Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2015.1076354

57 (2016) 15759–15771
July

Taylor & Francis
Taylor & Francis Group

Control of mixing for optimal formation of dynamic membrane in MBRs

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Received 3 February 2015; Accepted 21 July 2015

ABSTRACT

Dynamic membranes (DMs) formed upon cost-effective mesh filters are considered as convenient alternatives to conventional membranes in membrane bioreactors (MBRs). This novel study investigates how hydrodynamics resulting from aeration rates of 2.5, 5, 10, and 15 L/min and agitation speeds of 100, 200, 300, and 400 rpm affect the sludge particle size, soluble microbial product (SMP), accumulation of sludge upon filter media, fouling propensity, effluent turbidity, and separation properties of DMs. The results conveyed that mixing flow and mixing intensity affect sludge properties considerably as well as DMs formed in the MBR. Despite fouling propensity, sludge mean particle size and dry weight of DMs decreased by increasing aeration rate and agitation speed. Optimum performance in terms of turbidity removal and blue pigment separation was obtained at the aeration rate of 5 L/min and the agitation speed of 300 rpm. In addition, more uniform DMs were formed by the flow pattern created by agitation which improved the performance. The DM formed by the agitation speed of 300 rpm could remove approximately 82% of blue pigments with a mean particle size of 0.9 μm which performs similar to microfiltration.

Keywords: Aeration; Agitation; Dynamic membrane; Filtration performance; Mean particle size

1. Introduction

Membrane bioreactors (MBRs) have become one of the most efficient technologies for wastewater treatment due to high quality of effluent and small footprint [1]. However, expensive membrane materials and unavoidable membrane fouling are the two main issues that have limited the application of MBR systems [2,3]. Recently, considerable investigations have focused on these obstacles to develop possible promising solutions. Replacing polymeric membranes with filter media including woven, non-woven fabrics, and filter cloth for MBR application has been greatly under examinations in recent years [4–10]. Comparing to the conventional MBRs, the quality of effluent decreases in bioreactors coupled with mesh filters due to their larger pore size. Nevertheless, most advantages of MBRs, i.e. high concentration of microbial community and small footprint are achievable in mesh filter bioreactors and the quality of effluent from these bioreactors can be considered similar to the quality of activated sludge system which is widely used for wastewater treatment [4].

Even though different studies have investigated the effects of several formation parameters such as cross flow velocity, formation pressure, and concentration of the materials on the separation performance

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and characteristics of dynamic membrane (DM), more research around the influence of fluid dynamics and sludge properties should be done [11–14].

Different results have been obtained about the impact of shear stress by air sparging applied for DM formation and performance. In some studies, higher turbidity was observed in effluent from mesh filter by enhancing aeration rate [8,15], whereas in others aeration intensity did not affect effluent turbidity and suspended solids (SS) significantly [16].

On the one hand, hydrodynamic forces reduce membrane fouling, while on the other hand, they are responsible for increase in SMP release and decrease in floc size [17]. Hwang et al. [18] claimed that the major forces determining the particle deposition and packing in the filter cake are dependent on particle size which can critically control filtration performance. They observed that increasing cross flow velocity led to finer particle size distribution, decrease in mass and porosity of the cake, and increase in the filtration resistance [18]. Liang et al. observed that a self-forming dynamic membrane (SFDM) with larger porosity of SFDM and lower filtration resistance would form faster by higher proportion of large particles, consequently energy consumption would be reduced [19].

Extracellular polymeric substances (EPS) and SMP play important roles in DM formation. They enhance sludge adhesion [20]. Also, EPS has been determined as a factor of fouling which blocks the membrane pores and forms a layer upon the membrane surface [21]. Liang et al. concluded extractable extracellular polymeric substances (eEPS), especially carbohydrates, control adhesion/cohesion strength among particles, and consequently the initial fouling rate of SFDMs [19]. In another study, polysaccharides led to the attachment of DM to the stainless steel mesh, and proteins were recognised to be the main factor of fouling [22]. EPSs, both in soluble and bound/colloidal form, are the major causes of membrane fouling in MBRs. In addition, reduction of mean floc size causes pore blocking which is in close relationship with membrane fouling [23].

