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FLOW PATTERNS AND PRESSURE DROP OF TWO-PHASE FLOW IN HORIZONTAL CAPILLARY

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Hydrodynamics behavior for two-phase flow was studied in horizontal capillary tube 3mm diameter for monolith reactor. Gas used was air while the liquid phase was water. Different flow patterns were observed for a range of gas and liquid flow rates. Pressure drop was measured across the whole length of tube. Effect of flow rates on bubble length was observed by photographic technique. It was found that pressure drop increases with increasing flow rate of liquid and it showed less dependency on gas flow rate. A correlation has been proposed for pressure drop using these results. It was also observed that Bubble length increases with increasing flow rate of gas.

Keywords: Monolith reactor, Pressure drop, Taylor flow, Bubble flow, Two-phase flow

1. Introduction

Two-phase gas-liquid flow have extensively been studied in a small diameter tube or capillary as a result of interest from chemical industry, where the catalyst is used to increase the rate of reaction that can either used in form of slurry or coated on the channel walls. Increasing interest in the flow on the capillary scale arise from development of monolithic reactor (Figure 1).

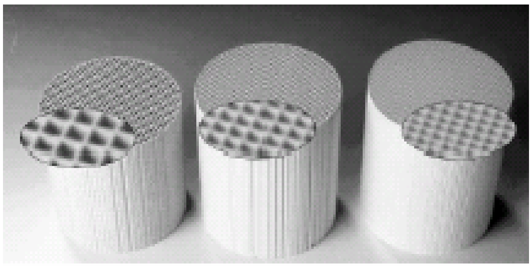

Figure 1. Typical monolith used as catalyst in monolithic reactor.

Monolithic reactor is the type of three-phase chemical reactor that has been using as an efficient reactor in chemical, petroleum, petrochemical and biochemical industries since last few decade [1, 2]. It is made up of large numbers of small diameter parallel channels in a single structure or block manufacture by extrusion process [3]. Channels can be circular, triangular or squared whose inner sides are coated with catalyst. The block is made up of ceramic or metal. Metal is used where the role of heat transfer is more significant [4].

The liquid flow through these channels co-currently or counter currently with gas which flow in the core in the form of train of elongated bubbles called “bubble train flow” or Taylor flow. Liquid remains in continuous phase while the gas phase is dispersed. Large contact area between phases because of large number of parallel channels, Low pressure drop because of laminar flow, excellent mass transfer because of less diffusion distance, no back mixing because of packed bubbles, prediction of behavior of fluid at any time and space coordinates are the advantages that give an edge to monolith reactor on other three-phase chemical reactors [5-9].

Historically, the bubbles were used to determine the liquid velocity inside the capillary till Fairbrother and Stubbs in 1935 [10] performed an experiment and showed that gas bubbles faster than the liquid due to the thin film formed between the bubble and wall of capillary and showed that thickness of liquid film is directly proportional to Capillary Number ‘Ca’. The capillary number is the ratio of viscous stress to the interfacial stress.

$Ca = \mu u/\sigma$

Where μ = viscosity of liquid

U = velocity of bubble

σ = interfacial surface tension

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Taylor in 1960 [11] performed experiment for wide range of Capillary Number. He gave the rough sketch of possible stream lines of counter vortices inside the liquid slug (Figure 2) which were then proven by Thulasidas in 1997 [12] using video imaging technique. Due to this internal recirculation in the liquid slugs of Bubble train flow, the transport of mass and heat between liquid and wall of channels is enhanced as compared to mass and heat transfer in a continuous liquid flow without gas.

