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Studies of Air Slug Distributions and Preliminary Membrane Fouling by Optical Monitoring in a Side-Stream Membrane Module

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Abstract: This article is aimed to propose an alternative method to characterize an air/water flow and new designs of rotating air distributors for membrane fouling control in a side-stream membrane module for a membrane bioreactor. A new optical sensor technique was experimentally demonstrated for the characterization of slug flows in a tubular ultrafiltration membrane module. The experimental results showed that the optical sensor system had high sensitivities for measurements of slug velocities, lengths, and frequencies in each membrane tube. The phenomena of slug coalescence/spilt were discussed. The rotating air distributor significantly improved the air slug distributions and had the potential to reduce the membrane fouling.

Keywords: Cross-flow filtration, membrane bioreactor, optical sensors, two-phase flow distribution

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INTRODUCTION

A two-phase flow using air bubbles or slugs can enhance the performance of membrane processes and significantly reduce membrane fouling (1). For flow inside a tube or hollow fiber air slugs are favored over bubbles because of the higher shear stresses generated and improved fouling control (2,3). An important application of the two-phase flow is the side stream membrane bioreactor (4). In such a system the membrane module comprises multiple parallel tubes, or large bore hollow fibers mounted vertically. Homogeneous distribution of slugs over the cross-section of the module is required to achieve an optimum fouling control in the side-stream MBR. The hydrodynamic characteristics of air slug flow have been investigated both computationally and experimentally for a single tube and multi tubes in membrane modules. Methods such as the infrared (IR) beam-based technique (5,6) and the electrical conductivity probe based technique (7) have been used to study the hydrodynamics of slug flow in a single membrane hollow fiber and in a transparent tube. These "direct" methods can provide real-time data on the two-phase flow characteristics. The electrical conductivity probe technique relies on the differences in electrical conductivities between air and water. In the reported study (7) the conductivity probes were connected in series and tested with a transparent PVC tube to determine the void fraction, and bubble rise velocity. However, the stainless steel ring electrodes for the conductivity probe technique needed to be inserted inside the tube for conductivity measurement and this can disturb the air slug flow since lengths and velocities of slugs may be prolonged and increased when the cross-section area inside a tube is reduced. The IR beam method (5,6) is based on the IR light transmittance through the tubular membrane providing important hydrodynamic characteristics such film thickness, bubble rise velocity, and bubble shape inside a single hollow fiber. The differences in the degrees of IR light transmittance between air and water were analyzed to generate the analog signals for bubble flows. The shapes of bubbles can be determined (indirect visualization). However, sizes of both emitting and tracing IR photodiodes were relatively large which may require a large space for installation. In addition, one pair of the photodiodes can be used to monitor the bubble flow in only one membrane tube. These cause a difficulty to monitor inner membrane tubes in the bundles in an actual side-stream membrane module, and the IR technique has not been used to date to study simultaneously the two-phase flow characteristics in a multi-tube array. Therefore, the direct methods have not been successfully applied for the two-phase flow characterizations in the multi-tube membrane modules.

Characterization and hydrodynamic studies of the air-water flow for the multi-tube modules have also been performed by "indirect" techniques in which only some average characteristics were measured. The equipments and procedures of the indirect methods are conventionally installed and externally performed to monitor the effluent of air/water flow leaving from the modules. Water distribution and water flow velocities were measured by gravimetric methods (8,9) in which water from each tube was collected over a period of time. However, this did not give a simultaneous measurement of all tubes or temporal variations within an individual tube. The distribution factors of water and the uniformity coefficients of water velocity over a cross section in the membrane module were determined. In another work, a photographic method (10) was used to determine the air distribution and to measure bubble sizes, and gas volume ratios in a membrane module in order to compare different types of membrane aerators. Transparent PVC tubes were horizontally positioned and connected to the outlet of a vertical membrane module equipped with different aerators and photographs of the flow in individual PVC tubes were taken and analyzed. However, neither weighing nor photographic methods can measure the bubble rising velocity or its distribution in the membrane modules although these bubble characteristics play a most important role in the control of membrane fouling. In addition, these indirect methods are likely to have low sensitivity and are not suitable for a real-time measurement.

In order to obtain the information on individual slugs or bubbles in individual tubes in a membrane module in real time, we have adapted the IR beam technique of Cui and coworkers (5,6) used in their single tube measurements since the utilization of the IR beam allows high sensitivity in the measurement. In this investigation we have developed and demonstrated a method incorporating highly sensitive IR optical sensors (originally used for a water level control) for air-water flow characterizations in a side-stream membrane module. The IR optical sensors were selected in this study because the sizes of the optical sensors were relatively small to be installed in an external multi-tube array. The IR optical sensors proposed in this study relied on the different principles from the IR beam method (5,6). The effects of air and water flow rates on the hydrodynamic characteristics of air slug flow and on the air slug distribution over the cross section in a membrane module have been investigated. The distribution factors of the hydrodynamic characteristics such as bubble rise velocity, bubbling frequency, slug length, and void fraction have been determined and discussed. In addition, a novel rotating air distributor has been evaluated for improved distribution and better fouling control in side-stream membrane filtration.

