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Effect of Junctions on Pressure Drop and Flow Patterns in the Rectangular Micro-channel for the Gas-liquid System

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Abstract—*Process intensification in microchannels has become one of the attractive research focus. Gas-liquid operations like gas absorption in microchannels have proven to be highly efficient than conventional operations. This work is focused on hydrodynamic studies (pressure drop and flow patterns) in rectangular microchannels for the nitrogen-water system at 27 ℃ temperature and 1 atmospheric pressure. Y-junction(45º), Cross-T-junction(90º), and T-junction (180º), rectangular microchannels with the following dimension, (LxWxH) (45 mm x 0.5 mm x 0.75 mm) were used in this work. The effect of channel junction on the pressure drop was evaluated. The highest pressure drop was recorded in Cross-T-junction than the Y- junction channel and lowest in the T- junction microchannel. The pressure drop was in the range 0.6 to 8.2 kPa, 1.5 to 8.6 kPa and 0.4 to 8 kPa for Y, Cross-T and T Junction respectively. Finite element analysis (FEA) was conducted for the pressure drop calibration. Simulation and the experimental results were fairly in agreement with each other. Slug flow, slug-annular flow, churn flow and annular was observed in the microchannel with different junctions.*

Keywords: *Microchannel; Pressure drop; Hydrodynamic; Two-Phase flow; Nitrogen; Water; Rectangular cross-section; Y-junction; Cross-T-Junction; T-Junction.*

1. INTRODUCTION

Gas-liquid two-phase systems are encountered in a gas-absorption process. They have several applications like separation of pollutants COx, SOx, NOx, from industrial exhaust gases, dehydration of natural gas using liquid solvents and more. Conventionally equipment like stirred tank [1-2], mixer-settler [3-4], tray columns [5-7], rotating disk [8], pulsed [8], packed tower [9-10], spray tower [11-12], columns are used. This equipment has many drawbacks such as less efficiency, large size, less precision control, economic, etc. Process intensification in chemical industries has become the central focus of research. The aim of this intensification step is to reduce the cost of operation, equipment, by making changes in the processes, equipment design, utilizing the smaller equipment and energy-efficient ones. One of the techniques of achieving process intensification is employing microchannels. Microchannels offer high specific surface area, high heat, and mass transfer rates, precise control over the bubble and the slug size. They are suitable for handling hazardous and expensive chemicals as they use very less quantity of reagents.

A significant number of reports are found in the literature related to gas-liquid systems. The surface area of the slugs or bubbles, pressure drop and flow maps as a function of Capillary and Weber numbers are part of the hydrodynamic study [13-17]. Among them, hydrodynamics (flow regimes and pressure drop) estimation is important for evaluating the efficiency and the energy requirement of the process.

Few studies reported the hydrodynamics of flow and pressure drop of gas-liquid systems in microchannels [18-22]. Most of the two-phase flow was conducted in circular cross-section microchannels, [18, 23-24] while rectangular, square, triangular and trapezoidal shape microchannels are also used. [25-26]. Triplett et al. [27] reported different flow regimes, namely bubble, slug, churn and annular flows in a 1 mm diameter pipe. Kawahara et al. 2002, used a 100 µm hydraulic diameter circular channel and gas-liquid flow patterns were determined at the range superficial velocities of 0.1–60 m/s for gas, and 0.02–4 m/s for liquid, and observed slug, bubble, and annular flow. Typical flow patterns were reported by Kreutzer et al. 2005, such as liquid ring flow, stratified flow, fluid or gas lumped flow. Chung and Kawaji, 2004, conducted a hydrodynamic study in a square and circular channel of size 100 micrometers. They reported the flow map and concluded that the void fraction of the phases was independent of the shape of the channel. Choi et al. 2011, investigated the effect of aspect ratio on flow patterns and void fraction, in three different microchannels having three hydraulic diameters. They observed that the void fraction is dependent on the aspect ratio. In 2009, Yue et al was studied pressure drop in the rectangular microchannel, and the divided flow model was modified for 200 to 667 µm rectangular channels.