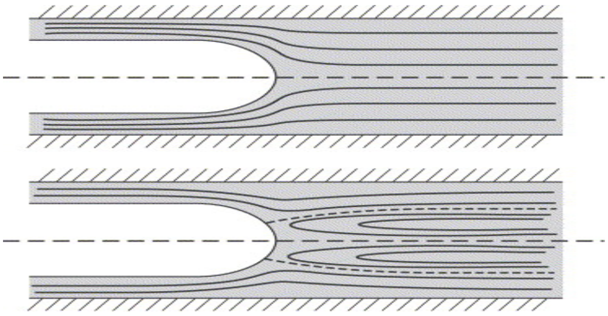

Figure 2. Sketch of possible streamlines for the flow of elongate bubbles in capillaries given by Taylor (1961).

Satterfield and Ozel [13] was pioneer in studying the characteristics of gas-liquid flow in monolithic reactor. They showed that the performance of two-phase flow in single channel of monolithic reactors could be characterized by the two-phase flow in flow in single capillary.

In this study different flow patterns has been observed using photographic technique and is aimed to determined pressure drop at different flow rates. A pressure drop correlation has also been proposed using the results obtained.

2. Experimental Setup

The schematic diagram of experimental setup is shown in Figure 3. A pump pushes the liquid from liquid reservoir into the mixer before which water rotameter was installed that measures the volumetric flow rate of the process fluid. Air was supplied by compressed air cylinder which passes through pressure regulator followed by air rotameter and then inserted into the side arm of the mixer. The two-phase flow that developed in mixer, flow through 5 feet long capillary made of Pyrex glass of 3mm internal diameter. The detailed structure of mixer is shown in Figure 4. Mixer is made up of Perspex block. The block is drilled throughout its length equivalent to internal diameter of glass tube to overcome non uniformity when the fluid enters into the capillary tube. One end of which is connected with water supply while at the other end capillary tube was inserted and sealed with epoxy resin. Side arm is made for air supply and other side arm was made for pressure measurements, which is just 3mm before glass tube ends. At other end of glass tube there is same type of Perspex block but with one side arm only which was connected with differential pressure transducer (DPT), that measure the pressure difference between two ends of capillary tube. Due to the bubble train flow, DTP gave fluctuating values at same flow rate therefore it was connected with data acquisition system where these values were recorded and then averaged for a single flow rate. The pressure drop in 3mm extra length inside the mixer on both side of capillary is assumed to be negligible as compared to pressure drop across the whole length of the tube. Capillary was kept horizontal. Air and water were allowed to flow co-currently whose ranges are given in Table 1. Snap shots of flow were captured using digital camera with shutter speed 1/250 s^{-1} which were then observed using computer.

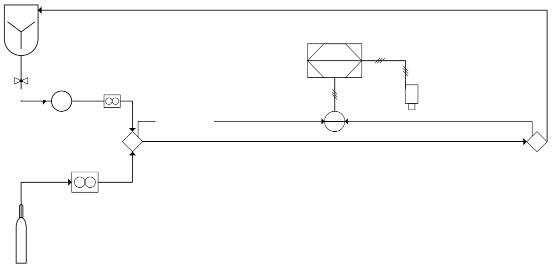

Figure 3. Schematic diagram of experimental setup.

Table 1. Flow rate ranges (ml/min).

Fluid	Minimum	Maximum
Air	100	350
Water	50	350

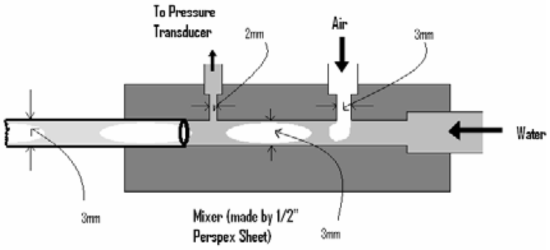

Figure 4. Detailed diagram of Mixer.

3. Results and Discussion

3.1 Flow Patterns

Flow patterns observed in two phase flow are shown in Figure 5.

Figure 5. Observed flow patterns. (a) Annular flow; (b) Annular to Taylor transition; (c) Taylor flow; (d) Taylor to Bubbly transition; (e) Bubbly flow; (f) bubbly to churn transition

3.1.1 Annular flow

At very high gas flow rate and very low liquid flow rate annular flow was observed (Figure 5a). In annular flow gas flow in the inner core of capillary as a continuous phase while liquid flow in form of film at the walls.