MATERIALS AND METHODS

The experimental setup for air-water flow characterization by the optical sensor technique is shown in Fig. 1. An OMRON optical sensor system was used, comprising the Omron photomicrosensors EE-SPX613, and the programmable controller, Omron SYSMAC CJ1 M. The photomicrosensors (optical sensors) with infrared (IR) LEDs are designed to detect water levels in transparent tubes or pipes and are already optically calibrated by OMRON. The sensors have light emitters and receivers for an infrared (IR) light to monitor the bubbles by detecting the difference in refractive indexes between air and water. The emitted IR light is reflected by the tube wall and reaches the light receiver if air is passing the sensor. If water is passing the sensor, the emitted IR light must pass through the water and will not reach the light receiver. Digital signals from the optical sensor are '1' if air passes the sensor and '0' if water passes the sensor. Details of the photomicrosensor are provided in Table 1. The optical sensors have built-in amplifiers and sensitivity selectors providing flexibility for operations. The aim was to monitor bubbles/slugs from each membrane tube and to facilitate this, a short section of transparent (acrylic) tube was connected to each membrane tube. Two optical sensors connected in series were vertically mounted in each acrylic tube with distance of 5 cm, shown in Fig. 2(a). The

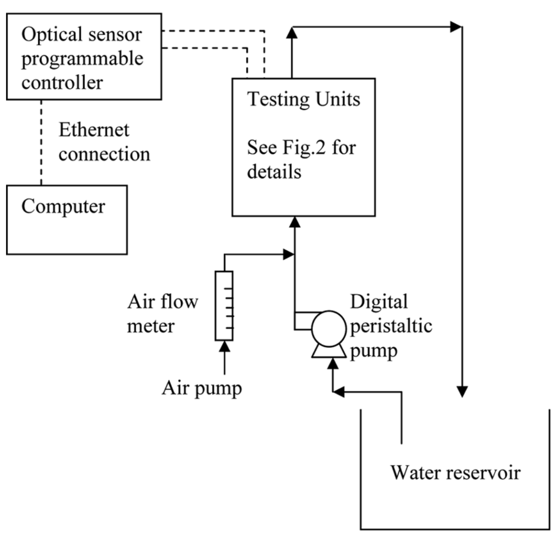
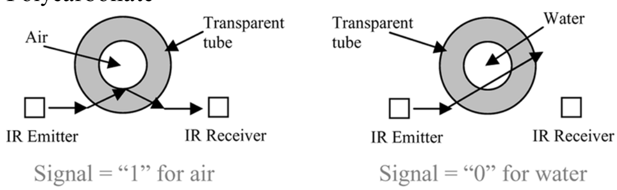


Figure 1. Experimental setup for air-water flow characterization by optical sensor system.

Table 1. Details for photomicrosensor OMRON EE-SPX 613

Type and output configuration	Slot type, selectable dark-on or light-on
Operating ambient	Temperature: −10 to +55 C Humidity: 5% to 85%
Light source	Infrared LED with a wavelength of 940 nm
Current consumption	30 mA
Overall dimensions (L∗W∗H)	17 mm × 26 mm × 16 mm
Material for body	Polycarbonate
Air/water detection and sensor signals	

controller and computer were linked by an ethernet connection. Software provided by OMRON for the SPU and EDMS consoles were used to operate and control the optical sensor system.

The experiments to evaluate the slug flow distributions using the optical sensor-based technique and the effect of the rotating air distributor consisted of 3 parts:

(i) hydrodynamic experiments for a single transparent tube,
(ii) hydrodynamic experiments for multiple membrane tubes with and without rotating air distributors, and
(iii) a preliminary evaluation of membrane fouling control by the rotating air distributors in cross-flow filtration.

A transparent acrylic tube with an inner diameter of 5.1 mm was employed for the single tube experiments to evaluate the performance of the optical sensors, shown in Fig. 2(a). The single tube experiments were used to determine the average hydrodynamic characteristics (see section 2.1 for detail) of bubble rise velocities, bubbling frequencies, void fractions, and slug lengths which were subsequently used for the calculation of the distribution factors (Eq. (1)). The second set of experiments was to determine the distributions of air-water flow over a cross section of the membrane module with and without the rotating air distributors for a range of air and water flow rates. The bubble velocities and number of bubbles/slugs in each membrane tube in the module were measured.