It has been identified that most experimental studies were conducted to identify the effect of shape (triangular, rectangular and circular), dimension, flow rates on flow patterns and pressure drop. Studies related to the effect of channel junction in microchannels are very limited to certain extent. Hence, this work focuses on conducting the effect of Y-junction(45º), Cross-T-junction(90º), and T-junction (180º) on pressure drop and flow regimes in microchannels at various gas and liquid flow rates.

2. EXPERIMENTAL AND METHODOLOGY

2.1 Microchannels Fabrication

Rectangular microchannels were fabricated by the leaser engraving technique on the acrylic sheets. Three types of junctions were used, Y-junction(45º), Cross-T-junction(90º), and T-junction (180º). Junctions were 10 mm apart from the main channel starting point and had a width of 0.5 mm and a depth of 0.75 mm. The main channels had the following dimensions, width 0.5 mm, depth 0.75 mm and length 45 mm.

2.2 Experimental setup

The schematic diagram of the experimental set-up is shown in Figure-1. It consists of a 10 ml glass syringe, a syringe pump, microchannel, nitrogen gas cylinder, mass flow controller (MFC), digital manometer, collection beaker, PVC tubes for connections, monochromatic light source, a high-speed camera and a computer for data recording. The 10 ml glass syringe is made of borosilicate glass supplied by Top Syringe Pvt Ltd, Thana, India. The syringe pump having the flow range 0.01 ml/min to 9.99 ml/min was supplied by Yashtech India Pvt Ltd, Nashik, India, Nitrogen gas is GC-grade and was supplied by Dinesh Gases, Jaipur, India. The mass flow controller (Model No.: MC-200SCCM-D/5M,5IN, Alicat Scientific, Tucson, USA) is having a flow range from 0 to 250 SCCM (stander cubic centimeter/ ml/min). Digital manometer (Modell No.: PM-9110SD, Lutron Electronics Ent. Co. Ltd. Taiwan) was supplied by Bright instruments, Mumbai, India. PVC tubes with a 3 mm internal diameter were used to connect the syringe and the microchannel. A monochromatic light source and the high-speed camera that is the part of Goniometer (Model: DSA 25E) Kruss GmbH. Kruss GmbH is Made in Germany, was used to capture the images of flow patterns during the flow. The computer was used to record the flow. All experiments were conducted at 27 ℃ and atmospheric pressure.

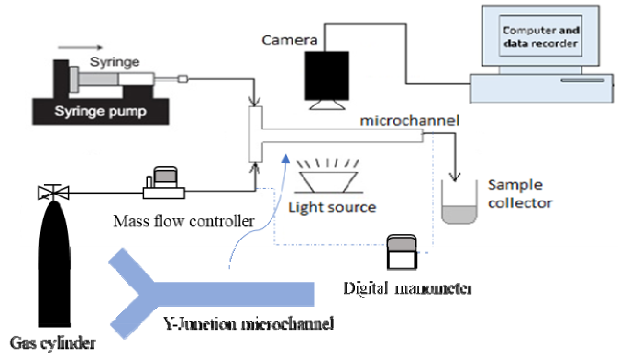

Figure 1: Schematic of the experimental set up for pressure drop and flow patterns

2.3 Experimental procedure

Distilled water was used for the liquid phase. It was injected inside the channel by the syringe pump at the following flow rates from 0.25 to 5 ml/min. Nitrogen gas was fed into the microchannel through the mass flow controller at 2.5 to 80 SCCM. The liquid flow rate was varied at a constant gas flow rate. Pressure drop was measured at different liquid flow rates. This experiment was repeated at different gas velocities. The experimental pressure drop was validated by simulation using Finite element analysis (FEA). The experiments were repeated three times and the average value is reported.

