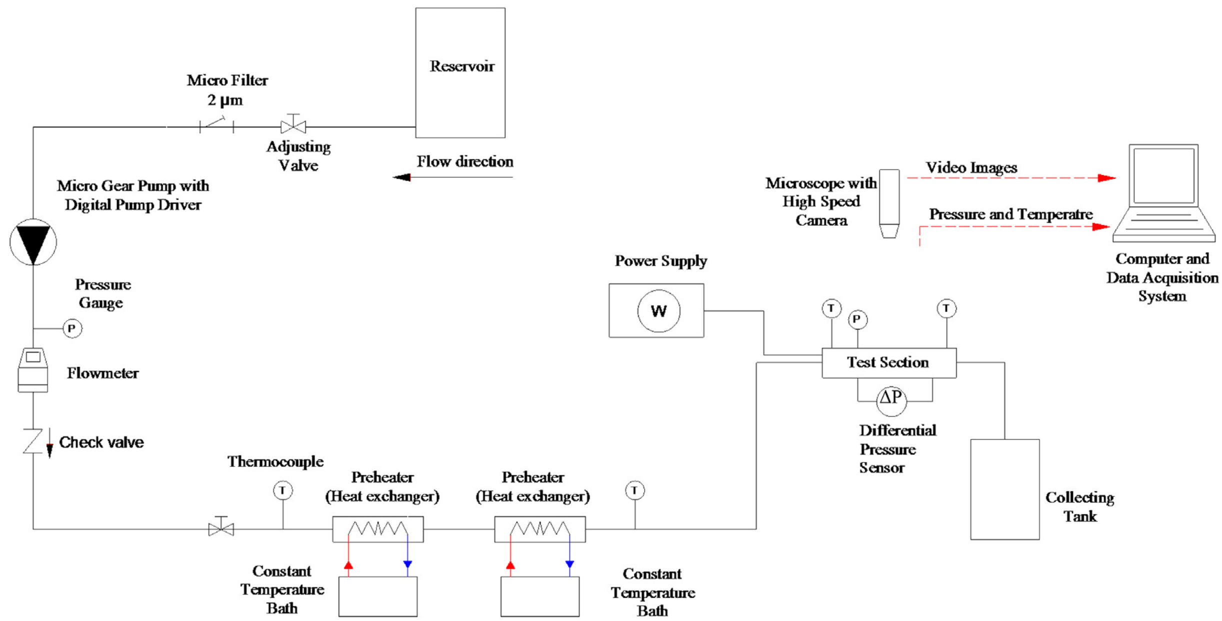

Fig. 1. The schematic diagram of the experimental setup.

1.2 mm hydraulic diameters. They concluded that heat transfer coefficient increased with increasing heat flux, while it decreased with increasing vapor quality. Tibiriçá et al. [13] performed an experimental study for flow boiling heat transfer coefficient and critical heat flux in small flattened tubes with equivalent internal diameter of 2.2 mm (but with different aspect ratios). The working fluids used are R134a and R245fa. They compared their results with the ones of circular tubes. They stated that, for high mass fluxes, both the circular and flattened tubes showed similar heat transfer coefficients due to the negligible characteristics of stratification effects. Marzoa et al. [14] studied flow boiling of R245fa in a horizontal polyimide tube with the inner diameter of 2.689 mm. They stated that mass flux and vapor quality significantly affected the heat transfer, however, heat flux and the saturation temperature had mild influence on it. Yin and Jia [15] focused on the bubble growth characteristics and heat transfer performance of flow boiling of deionized water in a single rectangular channel. The channel had a cross section of 0.5 mm × 1 mm. They emphasized the role of the confinement effect and concluded that contrary to the mass flux, the heat flux had a considerable effect on the heat transfer. Dang et al. [16] experimentally studied flow boiling of R134a and zeotropic mixture R407C in a single rectangular channel with the cross section of 1 mm × 1 mm. They defined various flow patterns (bubbly, confined bubble, slug, churn-annular, annular, annular-dryout and dryout) and presented relevant maps. They stated that the critical heat flux (CHF) increased with mass velocity, and R407C showed higher CHF than that of R134a. Kuang et al. [17] focused on flow visualization experiments to investigate the flow boiling and instabilities of ammonia in a parallel channel evaporator. The cross section of the channels was 1 mm × 1.1 mm. They stated the existence of the periodic flow with rewetting and annular film evaporation stages. They also concluded that frequency of the pressure drop oscillation increased with the mass flux and the saturation temperature. Linlin et al. [18] experimentally and theoretically investigated flow boiling heat transfer of carbon dioxide in horizontal tubes with inner diameters of 0.6 and 1.5 mm. They concluded that heat transfer coefficient increased with increasing mass flow rate, while it decreased with increasing tube diameter and saturation temperature.

The flow boiling in mini or microchannels is a hot research topic. However, there are ongoing debates with regard to the effective heat transfer mechanisms or how the governing parameters affect the flow boiling characteristics, which are also underlined by lots of researchers such as Deng et al. [19] and Wang and Wang [20]. In addition to this fact, flow boiling with low mass fluxes has a particular importance. Flow boiling in mini/micro channels with low mass fluxes and high heat fluxes may lead to thermal damages such as occurrence of the critical heat flux condition, burning of the heat transfer surfaces and the systems failure. As stated by Lee et al. [21] flow rate is related to the operating cost and the volume of a device is related to the system cost. Therefore, concentrating on the flow boiling with low mass fluxes in mini/micro channels is critically important. However, studies on the saturated flow boiling with low mass fluxes in rectangular mini/microchannels are scarce. Wang et al. [22] focused on both the subcooled and saturated flow boiling of water in a rectangular minichannels with the hydraulic diameter of 3 mm. They stated that there were agreement between the experimental results and macrochannel correlations. Zhuan and Wang [23] studied flow boiling of R134a in a microchannel array heat sink with low mass velocities. Mosyak et al. [24] focused on subcooled flow boiling of water in parallel rectangular microchannels.

As it is seen, in brief, there are ongoing debates in the small-scale flow boiling phenomena, and especially, there is a serious lack for lower mass flux cases in the relevant literature. Motivated by the above mentioned facts, in this study, we aim to experimentally investigate the saturated flow boiling phenomenon in a small scale rectangular channel with low mass velocities. For a detailed analysis of the flow physics and to provide a complementary attempt of the interpretation of the experimental measurements, high speed flow visualization has been performed extremely.

2. Experimental setup and test section

The schematic diagram of the experimental setup is shown in Fig. 1. The major parts of the setup can be listed as: A flow line (as an open loop), a test section, a high speed visualization system and a data acquisition unit. The working fluid (deionized water) is forced by a micro gear pump in the system. The flow rate is adjusted through a digitally controlled driver of the pump, which is also monitored by a digital flowmeter (Cole Parmer TW-32709-52). The inlet temperature of the deionized water is adjusted by heat exchangers. Temperatures in the inlet and outlet plenums (shallow plenums) are read by K-type thermocouples while the inlet pressure (in deep plenum) is measured by an absolute pressure transducer. For the total pressure drop (between the inlet and outlet deep plenums), a differential pressure transmitter