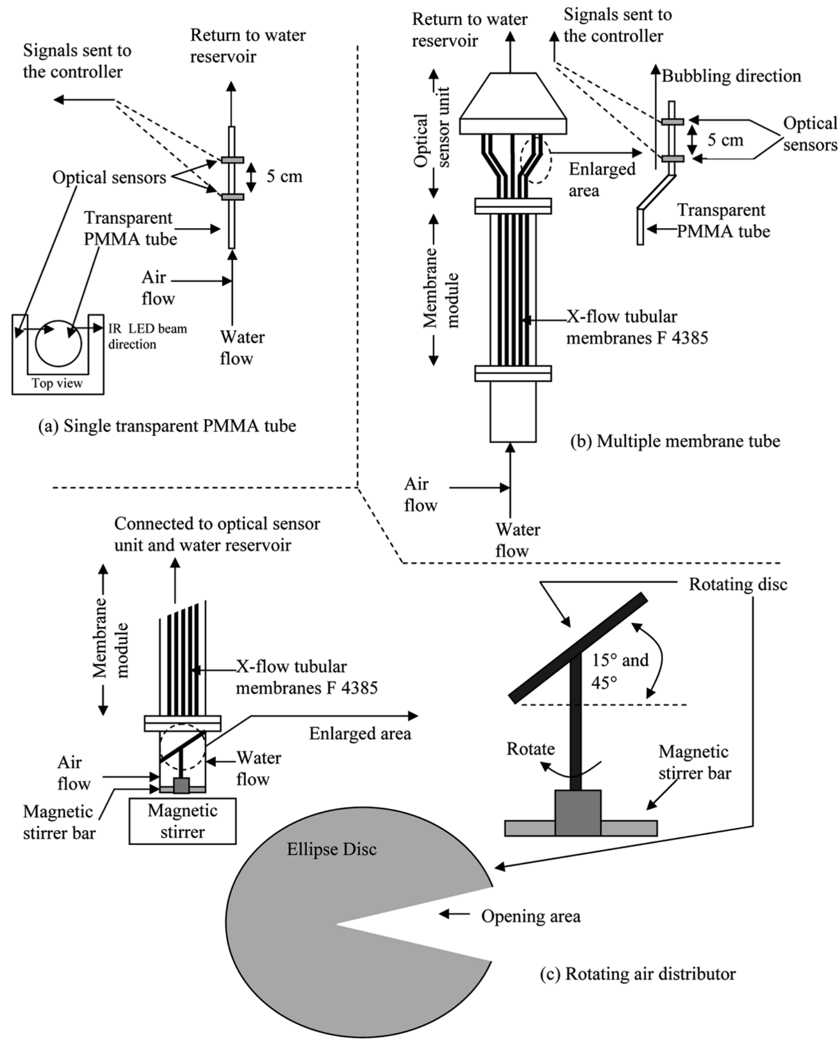


Figure 2. Installations of optical sensors and rotating disc for two-phase flow characterization. (a) Single transparent PMMA tube; (b) Multiple membrane tube; (c) Rotating air distributor.

The third set of experiments involved a cross-flow filtration of mixed liquor suspended solid (MLSS) to determine the fouling control efficiency achieved by the rotating air distributors.

Nineteen X-flow tubular UF membranes (F 4385, hydrophilic PVDF, 5.2 mm inner diameter) were mounted and potted in the acrylic

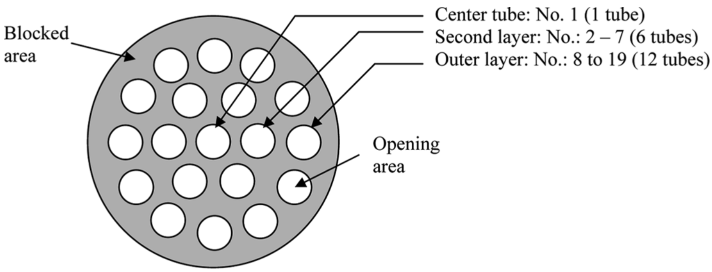


Figure 3. Layout of tubular membranes in the side-stream membrane module.

module with the layout shown in Fig. 3. The module had an effective module length of 17.5 cm and effective membrane area of 543.2 cm^2. The membrane tubes were numbered 1 to 19. The optical sensor system was located above the membrane module and consisted of nineteen transparent acrylic tubes (5.1 mm ID) which were precisely connected to the module and membrane tubes as shown in Fig. 2b. The slight difference in inner diameters between the transparent tube (5.1 mm) and membrane tube (5.2 mm) was assumed to give negligible disturbance to the two-phase flow.

The rotating air distributors were developed to improve the air-water flow distribution in the module, depicted in Fig. 2(c). The concept allows the flows of water and air to be directed to a small sector of the module cross section. The slow rotation exposes all of the membrane openings to an intensified flow with the aim reducing slug maldistribution. The rotating distributors tested had a sector-shape opening area equal to 16% of the total area. High grade acrylic sheets and rods were used to make the rotating disc sets. A magnetic bar was connected to the disc, and an external magnetic stirrer was used to control the rotation speeds for the distributors. The efficiency of the new distributors for the slug flow distributions may depend on

(i) shape and size of open area,
(ii) the angle of the rotating disc, and
(iii) the speed of rotation

Disc angles of 15 and 45° (see Fig. 2(c)) and rotation speeds of 4, 8, and 15 rpm were used in the experiments.

Sensitivity of the optical sensors was maintained at 2 millisecond (ms) for all experiments (signals taken and sent every 2 ms). The multi-sensor unit allowed the hydrodynamic characteristics of air bubbles/slugs in all tubes to be measured simultaneously. The optical sensor system was preliminarily tested under relative low water velocities in this paper and the experiments under higher water velocities will be reported in the future. Superficial velocities ranged from 1.07 to 8.59 cm/s for water flows (flowrates: 250–2000 ml/min) and 2.15 to 6.44 cm/s for air flows (flowrates: 500–2000 ml/min) with air-to-water flowrate ratios of 0.33–6. A single-orifice aerator (3 mm diameter) located in the central position of the cross section was used for aeration. At each experimental condition, data were collected over 15 seconds, and this was repeated 3 to 4 times at each condition.

The digital signals of slugs in each tube were recorded chronologically by the optical sensor system. Microsoft Visual Basic in Excel was used to analyze the signal records of the air slugs and then bubble rise velocities, bubble/slug lengths, bubbling frequencies and their distribution were calculated, and phenomena of bubble coalescence and splitting in the slug flows were assessed. The timing signal diagram shown in Fig. 4 is an example of the chronological digital signal records. Bubble rise velocities were determined from the digital signals of two optical sensors located 5 cm apart. The time delay for bubbles/slugs moving from the bottom sensor to the top sensor (t) can be used to calculate the bubble rise velocities as v_g (cm/s) = 5/t. Slug lengths were determined by taking the average time intervals of slugs detected by the optical sensors (τ) multiplied by the calculated average bubble rise velocity (See Fig. 4). Since air and water were distinguished by the optical sensors, void fractions were calculated by the ratio of total time occupied by air with signal "1" to total time of experiment (15 seconds).

