Fouling Reduction in Ultrafiltration using Gas Flow Injection

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Abstract

The influence of two-phase flow patterns especially slug and bubble patterns has been investigated in the recent studies of effect of gas injection on membrane fouling. The consequences demonstrate that slug flow is more effective than bubble flow in terms of enhancing shear force and permeate flux. In this paper, an experimental study is performed to investigate the fouling reduction in an ultrafiltration process using gas flow injection. The effect of slug and bubble patterns on permeate flux in the ultrafiltration process in a flat sheet module is analyzed with a video system facilitated with a high speed camera. The characteristics of bubbles such as their distribution and velocity are measured by image processing. The results show that the amounts of fluctuating and average velocity of the slug flow were larger than those of the bubble flow. The higher velocity of bubbles in the slug flow enhances permeate flux more.

Key words: slug flow, bubble flow, image processing, membrane fouling, ultrafiltration

Nomenclature

CP	Concentration Polarization
J	Permeate flux
J_o	Permeate flux of initial time
L	Length of flow cell
W	Width of flow cell
U	Velocity in X direction
V	Velocity in Y direction
VOF	Volume of fluid
S	Membrane area
ρ	Density
TMP	Transmembrane pressure
Δm	Mass interval
Δt	Time interval

1. Introduction

Gas injection is one of the most effective ways to ameliorate membrane fouling by enhancing shear force. As a matter of fact, bubbles, injected to generate two-phase flow, increase turbulence intensity which in turn increase shear force. One of the most significant problems of advanced ultrafiltration technology is membrane fouling which not only increases the operational costs but also causes the delays in filtration process for membrane cleaning purposes. The main reason of fouling is Concentration Polarization (CP) [1] which is the tendency of material to accumulate at the surface of the membrane [2]. Any process that limits the CP is a suitable way to ameliorate the membrane fouling. The CP can be reduced by several available choices: turbulence promoters [3, 4], pulsatile flow [5], vortex generation [6], gas injection or bubbling [7] and ultrasound [8].

Gas injection decreases membrane fouling dramatically by enhancing shear force [9]. In fact, the high efficiency in fouling decrease, on one hand, and less detrimental effects on the environment, on the other, has led to the extensive use of gas injection. One of the most common strategies for gas bubbling is to inject gas into the liquid phase. In recent experimental studies, several factors that affect the gas injection have been studied. Fu et al. [10] examined the effects of aeration (air injection) flow rate, aeration time and aeration position on membrane fouling in a submerged membrane bioreactor. The results showed that the aeration flow rate is more significant than aeration position, and the aeration time is less significant than aeration position. The effect of intermittent and continuous gas injection has been investigated by Tian et al [11]. They found that the continuous gas injection is more effective for alleviating the amount of transmembrane pressure (TMP) than intermittent gas injection. Ceron-Vivas et al. [12] investigated the effect of gas injection combined with intermittent filtration on the membrane fouling. The results showed that this method was an effective operation strategy in order to reduce the membrane fouling. Among all different types of two-phase flow, slug and bubble flows are the most used patterns because of their relatively low gas flow rates [9]. In numerical studies, a well-known method for tracking the free surface of a liquid is volume-of-fluid (VOF) technique [13]. Therefore most of the CFD modeling of two-phase flow in modules is based on the VOF technique. The slug flow ultrafiltration process in tubular membranes was modeled with the commercial software FLUENT at two parts by Taha and Cui [14]. In the first part, the properties of the slug and the distribution of local wall shear stress in the membrane tube were calculated; in the second part, a connection between the local wall shear stress and the local mass-transfer coefficient was established. The shape and the motion of a spherical cap bubble in flat sheet module was simulated by Essemiani et al. [15]. The major problem of this model was that wall shear stress and pressure distributions in the flat sheet module were not calculated. Wei et al. [16] simulated a single 3D slug bubble rising in a flat sheet module. The results showed that increasing the size of bubble enhanced the induced shear stress in the module.

The missing pieces of these studies are an investigation on the characteristics of bubbles in various two-phase flow patterns especially slug and bubble flows, and their effect on the membrane fouling and permeate flow. The objective of the present paper is an experimental study on the slug and bubble flows in a flat sheet module in which the effectiveness of two-phase flows on membrane fouling will be investigated by a precise analysis of properties of bubbles using image processing technique.