3. RESULTS AND DISCUSSIONS

3.1 Pressure drop analysis

The experimental pressure drop values in T-Junction, Y-junction, and Cross-T-junction microchannels are given in Figure 2, Figure 3 and Figure 4. It can be seen that pressure drop increases with the increase in liquid flow rate for a given gas flow rate in all three channels. Also, an increase in gas flow rates leads to increased pressure drop. A similar trend is also reported by Su et al, used stainless steel microchannels with a diameter of 0.56, 1.00, and 1.80 mm and nitrogen used as the tested fluid for study the effect of flow rate on pressure drop by Su et al. For instance, in the T-junction microchannel, shown in Figure-2, at gas flow rates less than 10 SCCM, the slope of the pressure drop curve is less, i.e., the pressure loss is very less as expected which is less than 3.8 kPa. At gas flow rates above 10 SCCM, the pressure difference changes gradually from 1.25 to 8 kPa at 80 SCCM gas flow rate. This may be due to a significant shear effect inside the microchannels. Similarly, Figure-3 shows the pressure drop results in the Y-junction. The gas and the liquid flow rates were maintained the same as in all three junction microchannels. It can be seen that the ΔP values are almost similar in both cases(T and Y junction). At low gas flow rates up to 40 SCCM, a linear behavior is observed between the pressure drop and the liquid flow rates. Above this value, the ΔP curve tends to show polynomial behavior. A comparison between the experimental pressure drop and the simulation results were made which is given in Table 1. In these two values are shown at low gas and liquid flow rates, both the pressure drop values are matching are in good agreement. Cross-T-junction microchannel shows the highest pressure drop among three junctions microchannel, because of the slug breaking phenomena. Pressure drop in the Cross-T-junction microchannel is in the range between 1.5 kPa to 8.6 kPa

Table 1: Validation for pressure drop studies

Velocity (m/s)	Experimental (kPa)	Simulation (kPa)	Error (%)
Gs: 0.1111; Ls: 0.0111	0.4	0.397	0.75
Gs: 1.777; Ls: 0.2222	6.3	6.53	3.65

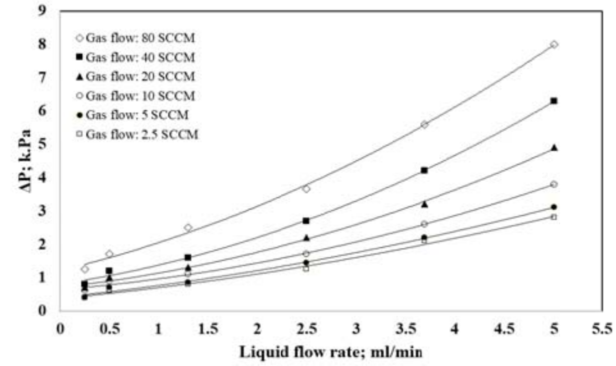

Figure 2: Effect of liquid flow rate on pressure drop in T-Junction rectangular microchannel at temperature 27 ºC and atmospheric pressure

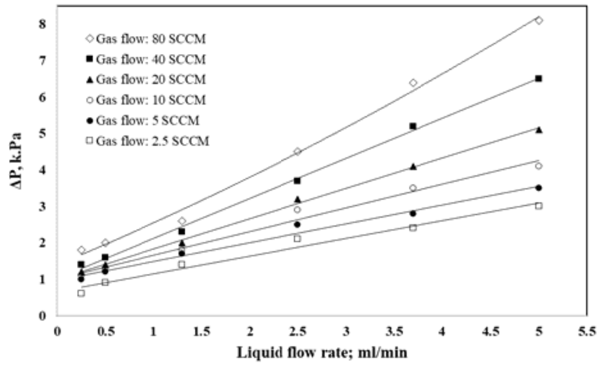

Figure 3: Effect of liquid flow rate on pressure drop in Y-Junction rectangular microchannel at temperature 27 ºC and atmospheric pressure

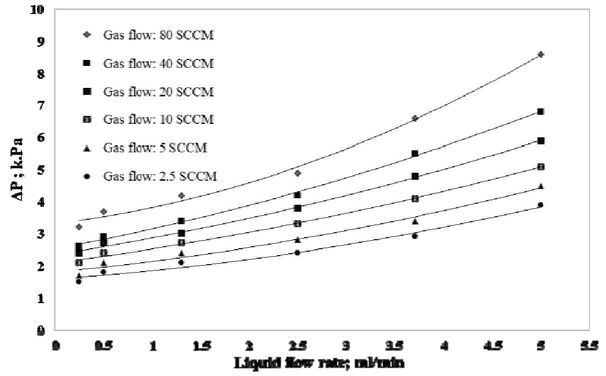

Figure 4: Effect of liquid flow rate on pressure drop Cross T-Junction rectangular microchannel at temperature 27 °C and atmospheric pressure