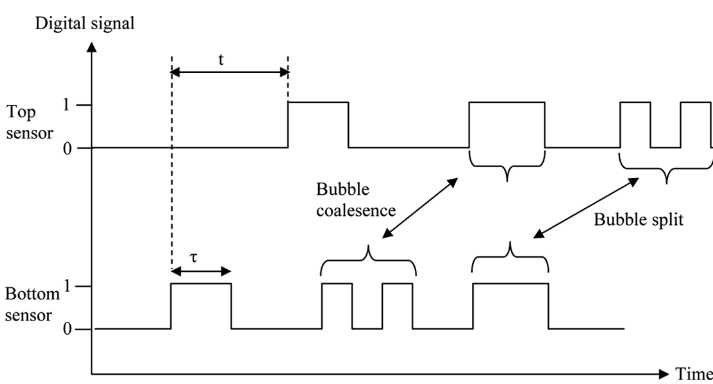


Figure 4. Timing signal diagram obtained from the optical sensor system for air-water flow characterization.

Characteristics of Two-Phase Flow Distribution

The distributions of air slug flow over a cross section in the membrane module can be described by several parameters such as the percentage of the membrane tubes having slugs and the distribution factors (γ_c) (8,10) which conventionally refers to a uniformity of hydrodynamic characteristics of two-phase flow, expressed in Eq. (1).

$$\gamma_c = 1 - \frac{\omega_c}{2} \tag{1}$$

Overall uniformity (ω_c) is calculated from a local uniformity coefficient ($\omega_{c,i}$) for each membrane tube in the membrane module, expressed in Eqs. (2) and (3). The uniformity is defined as a relative difference between the measured hydrodynamic characteristic (c_i) and the average hydrodynamic characteristic ($\bar{c}$)

$$\omega_c = \frac{\sum_{i=1}^{i=n} \omega_{c,i}}{n} \tag{2}$$

$$\omega_{c,i} = \frac{|(\bar{c} - c_i)|}{\bar{c}} \tag{3}$$

The average hydrodynamic characteristics are defined as the hydrodynamic properties that are supposed to be the same in all membrane tubes under a perfectly even two-phase flow distribution. Some average characteristics such as void fraction or air injection ratio (ε) for homogeneous two-phase flow condition, calculated by Eq. (4),

$$\varepsilon = \frac{u_g}{u_g + u_l} \tag{4}$$

Where u_g and u_l are superficial air velocity and superficial water velocity, respectively. Average characteristics of bubble rise velocities, average bubbling frequencies, and slug lengths can be determined from the two-phase flow experiments with a single tube (see section 3.1) at the same superficial air and water velocities.

Filtration with Rotating Air Distributor

The potential efficacy of the rotating air distributor for the membrane fouling control in a side-stream MBR module was examined in cross-flow filtration experiments using mixed liquor suspended solid (MLSS) from a laboratory MBR with a solid concentration of approximately 6 g/L. The experimental setup for the side-stream filtration experiments was similar to Fig. 2, except MLSS was used. Trans-membrane pressures (TMP) were monitored and compared between the filtration experiments with and without the 45° angle rotating air distributor. In these preliminary experiments the rotation speed of the air distributor was kept at 4 rpm, and the superficial velocities of air and MLSS flow were controlled at 2.15 and 6.44 cm/s, respectively. Digital pressure transducer (KH-68075, Cole-Parmer) with accuracy of ±0.25% was used to monitor the trans-membrane pressures during the filtrations which had 3 hours duration. NI DAQ (6210) card and Labview 7 were used for data collections.

RESULTS AND DISCUSSION

Hydrodynamic Experiments for Bubbling Characteristics in a Single Tube

The experimental results for the single tube tests are summarized in Table 2. Lengths of bubbles detected by the optical sensors were much larger than the tube diameter (5.1 mm), referring that slug flow occurred in the system. Bubble rise velocities substantially increased with increasing superficial water velocities and slightly increased with increasing superficial air velocities. The slug lengths increased with increasing superficial air velocities but decreased with increasing superficial water velocities. The bubbling frequencies increased with increasing both water and superficial air velocities. The standard deviations of bubble rise velocities and slug lengths provided some information of uniformity of the bubble rise velocities and the slug sizes of two-phase flow in the single tube. It should be noted that the standard deviations reflect temporal variations in the respective characteristic. Table 2 shows that better uniformities of the bubble rise velocities and the slug sizes were obtained at higher superficial velocities of water with low air-to-water flowrate ratios. Even a two-phase flow in a single tube was observed at the 4th run with air/water ratio of 0.33, and standard deviations of the bubble rise velocity and slug length were approximately 2 and 4% of the average respectively. The void fractions measured by the optical sensor system were close to the theoretical value calculated by Eq. (4) with an average deviation of only 6%. The bubble coalescence and bubble split were also detected by the optical sensors. These phenomena are likely to occur in real situation in a multiple-tube membrane module and may be important because they can affect the slug sizes and shear stress. The optical sensor