2 Experimental

2.1 Setup

The experimental setup used is shown in Figure 1. The system consists of a feed tank, a peristaltic pump (Deng Yuan, Taiwan), a gas flow meter (Azmoon Motamam, Iran) for the gas flow, a rotameter (Azmoon Motamam, Iran) for the liquid flow, a digital balance (A&D, Japan) for measuring permeate flux and a flow cell. The flow cell, shown in Figure 2, is made from 2cm thick PMMA plates and has a rectangular channel of 0.5cm×10cm for the flow. The flow cell was positioned vertically for all experiments. Polyethersulfone flat sheet membrane (Sepro, USA) with an effective membrane area of 300 cm^2 was placed between these thick plates. All experiments lasted for about 30 minutes in a fixed room temperature after which the membrane was renewed for the next experiment. In order to generate slug and bubble flows at the entrance of flow cell [17], the liquid flow rates were selected 75 $^{lit}/_{hr}$ and 150 $^{lit}/_{hr}$, with a gas flow rate kept constant at 60 $^{lit}/_{hr}$. A high speed camera (Sony, Japan) with a Zoom lens (Canon, Japan) was used in order to observe two phase flows. The camera at a working distance of 50 cm was connected to a PC. This system was recorded at a frame rate of 400 fps at a resolution of 1920 × 1080 pixels.

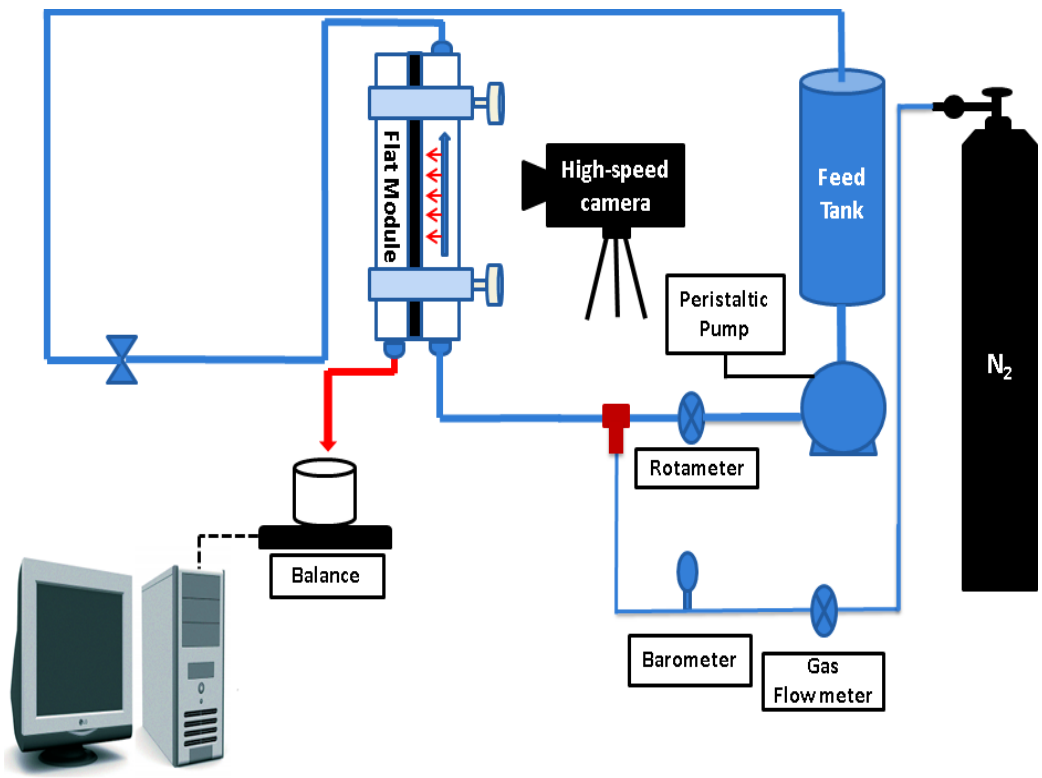

Figure 1: Experimental setup of cross flow ultrafiltration with gas bubbling injector