Jamal Khan and Visvanathan [24] supplemented hollow fiber MBRs by mechanical stirring at 150, 300, and 450 rpm. An optimum mixing speed of 300 rpm improved the biofilm permeability by inducing sufficient shear stress on membrane fibers which decreases clogging of hollow fiber bundle and releasing low biopolymer concentration in the biofilm. Higher shear stress broke sludge flocs into smaller particles [24].

To increase the stability and efficiency of the DM, hydrodynamic conditions under which membrane is formed and performs must be chosen carefully. However, mixing is a key factor in the formation of DMs and has a great impact on sludge properties, it has not been studied thoroughly. Therefore, in this study, two different types of mixing by aeration at four rates (F_g) of 2.5, 5, 10, and 15 L/min and agitation at four speeds (N) of 100, 200, 300, and 400 rpm were chosen to develop mixing and surface tension requirements. Effects of different hydrodynamic conditions on the mean particle size (d_m) of activated sludge, permeate turbidity from dynamic membrane bioreactor (DMBR), trans-membrane pressure (TMP), dry weight per unit area of mesh filter (M_A), and pore size of membrane formed were investigated.

2. Materials and methods

2.1. Experimental setup

The schematic process flow diagram of experimental setup is illustrated in Fig. 1(a). The filtration tests were carried out in a rectangular Plexiglas vessel, 0.15 m wide, 0.2 m long, and 0.4 m high. The monofilament mesh filter made of polyester was used with an average pore size of 48 μm. The resulting effective area was 156 cm^2. A rectangular holding frame made of polyethylene, as shown in Fig. 1(b), was applied to support the mesh filter. The holding frame of the filter medium was vertically submerged in the center of the bioreactor. A high-precision pressure transducer was installed in the filtrate line as close as possible to the filter module to measure the pressure drop across the filter medium. A peristaltic pump which operated at a preset flow rate sucked the treated flow through mesh filter and subsequently transferred the effluent to the bioreactor by a recycle line to keep the level of bioreactor constant. In addition, the amount of water taken from bioreactor for turbidity testing during the experiment was negligible compared with the working volume of the bioreactor.

To create an almost complete suspension of the solids and to provide sufficient dissolved oxygen (DO) two methods of aeration and agitation were used. In the aeration method, the bioreactor was equipped with four air pipe spargers evenly installed at the bottom of the bioreactor. The rate of air sparging was monitored by a calibrated rotameter. Clean air which passed through an air manifold mounted on the top of the bioreactor was supplied by a blower. The air flow was separately distributed into four parallel tubes mounted on the inner side wall of the bioreactor in such a way that it could be removed. The inner diameter of the pipe sparger was 0.04 m which