Table 2. Experimental results of single tube experiments at various superficial air and water velocities

				Experimental results						
				Bubble rise velocity (cm/s)		Slug length (nm)			Void fraction (–)	
Experiments	Superficial velocity of air flow (cm/s)	Superficial velocity of water flow (cm/s)	Air to water ratio (–)	Average	Standard deviation	Average	Standard deviation	Bubbling frequency (bubble/s)	Calculated, Eq. (4)	Measured
1	2.15	1.07	2.00	4.54	0.83	19.78	16.86	1.40	0.67	0.62
2		2.15	1.00	5.46	0.62	10.37	7.17	2.27	0.50	0.44
3		4.29	0.50	8.80	0.36	12.26	6.12	2.93	0.33	0.40
4		6.44	0.33	11.70	0.22	11.10	0.48	3.17	0.25	0.30
5	3.22	1.07	3.00	6.32	1.36	29.37	17.66	1.55	0.75	0.70
6		1.63	1.97	6.39	1.15	21.14	17.54	2.11	0.66	0.68
7		3.22	1.00	8.91	1.29	14.76	8.45	3.17	0.50	0.52
8		5.37	0.60	11.40	1.35	14.76	6.74	3.23	0.38	0.41
9		6.44	0.50	12.92	0.83	14.74	5.40	3.33	0.33	0.37
10	4.29	1.07	4.00	7.00	0.52	32.66	22.97	1.66	0.80	0.78
11		2.15	2.00	9.53	3.00	21.43	22.99	2.93	0.67	0.66
12		4.29	1.00	11.67	0.59	20.73	11.02	3.11	0.50	0.55
13		6.44	0.67	14.28	0.72	13.96	6.50	4.01	0.40	0.43
14		8.59	0.50	17.21	1.20	14.74	6.61	4.16	0.33	0.35
15	5.37	1.07	5.00	7.96	0.70	37.68	32.24	1.62	0.83	0.77
16		3.22	1.67	10.57	1.19	18.43	15.94	3.64	0.63	0.62
17		5.37	1.00	14.11	1.11	17.83	9.17	4.09	0.50	0.52

(*Continued*)

Table 2. Continued

				Experimental results						
				Bubble rise velocity (cm/s)		Slug length (nm)			Void fraction (–)	
Experiments	Superficial velocity of air flow (cm/s)	Superficial velocity of water flow (cm/s)	Air to water ratio (–)	Average	Standard deviation	Average	Standard deviation	Bubbling frequency (bubble/s)	Calculated, Eq. (4)	Measured
18		6.44	0.83	15.43	0.78	16.05	7.67	4.44	0.45	0.46
19		8.59	0.63	18.87	1.19	14.28	5.99	5.18	0.38	0.39
20	6.44	1.07	6.00	9.51	1.04	51.48	43.42	1.69	0.86	0.79
21		1.63	3.95	10.02	2.90	48.78	35.98	1.62	0.80	0.79
22		3.22	2.00	11.91	1.97	18.30	13.25	3.80	0.67	0.60
23		6.44	1.00	15.77	2.21	13.48	8.71	5.46	0.50	0.49
24		8.59	0.75	19.54	1.68	12.46	6.55	6.30	0.43	0.41

technique revealed that the bubble coalescence occurred more often than the bubble split by approximately 2 times. Both phenomena were found more often at high air flow rate or high air-to-water ratio.

Hydrodynamic Experiments of Bubbling Characteristics for Multiple Tubes in Membrane Module with and Without the Rotating Air Distributors

During the experiments, direct observations revealed the hydrodynamic disturbance and instability of the slug flow in the module. The hydrodynamic disturbance was found at the place when air bubbles collided with the blocked area (epoxy filled) of the membrane tube potting at the bottom (entrance) of the membrane module, leading to bubble coalescence before the bubbles flowed into the membrane tubes. These collisions would tend to make the slug size uneven and would be less likely at high packing density where the blocked area is reduced. The hydrodynamic instability was noticed during the experiments because of an unsteady state hydrodynamic condition in the two-phase flow distribution. The positions of membrane tubes having the slugs changed, approximately every 15–20 minutes and in this study, the new positions of the tubes having the bubbling were often found near the original positions in the same tube bundle layer in the array (see Fig. 3) as the tubes in the 2nd layer (numbers 2–7) for example. This can confirm that air-water flow characteristics should be measured in all tubes simultaneously.

The characterizations of the air-water flow distribution in the membrane module investigated by the optical sensor system can be expressed by 5 factors

(i) the percentage of membrane tubes having slugs,
(ii) the distribution factor of void fractions,
(iii) the distribution factor of bubbling frequencies,
(iv) the distribution factor of bubble rise velocities, and
(v) the distribution factor of slug lengths.

