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Pressure drop and point mass transfer in a rectangular microchannel ☆

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ABSTRACT

This paper describes the pressure drop and local mass transfer in a rectangular microchannel having a width of 3.70 mm, height of 0.107 mm and length of 35 mm. The pressure measurements were carried out with distilled water as working fluid at Reynolds numbers in the range of 100–845, while mass transfer measurements with a chemical solution at Reynolds numbers in the range of 18–552 by using the electrochemical limiting diffusion current technique (ELDCT). Experimental friction factors were slightly higher than those calculated by theoretical correlation. The Sherwood number correlation was also obtained.

1. Introduction

With the development of micro fabrication technology, microfluidic systems have been increasingly used in different scientific disciplines such as biotechnology, physical and chemical sciences, electronic technologies, sensing technologies etc. Microchannels are one of the essential geometry for microfluidic systems; therefore, the importance of convective transport phenomena in microchannels and microchannel structures has increased dramatically. In recent years, a number of researchers have reported the heat transfer and pressure drop data for laminar and turbulent liquid or gas flow in microchannels. The detailed reviews of these studies were given by several researchers [1–6].

Rectangular geometries are of particular interest in microfludic applications. There are several studies on friction factor and heat transfer of liquid flow through rectangular microchannel. In general, the results have been compared with conventional theories. Some researchers reported very different results of friction factor and heat transfer characteristics from those macro channel flow. Wang and Peng [7] studied the heat characteristics of water and methanol through rectangular microchannels with the hydraulic diameters in the range of 311–747 µm. They found that the liquid convection characteristics are quite different from those of the conventional cases. Peng et al. [8,9] investigated the heat transfer and friction factor of water flow in the rectangular channels with $D_H = 0.133$–0.367 mm. They developed the heat transfer and friction factor correlations for laminar and turbulent flow. They reported friction correlation as $f = C/Re^{1.98}$, and found the transfer from laminar flow to turbulent to occur at Reynolds number in the range of 200–700. Their results are quite different from classical theory. Peng and Peterson [10] reported that the geometric configuration, such as the aspect ratio and the ratio of the hydraulic diameter to the centre-to-centre distance of the microchannels, had a significant effect on the laminar single-phase convective heat transfer and flow characteristics. Pfund et al. [11] determined the friction factors for water flowing through high aspect ratio channels with the depths ranging from 128 to 521 µm. They reported that the transition from laminar to turbulence occurred at Reynolds numbers that were lower than the critical Reynolds number for macro ducts, and the transition Reynolds number decreased with decreasing channel depth. The friction factors in laminar flow were significantly greater than those of the classical values. Hegab et al. [12] reported that the transition from laminar to turbulent flow occurred at Reynolds number between 2000 and 4000, and friction factor and Nusselt numbers results were lower than the values predicted by macroscale correlations for rectangular channel with hydraulic diameters ranging from 112 to 210 µm. Hsieh et al. [13] studied experimentally the pressure drop characteristics of water flow in a rectangular channel with a hydraulic diameter of about 146 µm, and Reynolds numbers in the range of 50–1000. It was claimed that for $Re < 200$, $\Delta P/L$ shows a linear behaviour; while, for $Re > 200$, it exhibits a non-linear trend, and the friction factor data indicated a pressure drop higher than those predicted by the conventional theory. Shen et al. [14] investigated the single phase convective heat transfer in a compact heat sink consisting of 26 rectangular microchannels. It was found that the friction factors and the local and average Nusselt numbers significantly departed from those of conventional theories. They claimed that this can be attributed to the surface roughness.

On the other hand some researchers reported that the results of the heat and pressure drop in a microchannel are in good agreement with conventional theory. Lee et al. [15] conducted an experimental and numerical investigation on the thermal characteristic of the water flow through rectangular microchannels. Numerical predictions based on a classical, continuum approach was found to be in good agreement with the experimental data. They suggested that a conventional analysis approach can be employed in predicting the heat transfer

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Nomenclature

A	area [m^2]
c	concentration [mol.m^{-3}]
d	electrode diameter [m]
D_H	channel hydraulic diameter [m]
Di	diffusion coefficient [m^2.s^{-1}]
F	Faraday constant
f	friction factor
H	channel height [m]
I	current [A]
K	loss coefficient
k	mass transfer coefficient [m.s^{-1}]
L	channel length [m]
ΔP	pressure drop [Pa]
Re	Reynolds number $(=\rho u D_H/\mu)$
Sh	Sherwood number $(=kD_H/Di)$
u	mean velocity [m.s^{-1}]
x	axial distance [m]

Greek symbol

α	channel aspect ratio $(=H/W)$
ρ	density [kg.m^{-3}]
μ	viscosity [Pa.s]

Subscripts

b	bulk
c	channel
d	developed
e	exit
lim	limiting
p	plenum
t	total

behaviour in the microchannels for the dimensions considered in their study. Mishan et al. [16] studied the heat transfer and pressure drop of water flow in rectangular micro-channels with $D_H = 440$ μm. The experimental results of pressure drop and heat transfer confirmed that including the entrance effects, the conventional theory is applicable for water flow through micro-channels. Steinke and Kandlikar [17] reviewed the literature on single-phase liquid friction factors in microchannels and presented new experimental results of friction factor in microcahannel with $D_H = 8$–990 μm. They reported that the experimental results showed good agreement in value and trend with the conventional theory for laminar flow.