Lowering the gas flow rate first the transient state of annular to Taylor (bubble train flow) was observed (Figure 5b) and then Taylor flow was achieved (Figure 5c) comparatively at high flow rate of gas than liquid.

3.1.2 Taylor flow

Taylor flow is the most stable flow regime. It is the train of fully packed bubbles in regular and well define manner separated by the liquid slugs of almost equal lengths. Bubbles are elongate and cylindrical in shape with more front curvature then back. Liquid film always remained there between the bubbles and walls of channel.

Increasing the liquid flow rate lowers the length of bubble but it remains Taylor flow till the length of bubble becomes equals to channel diameter. Figure 5d shows the transient state of Taylor to bubbly flow. Such pattern was observed at almost same liquid and gas flow rates. At low flow rates this transient state give regular pattern of bubble and liquid slug but at high flows it become irregular and length between two bubbles varies but the bubble length remains constant.

3.1.3 Bubbly flow

At liquid flow rate comparatively higher than gas flow rate bubbly flow regime was found. In such type of flow bubbles do not remain fully packed and their length becomes less than the capillary diameter therefore bubbles hang to the upper section of capillary.

3.1.4 Churn flow

At high flow rates of both phases churn flow was observed. This flow pattern is most irregular and chaotic because of turbulence. Flow rates are high enough that most of two successive bubbles break the liquid slug and coalesce to form large bubbles. This phenomenon of coalescences was also observed in transient state of Taylor to annular flow where the liquid slug between very long bubbles is small enough that it could not sustain for long.

3.1.5 Bubble length

Length of bubble length increases with increase in flow rate of gas (Figure 6) and decreases with increase in flow rate of liquid (Figure 7).

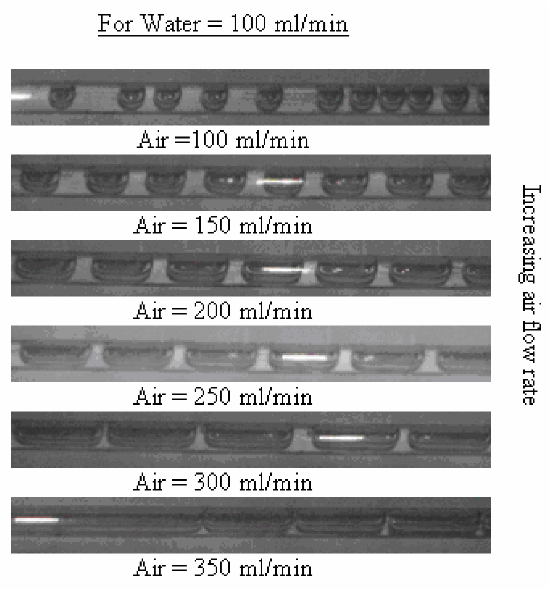

Figure 6. Effect of increasing air flow rate on bubble length.

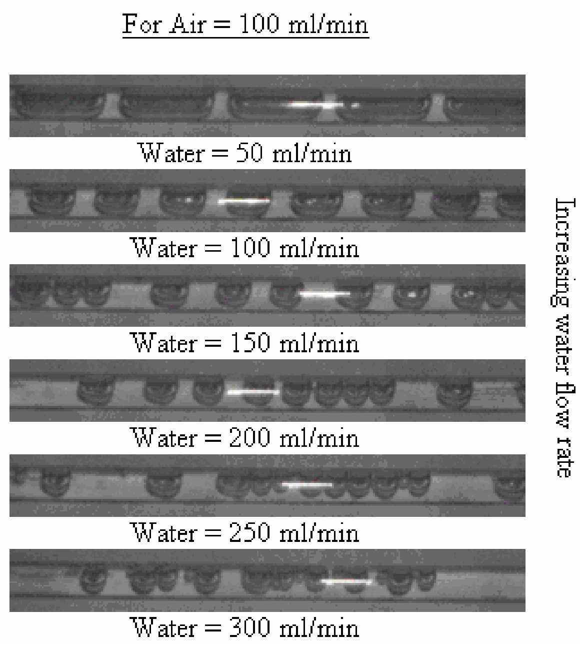

Figure 7. Effect of increasing liquid flow rate on bubble length.