Figure 5 shows the effect of air/water ratio on the percentage of the membrane tubes having slugs. Numbers of membrane tubes having slugs tend to decrease with increasing air/water ratios for superficial air velocities of 2.15 and 6.44 cm/s. More uneven air/water flow distribution seemed to occur at higher air/water ratios. This phenomenon may result from higher pressure variation/fluctuation inside the module when higher air/water flow ratios were used. A slight increase in the numbers

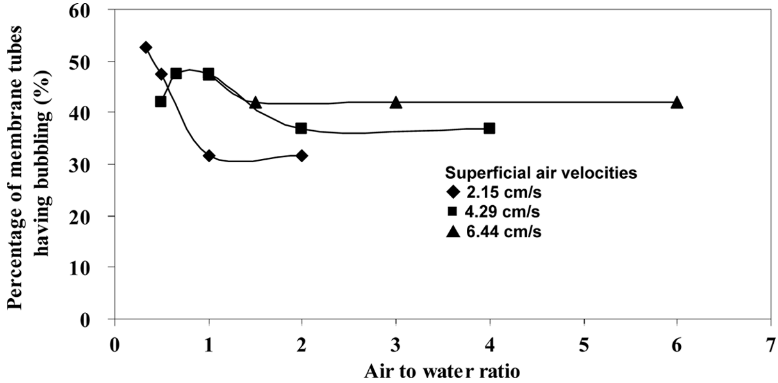


Figure 5. Percentage of membrane tubes having slugs at various air/water ratios for experiments with multiple membrane tubes.

of the membrane tubes was found at superficial air velocity of 4.29 cm/s in the range of air/water ratios of 0.67 to1 before the decreasing trend was obtained. When air/water ratio was higher than 1, the percentage of the membrane tubes remained constant at approximately 40%. Maximum percentage of membrane tubes having bubbling was found at 55% at air/water ratio of 0.33. It is worth noting that if this distribution is prevalent in an operating module then only 40 to 50% of the membranes will see the benefits of the two-phase flow.

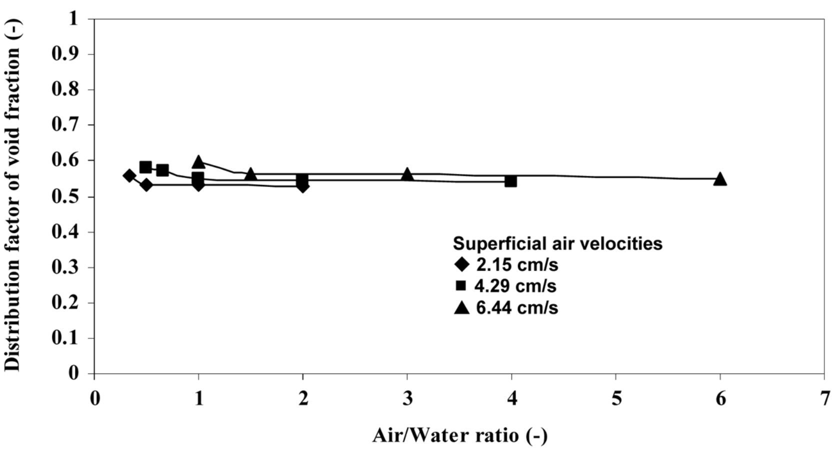


Figure 6. Distribution factor of void fraction various air/water ratios for experiments with multiple membrane tubes.

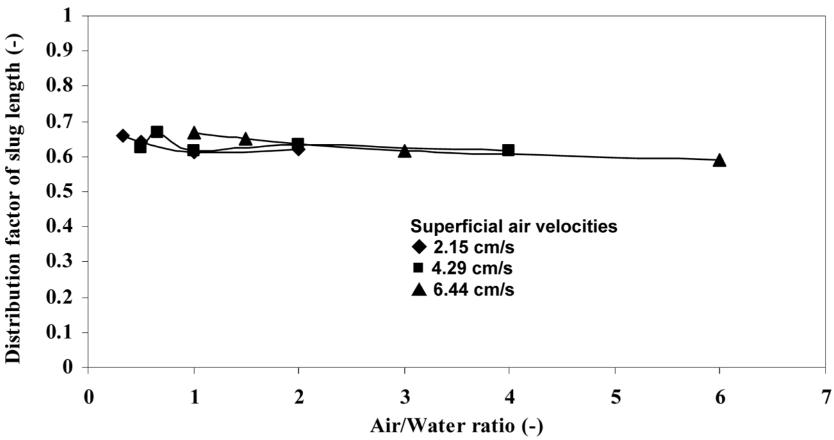


Figure 7. Distribution factor of slug length various air/water ratios for experiments with multiple membrane tubes.

The distribution factors of void fractions, bubbling frequencies, and slug lengths are shown in Figs. 6–8. It should be noted that a distribution factor of 1 signifies even distribution (property is similar to a single tube) and a factor approaching zero signifies very few tubes behaving similarly to a single tube. The trends in Figs. 6–8 are similar to those in Fig. 5. The

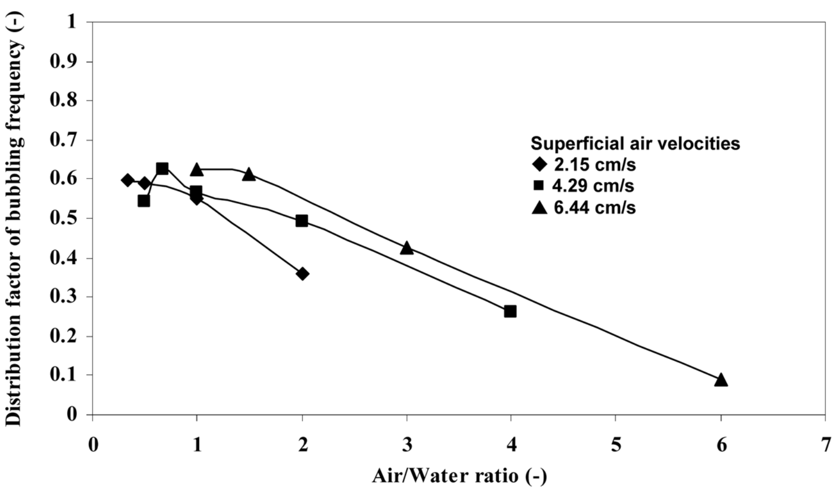


Figure 8. Distribution factor of bubbling frequency at various air/water ratios for experiments with multiple membrane tubes.