To summarize the above literature review and from previous review studies [1–6], it is seen that there are large scatter in the experimental results for flow fiction and heat transfer in rectangular microchannel. Therefore, further works is required to identify heat and momentum transfer mechanism in the microchannel. On other hand, the literature review also reveals that in spite of the many work on heat transfer and pressure drop in micro channel, the mass transfer studies are very limited. Acosta et al. [18] investigated experimentally mass and momentum transport in narrow flow gaps with the dimension of 0.2–0.5 mm, Reynolds number in the range of 1300–22,000. van Mala et al. [19] studied the heat and mass transfer in a square micro channel with asymmetric heating, both numerically and experimentally. They reported Nusselt and Sherwood correlations for the channel heated from topside for laminar and plug flow. Recently, Sara et al. [20] investigated laminar convective mass transfer and friction factor for circular microtubes with the diameter of 0.20 mm for different tube length.

This study provides an experimental investigation on point laminar forced convective mass transfer and pressure drop characteristic of liquid flowing through rectangular microcahannel having 0.208 mm hydraulic diameter by using the electrochemical limiting diffusion current technique (ELDCT).

2. Experimental set-up and data reduction

Fig. 1 shows the schematic diagram of the experimental set up, which was a modified system used by [20]. It consisted of a high-pressure nitrogen gas tube, multimeters, a DC power supply, a micro filter, a digital balance, a circulated water bath, data logger and test section. The flow to the test section was provided by high-pressure nitrogen gas and the flow rate was adjusted by a two-stage gas regulator. The fluid passed through a micro filter before entering the test section and was collected after the test section to weigh. Keithly 2700/7702 multi-channel multimeter was used to measure current, and a digital multimeter was used to measure the applied voltage. The temperature of the electrolyte, as working liquid, was kept constant at 25 ± 0.1 °C by circulating water bath. The schematic view of the test section is shown in Fig. 1(b). The rectangular channel (5) had a width of 3.70 mm, height of 0.1079 mm and length of 35 mm. The local electrodes (4) were mounted on its bottom surface to allow local current measurements. The test section was constructed as two parts; one of them (1) was made of acrylic on which rectangular channel was mechanically fabricated, and the other (2) which was equipped with nickel electrodes, was made of resin. The electrodes were flashed with the surface. The dimensions of the channel and the axial position and diameter of the electrodes were measured by NİKON MM 400 L video measuring microscope. 32 electrodes made of 0.25 mm nickel wire were used. As shown in Fig. 1b, at outlet a nickel tube with the diameter of 8 mm was attached as anode. The pressure drop through test section was measured by pressure transmitter made by KELLER in the range of 0–6 bars.

The mass transfer coefficients were determined by using the electrochemical limiting diffusion current technique (ELDCT). This technique is based on diffusion-controlled reaction at electrode surface [21]. The electrolyte used in the mass transfer measurement consisted of 0.005-mol dm^{-3} (M) potassium ferricyanide as cathodic reactant, 0.02 M potassium ferrocyanide as anodic reactant and 0.5 M potassium carbonate as supporting electrolyte. To assure a cathodic controlled-reaction, the anode surface area was chosen higher than the cathode surface area and the concentration of ferrocyanide 4 times higher than that of ferricyanide. The diffusion coefficient (Di) and Schmidt number (Sc) of the electrolyte were 6.85×10^{-10} m^2 s^{-1} and 1444, respectively [20]. The rate of the mass transfer to the local electrodes can be characterized by mass transfer coefficient (k) which can be expressed as follow:

$$k = \frac{I_{lim}}{nFAc_b} \tag{1}$$

where I_{lim} is the limiting current, A the surface area of the electrode, n the number of the transferred electrons in the electrochemical reaction (=1 for this study), F the Faraday constant and c_b the bulk concentration of the ferricyanide.

The measured pressure drop ΔP_t includes pressure drop contributions of the inlet ΔP_i, exit ΔP_e, pressure drop of L_o, ΔP_{Lo}, ΔP_{90}, and developing flow ΔP_d, (see Fig. 1b); the net pressure drop, ΔP_{net}, can be calculated by:

$$\Delta P_{net} = \Delta P_t - \begin{pmatrix} \Delta P_i + \Delta P_e + \Delta P_d \\ + 2\Delta P_{90} + 2\Delta P_{Lo} \end{pmatrix} \tag{2}$$

where ΔP_i and ΔP_e can be estimated by using the following relation:

$$\Delta P = K\frac{\rho u^2}{2}. \tag{3}$$