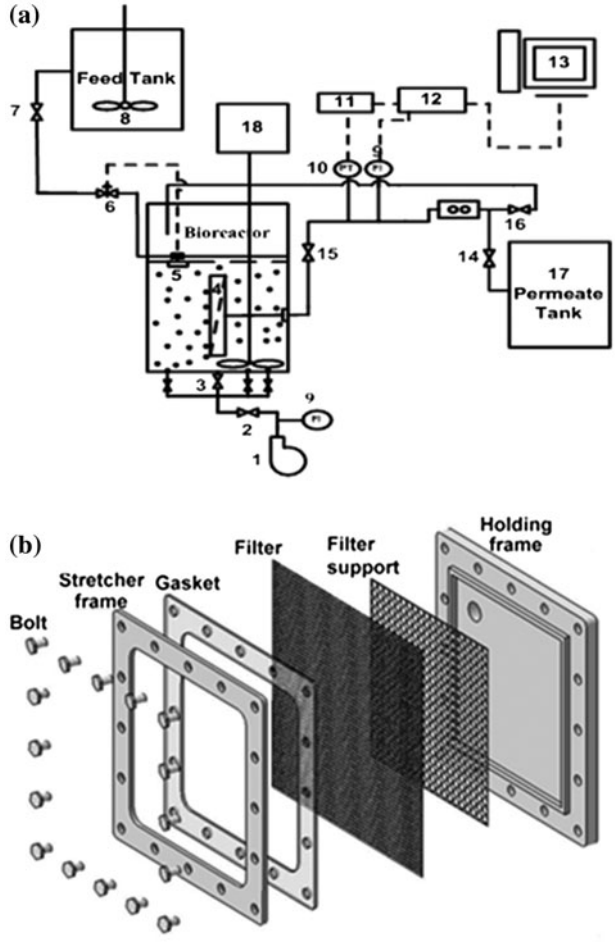

Fig. 1. (a) System process flow diagram and (b) mesh filter module.
Notes: (1) air blower, (2) blower outlet valve, (3) air manifold, (4) filter module, (5) level switch, (6) solenoid valve, (7) feed pump inlet valve, (8) feed tank, (9) flow indicator, (10) pressure transmitter, (11) pressure controller, (12) I/O module, (13) data acquisition system, (14) permeate pump outlet valve, (15) filter outlet valve, (16) recycle valve, (17) permeate tank and (18) electromotor with agitator.

generated fine bubbles. It had forty evenly spaced orifices symmetrically drilled on its top, bottom, and side surfaces. In the agitation method, an eight diameter stainless steel eight-blade turbine impeller was used to suspend the solid while the DM was being formed. The mechanical-driven agitator was placed on the right side and very close to the mesh filter module. The impeller was at a distance of 3 cm below the filter to establish appropriate flow pattern.

The working volume of the bioreactor was 7.5 L. The bioreactor temperature was set in the range of 20–23°C since the temperature fluctuation affects the performance of activated sludge. pH in the bioreactor was neutral. Each experiment took place within one hour. Activated sludge was adapted to synthetic glucose-based wastewater. Inoculated sludge was taken from the operating MBR plant (installed by Huber technology), dedicated for treating municipal wastewater. Then, the sludge suspension was loaded into the MBR. In all experiments, MLSS concentration was 8 ± 0.2 g/L and a constant operating flux equal to 150 LMH was provided by the peristaltic pump.

2.2. Analytical methods

The turbidity of the filtrate flow was determined by the use of spectrophotometer (Spectroquant Multy, Merck, Germany). MLSS concentration and dry weight of DM were measured using standard method 2540 [25]. DO was measured using DO meter (WTW 340 i, Germany). The supernatant was obtained by filtering mixed liquor through dead-end filtration (Whatman GF/C filter). Supernatant was analyzed for polysaccharide (PS) and protein (PT) concentration which are regarded as important parts of SMP materials. Protein content was determined according to the method of Lowry et al. [26]. Polysaccharide concentration was measured according to the method of Dubois et al. [27]. Temperature and pH were measured using pH meter (iSTEK pH-240L). Mean particle size of sludge (d_m) was determined using a Mastersizer 2000 (Malvern, UK), based on static laser light scattering. Fresh activated sludge samples were directly collected from the reactors. For analysis, the sludge concentration was fixed at an obscuration level in the range from 10 to 30% in the Mastersizer software.

The results of effluent turbidity from DMs categorized them as microfiltration membranes. Since the separation capacity of microfiltration (MF) is limited to particles in the 10^{-7}–10^{-6} μm size range [1], the rejection capacity of a solution containing 50 ppm blue pigments with mean particle size of 0.9 μm was determined to compare the pore size of DMs. Due to the fact that microfiltration is a separation process for insoluble particles like bacterial cells [1], the insoluble pigments were used and suspended in water using an ultrasonic bath (Elma S30H, Germany). Rejections were measured at a TMP of 0.5 bar. Two samples of permeate, 7 mL each, were taken each time and the average result was reported. Different concentrations of blue pigments were measured by the use of spectrophotometer at 360 nm (Spectrophotometer, Unico 2100, China).

3. Results and discussion

3.1. Characteristics of sludge

3.1.1. SMP content

Protein and polysaccharide contents of sludge were measured after aeration and agitation. These concentrations were determined when sludge was in the endogenous state. Fig. 2 shows protein content of sludge increases by elevation of aeration rate and agitation speed. It can be concluded that higher aeration rates and agitation speeds produced more surface tension on the particles resulting in cell lysis. Cellular lysis leads to the secretion of several soluble microbial polymers such as proteins and polysaccharides within micro-organisms that can be used by other micro-organisms. Apparently by increasing aeration rate and agitation speed, protein concentration increased but polysaccharide concentration did not change significantly. Increase in polysaccharide concentration is not detectable because endogenous micro-organisms utilized it in the absence of other carbon sources. Since SMP has been recognized as a major cause of membrane fouling in MBR, which influences the process cost in the separation step, it must be strictly noticed [28].