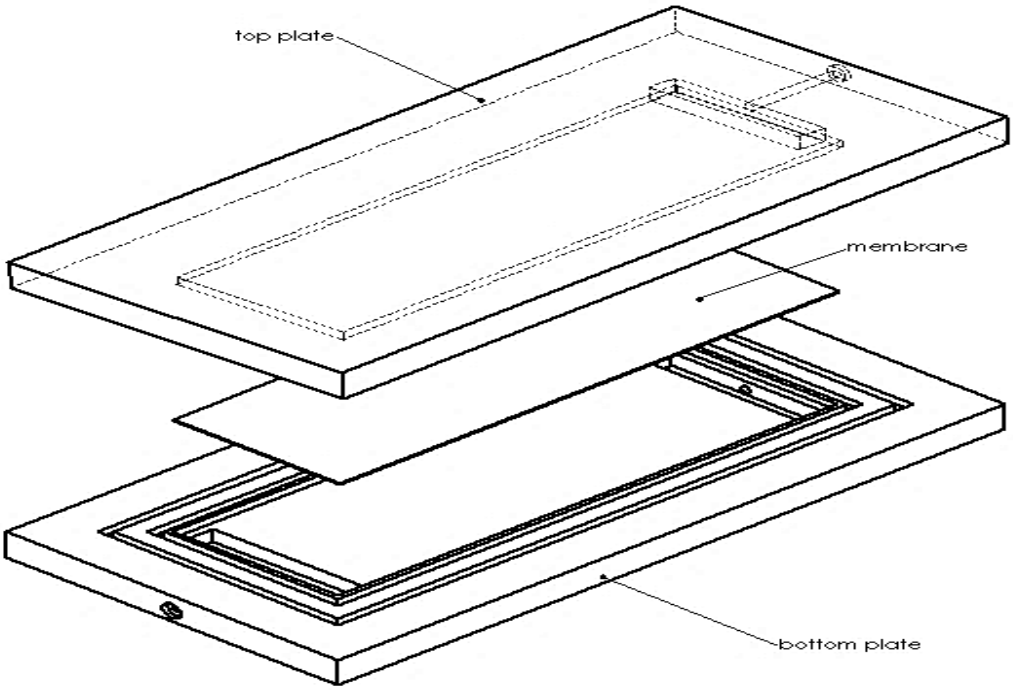

Figure 2: Schematic representation of the flow cell

2.2 Materials

Nitrogen with a purity of 99.97% was used as the gas phase and skimmed milk was used as the liquid feed for the ultrafiltration process. For image processing purpose, the liquid phase was demineralized water instead of skimmed milk since it improves the identification of bubbles. It should be noted that the physical properties of demineralized water and skimmed milk are very similar as shown in Table1.

Table1: Physical properties of demineralized water and skimmed milk

material	**Density** (Kg/m^3)	**Viscosity** $(centipose)$
skimmed milk	1032	1.470
demineralized water	998	1.002

2.3 Image processing

In order to obtain the velocity of bubbles, the video movies captured from the experiments was conducted utilizing image processing toolbox in the MATLAB software where the edge detection methods and strategies are employed. The edge is the boundary between the object which is to be extracted and the background. For this reason, the edge will distinct the object from the background. This technique in image processing is applied in numerous applications such as face recognition, image segmentation, and image enhancement. Consequently, it is vital to improve the accuracy of edge detection. In order to detect the bubbles accurately in a background of fluid flow, it is necessary to detect and extract an accurate edge. Traditional edge detection methods are conducted using Roberts operator, Sobel operator, Prewitt

operator and LOG operator. All of these mentioned operators are local window gradient operators which are interesting because of their simple methodology and fast detection. Nonetheless, they are more affected by noise [18]. Consequently, these methods are not completely suitable in experimental studies. In 1986, John Canny [19] suggested a new criterion based on which he could find an optimal edge detection operator, Canny operator.

3 Results and Discussion

In the present study, two-phase flow patterns (slug and bubble flow) were experimentally investigated to study their effects on the permeate flux. For this purpose, the permeate flux was measured in different cases and the characteristics of bubbles in flow was analyzed by using image processing with the MATLAB software. The permeate flux (J) was measured by using the following equation:

$$J = \frac{\Delta m}{\rho \times S \times \Delta t} \tag{1}$$

where Δm and Δt are mass and time interval, respectively.