average void fractions for each air/water ratio were calculated by Eq. (4), and the average bubbling frequencies, average bubbling frequencies, average bubble rise velocities, and average slug lengths were determined experimentally by the experiments with a single tube. Figure 6 shows that the distribution factors of void fractions were found in a narrow range of 0.5–0.6 and tended to slightly decrease with increasing air/water ratio. Similar results were obtained for the distribution factors of the slug lengths, shown in Fig. 7. The slug lengths were found in the range of 6–30 mm and increased with the air flowrates. The variations of the slug lengths in the same tube were relatively small but high among the tubes. The distribution factors of the slug lengths ranged from 0.59 to 0.67 which were slightly higher than the distribution factors of void fractions. The distribution factors of the bubbling frequencies depicted in Fig. 8 show that poor distribution of bubbling frequencies was obtained at high air/water ratio for all superficial air velocities. The distribution factors of bubbling frequencies were lower than 0.35 when air/water ratios were higher than 2.

Bubble rise velocities measured from the multi-tube experiments ranged from 16–106 cm/s which were significantly higher than the average bubble rise velocities obtained from the single tube experiments. If the air/water ratios were lower than 0.5, the distribution factors of bubble rise velocities were in a small range of 0.34–0.41. The bubble rise velocities in the central tube were substantially higher than other tubes in the membrane module. The results shown in Figs. 6–8 suggest that good air-water flow distribution can be obtained when air/water ratio is lower than 0.5, and that the use of high air-water ratios is detrimental. Although the distribution factors of void fractions, bubbling frequencies, and slug lengths were in acceptable ranges, the distribution factors of bubble rise velocity were relatively poor. This can imply that the distribution factor based on only single hydrodynamic characteristic may not adequately describe the homogeneity of the slug distribution in the membrane module. Additionally, bubble coalescence and bubble split were still found, where bubble coalescence more often occurred. These effects were location-dependent where bubble coalescence was likely to take place in the inner tubes and the bubble split was likely to take place in the outer tubes on the membrane tube bundle.

Improvement of the air-water flow distribution in the side-stream membrane module was obtained by using the rotating air distributor (see Fig. 2). The basic concept of this air distributor was to distribute the air slugs from the center of the module to the outer tubes. Figure 9 shows the comparison of the percentages of membrane tubes having slugs for the experiments without the distributor and with the distributors including 15° and 45° rotating discs at various air/water

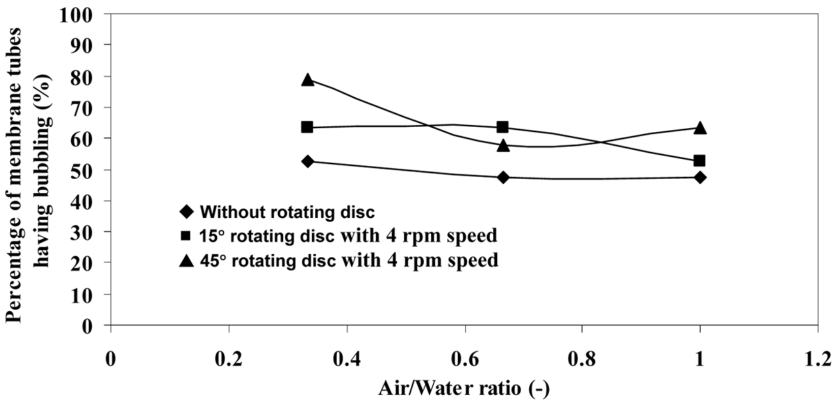


Figure 9. Comparisons of percentage of membrane tubes having slugs between experiments with and without the rotating discs.

ratios (superficial air velocity at 2.15 cm/s). The maximum percentage of the membrane tubes having slugs was 79%, provided by 45° rotating disc at air/water ratio of 0.33 with the rotating speed of 4 rpm. The 45° rotating air distributor provided higher percentages of the membrane tubes having slugs than those of the 15° rotating distributor. Both rotating air distributors significantly enhanced the percentages of the membrane tubes having slugs. Both rotating discs slightly raised the distribution factors of slug length from approximately 0.63 to 0.76, but the effect was lost at higher air/water ratios, shown in Fig. 10. The distribution factors of void fractions and bubbling frequencies were also slightly improved by the rotating air distributors. The effect of rotating speeds on the percentages of the membrane tubes having slugs is shown in Fig. 11 at air/water ratio of 0.33. Low rotating speed at 4 rpm provided higher percentages of membrane tubes having slugs. The calculation results by Eqs. (1)–(3) revealed that the rotating speeds were likely to have no effect on the distribution factors of void fraction and bubbling frequency.