3.1.2. Mean particle size of activated sludge

Aeration and agitation cause tensions which break large particles into smaller ones. Park et al. [29] reported that when aeration rate increased dramatically, more tension was applied to the sludge particles. This resulted in a decrease in the size of particles and releasing EPS [29]. Fig. 3 indicates how the mean particle size of sludge changed by applying aeration rates (a) and agitation speeds (b) after one hour. Aeration rates of 2.5, 5, 10, and 15 L/min changed the mean sludge diameter from 50.03 μm to 49.93, 39.16, 36.35, and 29.87 μm, respectively. Furthermore, the agitation speeds of 100, 200, 300, and 400 rpm changed the mean diameter from 50.03 μm to 49.13, 44.41, 38.35, and 36.16 μm, correspondingly. As can be seen,

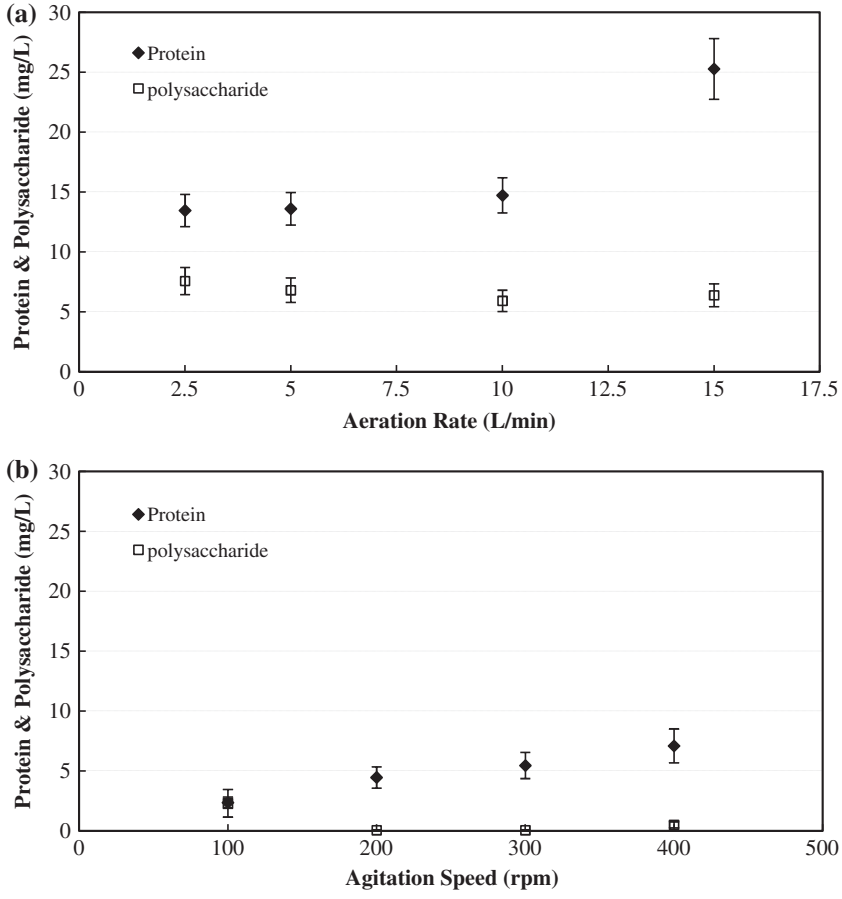

Fig. 2. Protein and polysaccharide contents of sludge after applying (a) aeration and (b) agitation.