3.1 Permeate flux

In order to examine the effectiveness of two-phase flow patterns, the permeate flux was shown in non-dimensional form $\left({}^{J}/_{J_o}\right)$ where J_o is the initial permeate flux. As can be seen in Figure 3, the permeate flux was increased significantly by the bubbling treatment. Due to a higher turbulence, the slug flow was more effective than the bubble flow in fouling reduction of the membrane.

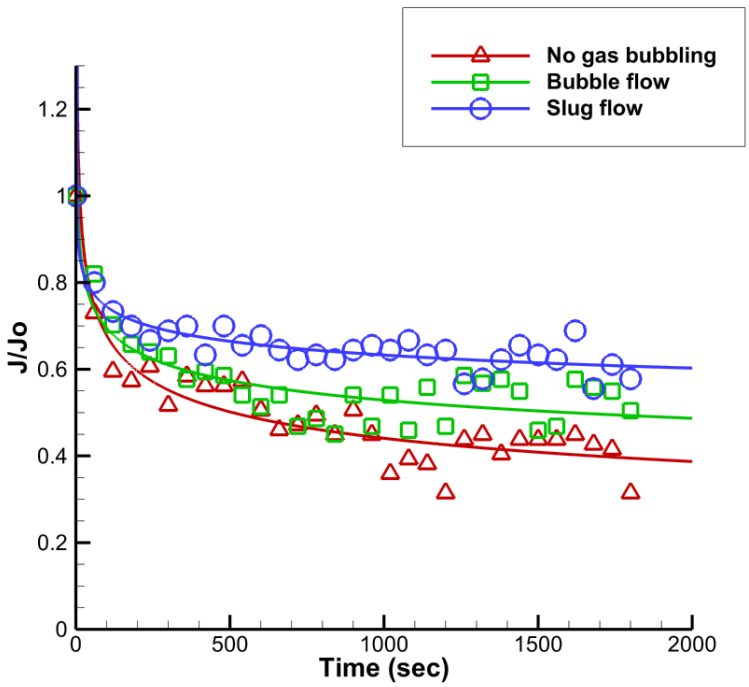

Figure 3: Permeate flux under different two-phase flow patterns

3.2 Bubbles distribution

The characteristics of bubbles in flow such as their distribution and velocity were identified and tracked over a period of 0.3 seconds; the results are displayed in Figures 4-6. It can be seen clearly that:

- The size of gas bubbles were less in bubble pattern than in slug pattern.
- The bubbles X position in both flows fluctuated in time. The period of fluctuation, however, was more pronounced in slug flow.
- The bubbles Y position in both flows grew moderately in time.