3.2 Flow Regime Analysis

The flow regimes in microchannels are function of flow rate, hydraulic diameter, inlet junction type and physical property of the fluids. The flow patterns generated in pipes may not be the same in microchannels [29-32]. A two-phase flow pattern was studied by Akbar et al. and Triplett et al. in microchannels [33, 27].

Typical flow regimes appearing in gas-liquid systems in microchannels are briefed here. The bubbly flow, in this type of flow the gas bubbles, were dispersed in the liquid. The gas bubble had a diameter less than the channel's diameter of the channel. These bubbles tend to disperse uniformly in the liquid when shear forces are dominant. Slug (Taylor) flow -the bubbles collide and coalesce to form elongated bubbles or which has a length greater than the channel width is called a slug. In this flow, a thin liquid film of the continuous phase, surrounds the slug separating the dispersed slug and the wall. Annular flow- in this flow type, the gas phase flows continuously (without dispersion) surrounded by a uniform thin liquid film on the wall. The liquid may be trained in the gas core as small droplets. Churn flow - at very high gas velocities or very low gas velocity, almost all the liquid is transported as small droplets at high velocity of a gas or almost all the gas is transported as small droplets at a low velocity of the gas. This type of flow is also known as dispersed or mist flow. All the liquid is entrained as small droplets in the continuous gas phase at high gas shear forces. Wavy flow occurs at greater gas velocities and has waves moving in the flow direction. When wave crests are sufficiently high to bridge the capillary, they form frothy slugs that move at much greater than the average liquid velocity [34].

The images captured during the experiments were used to categorize the four different flow patterns in the microchannels. Flow patterns were recorded the same liquid and gas flow range, in all three junction microchannel. In the T- Junction microchannel, annular flow, slug flow, and bubble flow were observed, while in Y-junction microchannel, wave flow, slug flow, and churn flow were identified and in cross-T-junction, annular flow, slug flow, churn flow and bubble flow were recorded at a different flow rate. Bubble flow was originated at low gas flow, 2.5 ml/min and 3.7 ml/min to 5 ml/min of liquid flow rate in T-junction and cross-T-junction microchannel, but not found in Y- junction. Slug flow was found.

At a given gas flow rate say 2.5 SCCM, and the variation in liquid flow rate from 0.25 to 2.5 ml/min, slug flow shows in all their junctions. After increasing the liquid flow rate from 3.7 to 5 ml/min at 2.5 SCCM in the T-junction and cross -T-junction channels show the bubble flow, while Y- junction shows churn flow. At gas flow rates from 5 to 20 SCCM, slug flow prevailed in the T-junction microchannel entire liquid flow range, which is 0.25 to 5 ml/min. Whereas, slug flow and churn flow are observed in Y-junction at a different liquid flow rate. But slug, churn, annular flow is seen in cross-T-junction. At the higher gas flow rate from 40 to 80 SCCM, wave flow was noticed in the Y-junction whole liquid flow range. At 40 SCCM, in T-junction, annular flow in the liquid flow range of 0.25 to 1.3 ml/min and slug flow after increases of the liquid flow range up to 5 ml/min were discerned, and in cross-T-junction, churn flow and annular flow are confirm from 0.25 to 2.5 ml/min and 3.7 to 5 ml/min of liquid flow range respectively. At 80 SCCM, Annular flow is seen in the complete range of liquid flow rate in T junction, On the other hand, churn flow followed by annular flow in cross-T-junction.