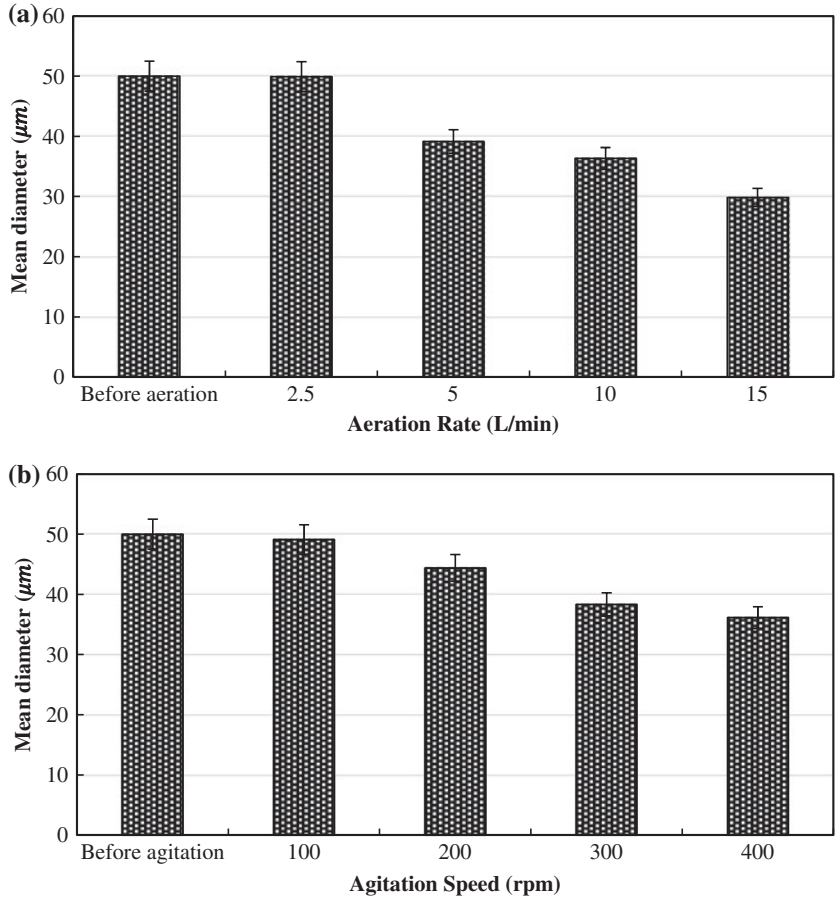

Fig. 3. Sludge mean particle size after applying (a) aeration and (b) agitation.

mean particle size of sludge decreased with elevation of aeration rate and agitation speed. It is obvious that increasing the aeration rate up to 5 L/min and agitation speed up to 300 rpm did not change the mean particle size significantly. But higher aeration rates and agitation speeds had more remarkable effects on the mean particle size which influences the formation and performance of DMs. These results are in accordance with those obtained by Jamal Khan and Visvanathan [24].

3.1.3. Regression correlations of mean particle size of sludge

In this section, effects of aeration rate and agitation speed on mean particle size of sludge is presented. All correlations were derived using of DataFit 9 software.

3.1.3.1. Different aeration rates. Considering a tolerance of 1.0E−10, regression correlation between the dependent variable (mean particle size of sludge) and independent variable (aeration rate) resulted in the following equation:

$$d_m = 62.77(F_g)^{-0.26} \quad (1)$$

$$(R^2 = 0.95)$$

The regression model shows that aeration rate had a negative effect on the mean particle size of sludge. Therefore, by increasing the rate of aeration, mean particle size diminishes. Also, a logarithmic regression between the reduction in the mean particle size and the rate of aeration per unit volume of the bioreactor is demonstrated in Fig. 4(a). The results show that the reduction in mean particle size of sludge intensifies with increasing the rate of aeration. In order to validate the mentioned regression model, three more tests were done. It can be seen that the model presented can satisfy the results of other tests as well.