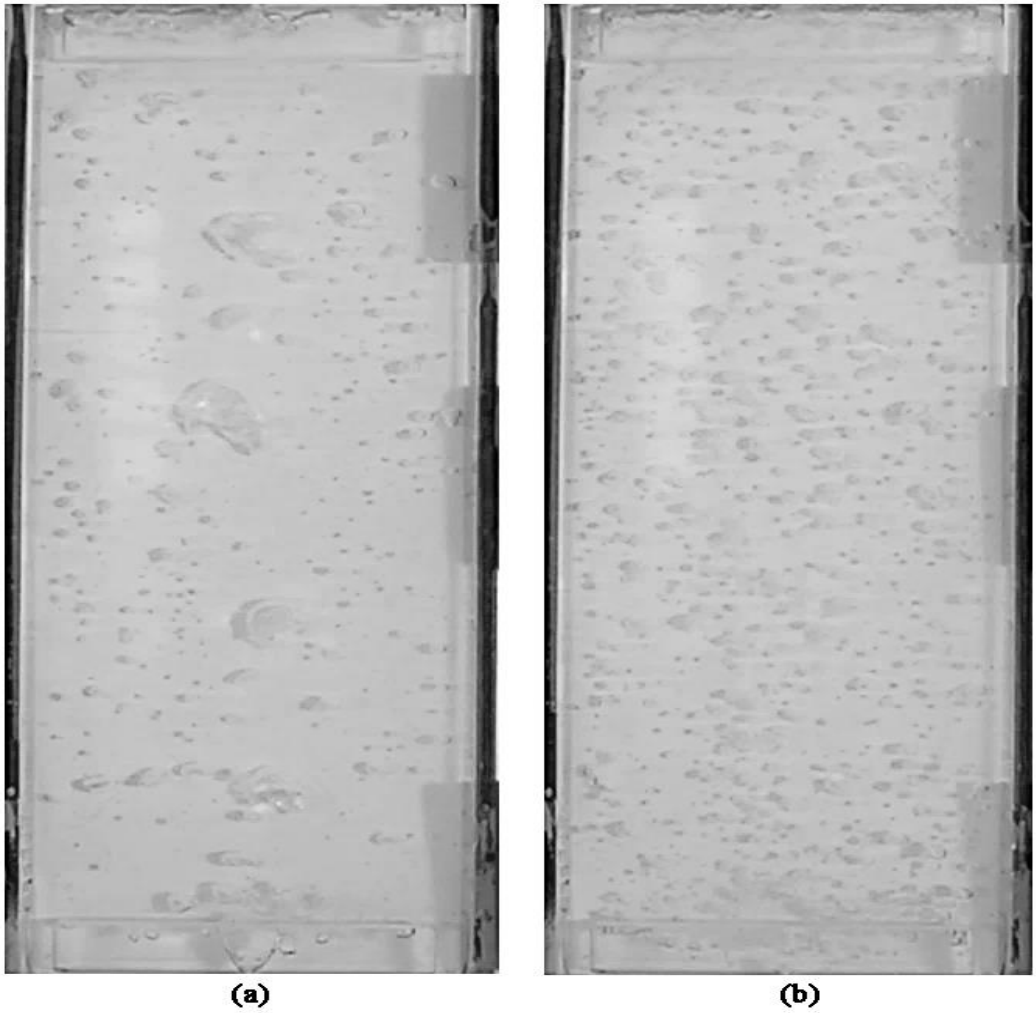

Figure 4: Bubbles distribution in (a) slug flow and (b) bubble flow.