3.1.6 *Pressure drop*

Pressure drop for two-phase flow (air-water system) was measured and plotted against different flow rate of fluids. The effect of increasing liquid flow rate and increasing gas flow rate are shown in Figure 8, 9.

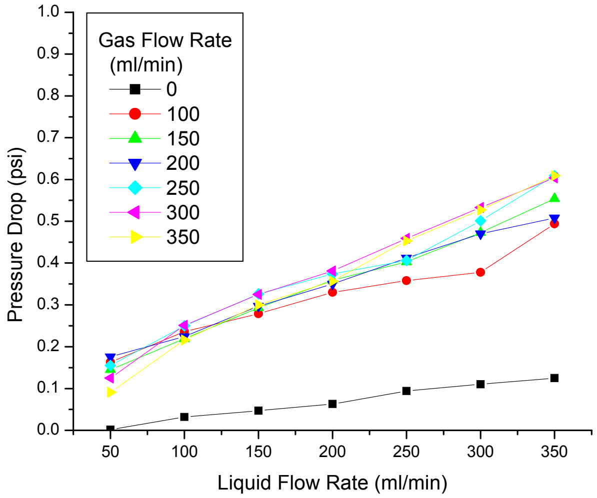

Figure 8. Effect of liquid flow rate on pressure drop.

Results shows that pressure drop increases with increases liquid flow (Figure 8) rate but it shows very less dependency on gas flow rate (Figure 9). The total pressure drop in Taylor flow results from the combination of gas bubbles and liquid slugs but as the shearing force on liquid film exerted by gas bubbles is so small that it can be considered negligible therefore Equation (1) developed for pressure drop by liner fitting of figure 8 is based only on liquid flow rate.

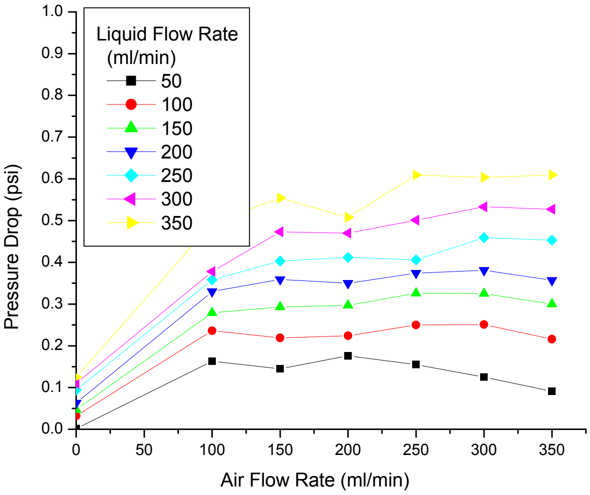

Figure 9. Effect of gas flow rate on pressure drop.

$$\Delta P = 0.0013Q + 0.895 \qquad (1)$$

Where ΔP = Pressure drop (Psi).

Q = Volumetric Flow rate of liquid (ml^3/min)

4. Conclusions

The two-phase gas-liquid co-current horizontal flow behavior was studied for air-water system in capillary tube of 3 mm internal diameter. Annular, Taylor and bubbly flow regime was observed. Flow regimes observed were similar to those found in literature. Taylor flow was found to be the most stable and well-ordered flow pattern. In Taylor flow, length of bubbles increases with increasing gas flow rate and decreases with increasing air flow rate. Pressure drop was also measured at different flow rates and it is concluded that the pressure drop across the whole length of capillary for Taylor flow is more dependent on liquid flow rate rather than gas flow rate.

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