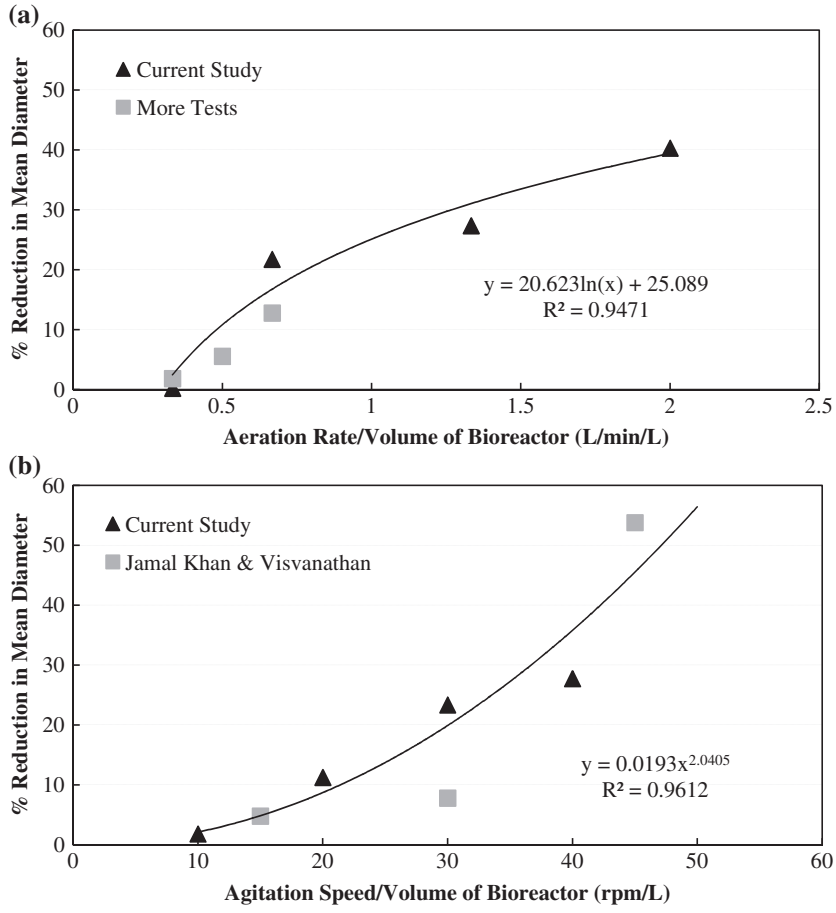

Fig. 4. Effects of (a) aeration rate and (b) agitation speed on the decrease in mean particle size of sludge.

3.1.3.2. Different agitation speeds. By considering the previous tolerance, the regression model between the mean particle size of sludge as an independent variable and agitation speed as a dependent variable was achieved as follows:

$$d_m = 138(N)^{-0.22} \quad (2)$$

$$(R^2 = 0.96)$$

In this model, agitation speed has a negative effect on the mean particle size of sludge. Moreover, the effect of different speeds of agitation per unit volume of the bioreactor on the decrease in the mean particle size in proportion to the blank sample has been derived based on the power regression fitted by data of this study. Data from another similar study [24] have been used to validate this model. Mean diameters of sludge were determined when the MBR systems became steady in the presence of agitator with the speed of 150, 300, and 450 rpm. Fig. 4(b) indicates all the data and correlation.

3.2. DM and filtration properties

3.2.1. Dry weight of DMs

Sludge particles near the support membrane are exposed to different forces including sucking stress of pump, shearing stress, depositing friction with support mesh filter, and lift force created by agitator or air bubbles. In this area, a very thin laminar flow boundary layer exists on the surface of flat support filter, which is characterized by a constant shearing stress (τ) and a linear velocity distribution from the interior to the exterior. When laminar flow boundary layer is equal to the DM thickness, DM and DMBR will run steadily. If laminar flow boundary layer is greater than or equal to DM thickness, turbulent eddies will not be able to destruct the DM. This can be estimated through using the boundary layer theory in the Newtonian hydrodynamics [30]. The MLSS of bioreactor suspension in this study is less than or equal to 8.1 g/L, and according to Xing et al. this mixed liquor can be considered as a Newtonian fluid for boundary layer theory calculations [31]. As the

aeration and agitation are the key factors of creating turbulence, applying different F_g and N results in the formation of DMs with different thicknesses. In this study, we measured the dry weight of DMs per unit area of mesh filter as a parameter to compare the thickness of DMs. Fig. 5 demonstrates the thickness of DMs formed under mentioned aeration rates (a) and agitation speeds (b). The results show that the dry weight of DMs per unit area of filter medium diminishes with increasing aeration rate and agitation speed. This can be due to the hypothesis that laminar flow boundary layer becomes thinner with the increase of turbulence created by higher aeration rate and agitation speed. This resulted in the formation of thinner DMs. Moreover, a little change in the M_A is observed when F_g and N are increased to 5 L/min and 200 rpm, respectively. However, higher values of F_g and N influence the M_A significantly. A future study on shear rate and velocity near the surface of membranes can complement fluid dynamic aspect of this research.