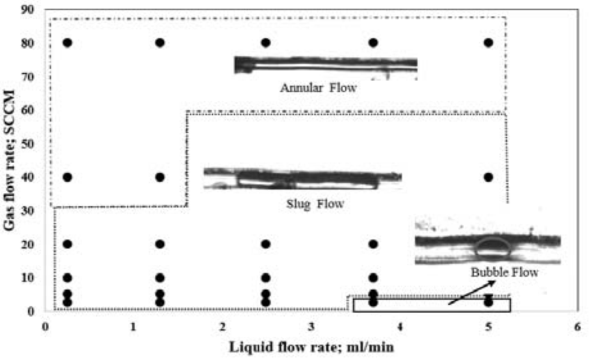

Figure 5: Effect of liquid and gas flow rate on the flow pattern in T- Junction rectangular microchannel at temperature 27 ºC and atmospheric pressure

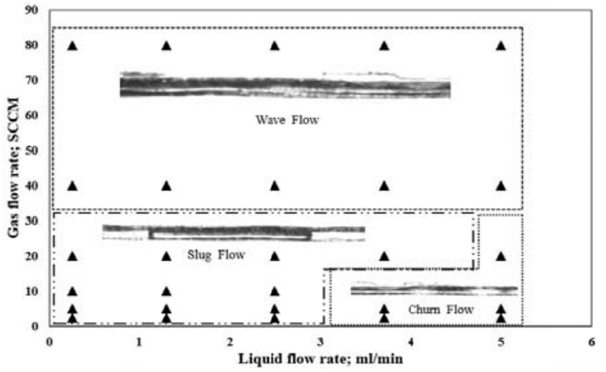

Figure 6: Effect of liquid and gas flow rate on the flow pattern in Y-junction rectangular microchannel at temperature 27 ºC and atmospheric pressure

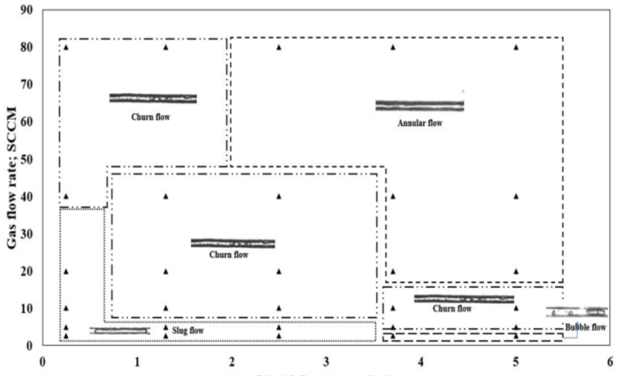

Figure 7: Effect of liquid and gas flow rate on the flow pattern in Cross-T-junction rectangular microchannel at temperature 27 ºC and atmospheric pressure

4. CONCLUSIONS

In this work, the gas-liquid flow was studied in a T, Y, Cross-T-junction microchannels. Flow regimes and the pressure drop characteristics of the two-phase flow was investigated.

I. Pressure drop was evaluated in all three microchannels. The values were similar in both channels. The pressure drop in T junction was in the range 0.40 kPa to 8 kPa, in Y-junction microchannel it was 0.60 kPa to 8.2 kPa and Cross-T-junction microchannel was 1.5 to 8.6 kPa at the given range of the gas and liquid flow rates.

II. The experimental pressure drop results were validated using simulation results from COMSOL Multiphysics, which implements for finite element method. The pressure drop values in both cases were in good agreement.

III. Several flow patterns were observed during the hydrodynamic studies in the microchannels. Flow regimes like bubble flow, slug flow, annular flow, Churn flow, wave flow and combination of them were observed. In the T-junction microchannel, mostly slug flow prevailed.

IV. The size of the slug increased with increases in the gas flow rate and decreased with the increase in the liquid flow rate in all three channels.

V. Bubbly slug flow, annular and wave flows were found to occur at the higher flow rate of the gas and liquid in T-junction microchannel.

VI. In the Y-junction micro-channel, slug flow is formed at lower gas and liquid flow rates. A change in a flow regime from wave flow to annular flow was found to take place at 80 SCCM.

VII. In the cross-T-junction micro-channel, mostly churn flow was observed. Slug flow and annular flow were observed at the low gas flow rate, which is less than 10ml/min. Bubble flow was identified at the high liquid flow rate and the low gas flow rate.

As results show the junction of microchannel plays a significant role in pressure drop and flow regime inside the channel.

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