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Analysis of air–water flow pattern in parallel microchannels: A visualization study

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ABSTRACT

Air–water adiabatic upward flows were measured in seven parallel microchannels. The total mass velocity was adjusted to 50, 100, 200 and 300 kg/m^2 s. Superficial air velocities ranging from 0.16 to 41.70 m/s were applied for each mass velocity. The superficial water velocity ranged from 0.005 to 0.30 m/s in order to maintain the mass velocity constant. A gas quality of up to 0.90 was obtained. The visualizations showed different flow configurations in each microchannel, although approximately homogeneous conditions were verified in the inlet manifold for single-phase flows. For the same time step, single-phase regimes (only liquid or only gas) were simultaneously obtained together with two-phase flow patterns (annular, bubbly, slug and churn, and their transitions) at each microchannel. The variety of single-phase and two-phase flow configurations was also observed for different time steps at the same microchannel. The Mishima and Ishii (1984) flow pattern map for single microchannels was reassessed with parallel flows. For quality over 0.08 and mass velocity over 100 kg/m^2 s annular flow patterns are predominant. This corresponds approximately to superficial gas and liquid velocities over 10 and 0.1 m/s, respectively, at the inlet manifold. For other inlet conditions there are miscellaneous flow configurations. Similarities to results of Niño (2002) indicate that the current analysis can be extended to air–water horizontal flows or to microchannels with other cross-sectional geometries if the hydraulic diameter is kept at around 1 mm.

1. Introduction

Two-phase flows in microchannels have been reported in numerous applications concerning miniature devices. Compact heat exchangers, biomedical and biochemical instruments, supercomputers, lasers and nuclear reactors are among the current applications in which microchannels are present (Ide et al. [1], Park and Punch [2] and Morini [3]). Differences in the two-phase flow behavior of micro- and macrochannels are often attributed to surface tension effects. Several authors have described the microchannel flow features related to the flow pattern, pressure drop and void fraction, such as Fukano and Kariyasaki [4], Triplett et al. [5], Bao et al. [6] and Fourar and Bories [7]. These studies highlight, in general, significant hydrodynamic differences (Triplett et al. [8]).

Numerous two-phase pressure drop and void fraction models have been developed recently for microchannels, e.g., Kawahara et al. [9], Lee and Lee [10], and Lee and Mudawar [11]. Each correlation is developed for the specific physical particularities of a flow pattern. However, experimental evidence (Hetsroni et al. [12]; Jassim and Newell [13]; Niño [14]) indicates the simultaneous presence of distinct two-phase flow configurations in parallel microchannel circuits. The objective of this research was to determine the probability of occurrence of a specific flow arrangement according to the design flow settings at the inlet manifold. The aim was to identify which type of correlation is suitable for particular inlet flow settings. To avoid misleading results due to inlet flow disturbance in the microchannels, the inlet manifold was homogeneously loaded by pipes resembling a fractal structure.

In this study, air–water adiabatic upward flows were measured in seven parallel microchannels for a wide range of qualities and mass velocities where different flow regimes coexist. Total mass velocities, G [kg/m^2 s], of 50, 100, 200, and 300 were applied. The microchannel pipe diameter was 1.2 mm. The following superficial air velocities were applied for each G value: 0.16, 7.05, 13.95, 20.83, 27.72, 34.79 and 41.70 m/s. The superficial water velocity ranged from 0.005 to 0.30 m/s to keep G constant. A gas quality of up to 0.90 was obtained.

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Nomenclature

a, b, c, d	Niño constants
D	hydraulic diameter (m)
F	time fractions for each flow pattern
g	Niño constant; gravitational acceleration (m/s^2)
G	mass velocity (kg/m^2 s)
j	superficial velocity (m/s)
l	microchannel length (m)
x	gas quality

Subscripts

g	gas
l	liquid

The structure of the paper is as follows. Section 2 presents relevant literature results. The experimental setup is given in Section 3. In Section 4, the main results are provided through a visual analysis and the Mishima and Ishii [15] flow pattern map is reevaluated for parallel microchannel arrangements. Finally, concluding remarks are given in Section 5 and situations to which the conclusions of this study can be extended are detailed.

2. Literature review

In gas–liquid flows, pressure drop and void fraction predictions have been shown to be dependent on the gas and liquid flow regimes (turbulent or laminar), represented by the bulk Reynolds number for each phase. This number is mainly dependent on the two-phase flow configuration (Chisholm [16], Lockhart and Martinelli [17], and Friedel [18]). As a consequence, research on two-phase flows has been focused on the development of flow pattern maps, e.g., Coleman and Garimella [19], El Hajal et al. [20], Zurcher et al. [21] and Mandhane et al. [22].