3.2.2. Effluent turbidity of DMs

One of the most important parameters in the formation of a uniform dynamic membrane is developing a proper mixing in the bioreactor. Proper mixing has two characteristics: (1) creating an appropriate flow pattern, which aids membrane formation, (2) making the bioreactor homogenous that contributes to perfect mass transfer. Effects of different aeration rates and agitation speeds on the DMs formed in one hour were investigated due to the importance of mixing. Fig. 6 shows the effluent turbidity during DMs formation under different aeration rates (a) and agitation speeds (b). From these figures, it can be concluded that these DMs can be categorized as microfiltration membranes [10]. The results demonstrate that DMs formed under the aeration rate of 5 L/min and agitation speed of 300 rpm have the lowest effluent turbidity among aeration rates and agitation speeds, respectively. Aeration rate of 2.5 L/min creates improper mixing compared with 5 L/min. This caused the formation of a non-uniform dynamic

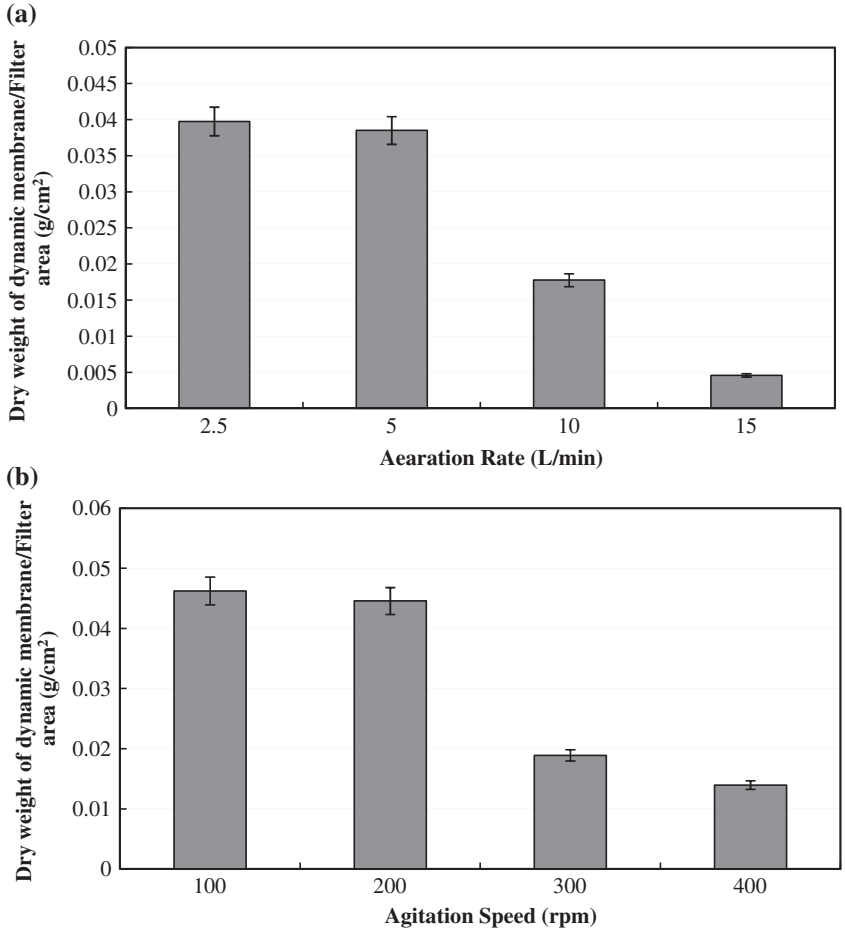

Fig. 5. Dry weight of DMs per unit area of mesh filter medium formed by (a) aeration and (b) agitation.