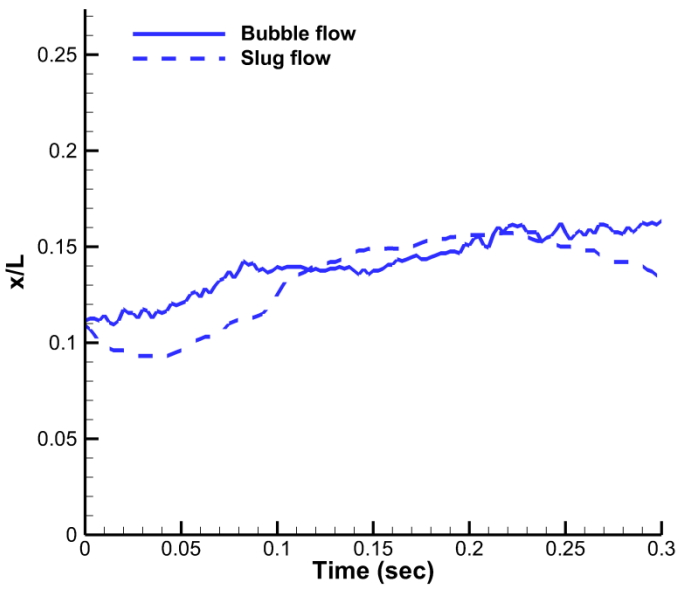

Figure 5: Time trace of X position

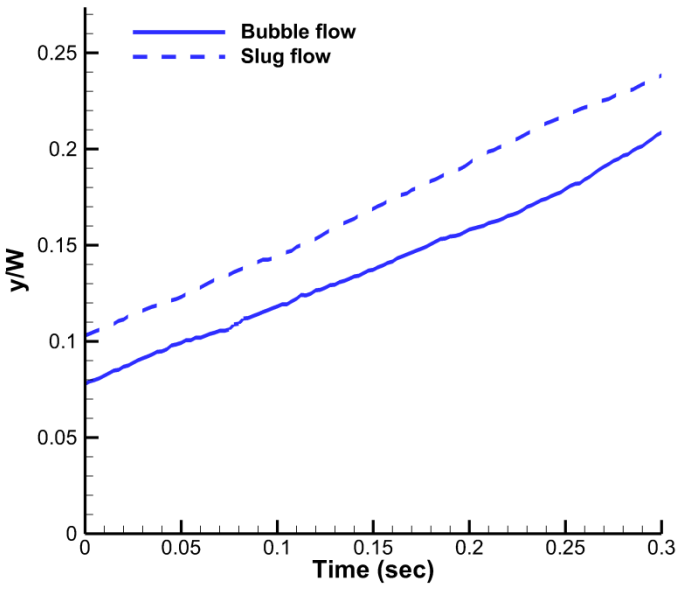

Figure 6: Time trace of Y position

3.3 Bubbles velocity

The bubbles velocity were calculated in both X and Y directions. According to Figures 7 and 8, average velocity in X direction is smaller than that in Y direction in both patterns. As far as velocity in X direction is concerned (Figures 7a and 8a), the fluctuating velocity in X direction of the bubble flow was bigger than that of the slug flow. However, the amounts of fluctuating and average velocity in Y direction of the slug flow were larger than those of the bubble flow (Figures 7b and 8b). This resulted in more collision of bubbles in the slug flow which ultimately led to more turbulence.

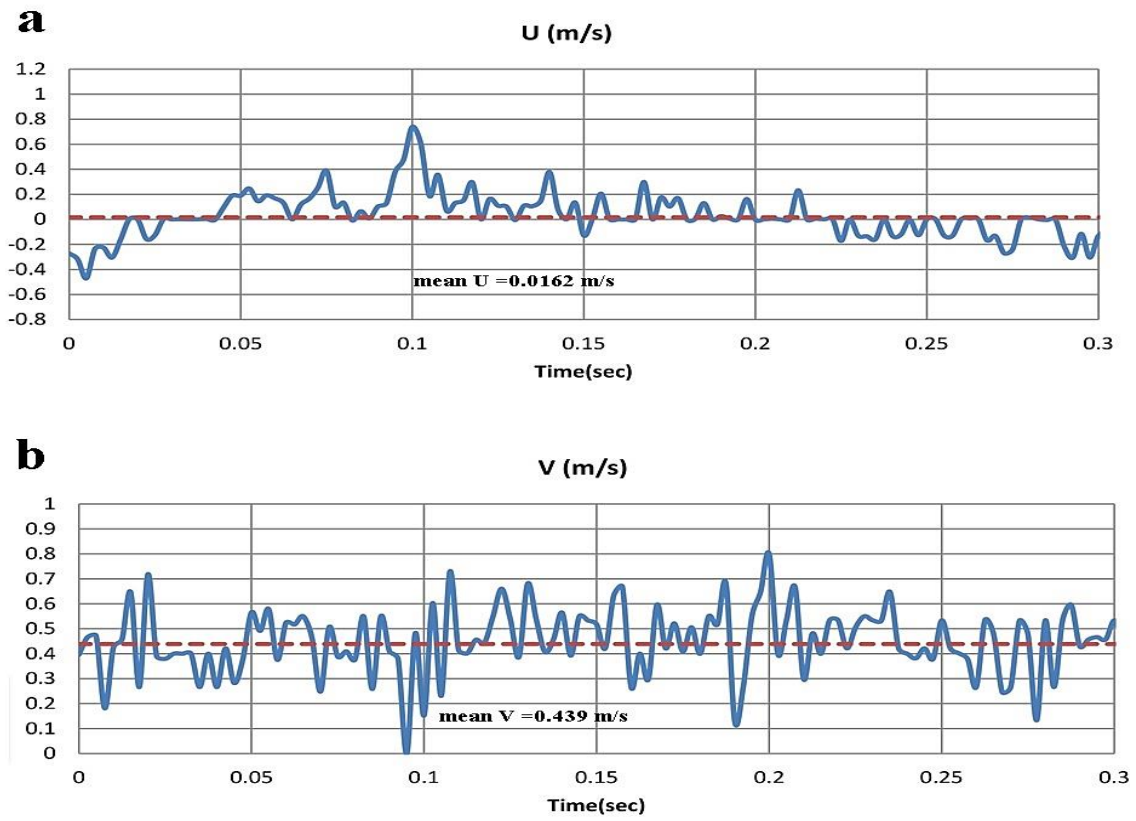

Figure 7: Velocities of bubbles of slug flow over a period of 0.3 seconds. a) velocity in X direction b) velocity in Y direction