Performance Evaluation of Rotating Air Distributor for Fouling Control

The potential benefit of the rotating air distributor was tested for the cross-flow membrane filtration with and without the rotating air distributor. The permeate fluxes were fixed and membrane fouling characterized by the increasing rates of the trans-membrane pressures (TMP), d(TMP)/dt, for the permeate fluxes of 6.7 and 10 $L/m^2 \cdot h$. The average d(TMP)/dt

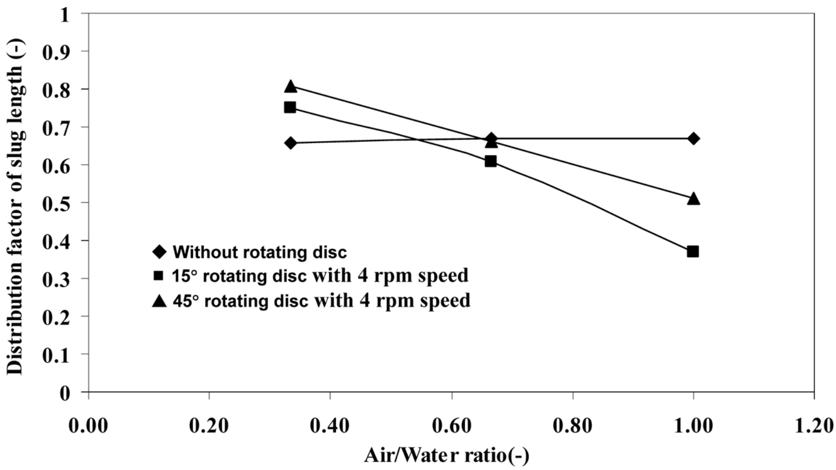


Figure 10. Comparisons of distribution factor of slug length between experiments with and without the rotating discs.

with and without the rotating air distributor were experimentally obtained and shown in Table 3. The trans-membrane pressure rises were significantly lower when the rotating air distributor was used during the filtrations, which implied that the fouling rate was reduced. These findings are preliminary and further optimization of the distributor and its application should be possible. The designs and operating methods of the rotating air distributor should be improved to get more homogeneous

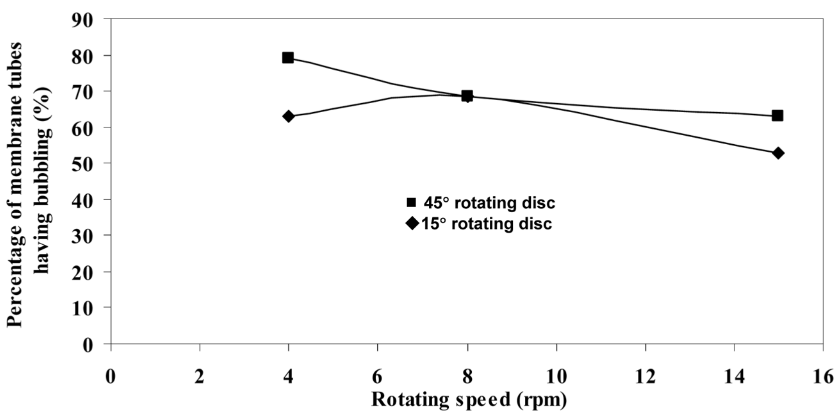


Figure 11. Effect of the rotating speed on the percentage of membrane tubes having bubbling.

Table 3. Fouling rates in term of d(TMP)/dt without and with rotating air distributor

Permeate flux ($L/m^2 \cdot h$)	d(TMP)/dt without rotation (bar/hour)	d(TMP)/dt with rotation (bar/hour)
6.7	0.039	0.015
10.0	0.071	0.019

air slug distribution and a maximum flux enhancement for real cross-flow membrane filtration.

CONCLUSIONS

The experimental demonstrations of the optical sensor system were performed to characterize air slug flow distributions in a multi-tube membrane module for a side-stream membrane bioreactor. The optical sensor system was designed to have both high sensitivity and flexibility for operations. The photomicrosensors provided the digital signals for analysis of the hydrodynamic characteristics of the two-phase flow. New designs of the air distributors as the rotating discs were developed and preliminarily evaluated for the membrane fouling control in the side-stream MBR module. The average bubble rise velocities, average bubbling frequencies, and average slug lengths were determined from the single tube experiments and used for calculations of the distribution factors for the multi-tube module experiments. The effect of air/water ratio on air-water flow hydrodynamics was investigated and expressed by the percentage of membrane tubes having slugs, the distribution factors of void fractions, bubbling frequencies, bubbles rise velocities, and slug lengths. High percentages of membrane tubes having slugs were obtained at the air/water ratio lower than 0.5. The distributions of bubble-rise velocities were likely to be poorest among the tested hydrodynamic characteristics. The phenomena of bubble coalescence and bubble split were found in which bubble coalescence occurred more often than bubble spilt. Investigations on the rotating air distributors to improve air-water flow distribution were performed, and the rotating air distributor with 45° disc angle provided better air-water flow distribution than the rotating distributor with 15° disc angle at rotating speed of 4 rpm. The optical sensor-based technique was proved to be one of highly sensitive indirect method to study air-water flow in the MBR module. More investigations and improvement are required for both optical sensor system and the rotating air distributor to obtain an optimum fouling control.

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NOMENCLATURE

c_i	measured hydrodynamic characteristic
$\bar{c}$	average hydrodynamic characteristic
ε	void fraction or air injection ratio
n	numbers of tubes
γ_c	distribution factor
ω_c	overall uniformity
$\omega_{c,i}$	local uniformity coefficient
u_g	superficial air velocity
u_l	superficial water velocity
v_g	bubble rise velocity
t	time

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