Available flow pattern maps are mostly determined by experiments in a single pipe or channel with a specific flow direction and for a limited number of fluids. Downscaling of heat exchangers revealed that new flow maps were necessary to predict flow configurations in microchannels due to the increasing relevance of the surface tension (Triplett et al. [8]). In addition, the liquid–gas mass density ratio was found to be important in the flow pattern determination and pressure drop prediction (Thome et al. [23] and Garimella et al. [24], and Jassim and Newell [13]). However, two-phase flows for practical applications occur in parallel circuit designs. In the past two decades, different approaches have been applied to analyze two-phase behavior in two or more channels.

Tshuva et al. [25] reported two-phase flows in parallel pipes with diameter of 2.4 cm and length of 3 m. It was observed that two configurations were possible: a symmetric distribution of liquid and gas in the two pipes and an asymmetric flow in which the two phases flow in a single pipe and a stagnant liquid column is present in the other pipe. The occurrence of each configuration was determined in several maps as a function of gas and liquid flow rates. Each map was created for upward inclined flows with inclination angles equal to 5°, 10°, 20°, 45°, 70° and 90°. The non-symmetric configuration was observed in low gas and liquid flow rates. The region of asymmetric flow increased with the angle of inclination. For the horizontal case, the flow was symmetric for all flow conditions.

Hetsroni et al. [12] noted the hydrodynamic instability that occurs in parallel microchannels, connected by common inlet and outlet collectors. The cross-section of each channel was an isosceles triangle, the base of which was 200–310 μm. The angles at the base were 55°. Different flow patterns were observed simultaneously in the various microchannels at fixed values of water and gas flow rates.

A study involving two-phase flow analysis in six-port parallel rectangular microchannels was carried out by Jassim and Newell [13]. Horizontal tests were conducted with R134a and R410A at 10 °C (saturation temperature) and with air–water (at the same temperature) by Niño [14]. Tests using hydraulic diameters of 1.54 and 1.04 mm were performed. The gas quality ranged from 0 to 1 and the mass velocity varied from 50 to 300 kg/m^2 s. The time fractions, F, for each flow pattern were recorded in each channel at a given mass flux and quality, x. This was accomplished by taking photos of the flow through a clear PVC test section. Flow configurations were defined as only liquid, intermittent or annular, and as only vapor or gas. The time fraction curves obtained by Niño [14] are given in Eqs. (1)–(4). Constants (a, b, c, d and g) for the air–water flows are shown in Table 1.

$$F_{liquid} = (1-x)^{a} \tag{1}$$

$$F_{intermittent} = (1-x)^{bx^{c}} - (1-x)^{d} \tag{2}$$

$$F_{gas} = x^{g} \tag{3}$$

$$F_{annular} = 1 - F_{intermittent} - F_{liquid} - F_{gas} \tag{4}$$

Probabilistic flow regime maps have also been investigated by Canière et al. [26]. Air–water flows in 9 mm horizontal tubes were classified based on a fuzzy clustering algorithm with a regression technique. The visualization technique was compared to measurements taken with an electrical capacitance sensor.

The simultaneous occurrence of flow patterns in two large parallel pipes and in microchannels motivated studies on the influence of the inlet geometry of the flow collector which feeds the channels (Marchitto et al. [27] and Byun and Kim [28]). Dario et al. [29] investigated the main geometrical and operating conditions which influence the two-phase flow distribution in parallel channels. They concluded that the header and the feeding tube positions were the main factors influencing the mass flow rate distribution in parallel channels. The effectiveness of heat exchangers is dependent on the uniformity of the mass flow rate distribution through parallel channels. However, uneven distributions generally occur, reducing the effectiveness of heat exchanger systems [29]. Such situations of irregular distribution are particularly unfavorable for two-phase flows due to the possible uneven phase split at each junction of the dividing header.

Some cases of uneven distribution in parallel channels can have little effect on heat exchanger performance, while others can result in significant loss of the effectiveness, leading to mechanical

Table 1
Time-fraction constants for air–water flow patterns reported by Niño [14].

	G = 50 kg/m^2 s	G = 100 kg/m^2.s	G = 200 kg/m^2 s	G = 300 kg/m^2 s
a	30.6	71.09	111.02	118.28
b	1.2	1.21	29.17	54.34
c	4.04	0.19	0.57	0.93
d	1.62	2.90	22.81	16.86
g	6.4	9.91	21.67	37.94