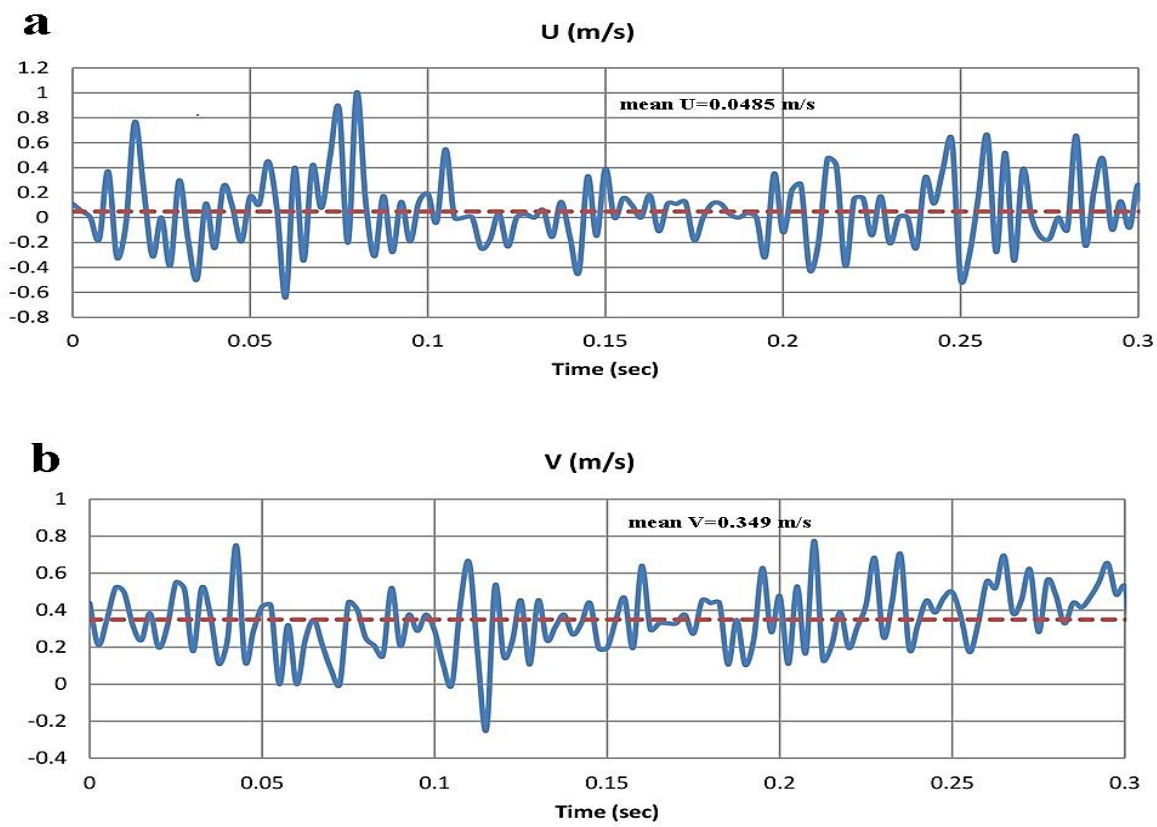

Figure 8: Velocities of bubbles of bubble flow over a period of 0.3 seconds. a) velocity in X direction b) velocity in Y direction

4 Conclusion

In this paper, the multiphase flow patterns through a flow cell were studied with a video system facilitated with a high speed camera. Firstly, the effectiveness of two phase flow patterns was shown with permeate flux measurement over fouled flow cell. Based on the results, the slug flow was found to be more effective than the bubble flow in increasing the permeate flux. The characteristics of bubbles in flow such as their size, distribution, and velocity were also analyzed based on image processing technique. The results showed that significant differences can be seen between the two patterns. For the same gas flow rate, the velocity and size of bubbles were larger in the slug flow which in turn enhanced the turbulence and shear force leading for more permeate flux.

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