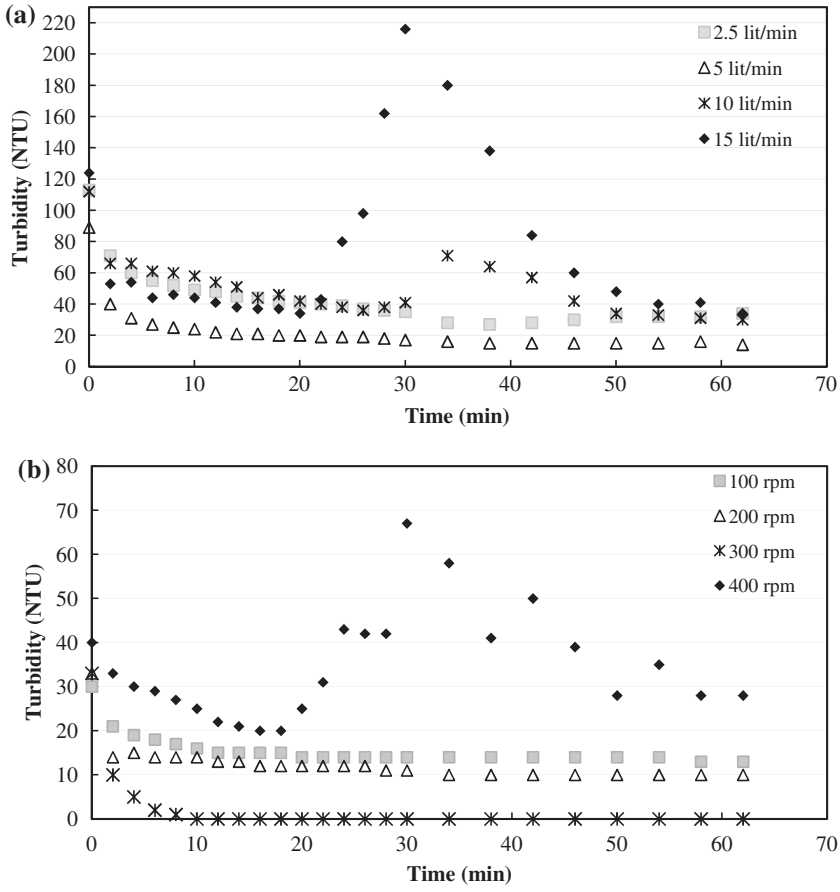

Fig. 6. Turbidity changes during the formation of DMs by (a) aeration and (b) agitation.

membrane. That is why more turbidity was detected in the effluent of the DM formed at this aeration rate. Same results were obtained for the DMs formed at the agitation speed of 100, 200, and 300 rpm. The DM formed at the agitation speed of 300 rpm was the most uniform one which had the best performance in the turbidity removal. DMs formed under the aeration rates of 10 and 15 L/min and agitation speed of 400 rpm did not follow a certain trend. The effluent turbidity declined as DM was forming, but it abruptly increased and then decreased again. This can be due to the large tension they applied on the surface and resulted in the destruction of the biofilm layer formed. Dry weight of DMs per unit area of filter medium verifies these outcomes. In addition, sludge particles broke into smaller ones. Therefore, more particles could go through the pores and eventually more turbidity in the effluent was obtained. Also, membranes formed under agitation speeds demonstrated a better performance in reducing turbidity in comparison with the ones formed under aeration.

3.2.3. Fouling propensity of DMs

One of the applications of aeration is developing tension on the surface of membranes which reduces membrane fouling [32]. Like aeration, flow pattern created by agitation develops tension upon the surface of membranes. Fig. 7(a) and (b) shows that TMP elevates faster with increasing aeration rate and agitation speed. During the formation of DMs, at first, DMs are formed and reach a stable thickness. Then, they start to get compressed and fouled. According to Carman–Kozeny equation, smaller particles result in more specific resistance of biocake and lower permeability of the membrane [33]. Particle size distribution has a major effect on the structure of DMs and fouling propensity of these membranes. Sludge suspension containing a higher proportion of large particles results in faster formation of self-forming DM with higher porosity and lower specific filtration resistance [19]. As illustrated in Figs. 2, 3, and 5, despite the concentration of proteins, mean particle

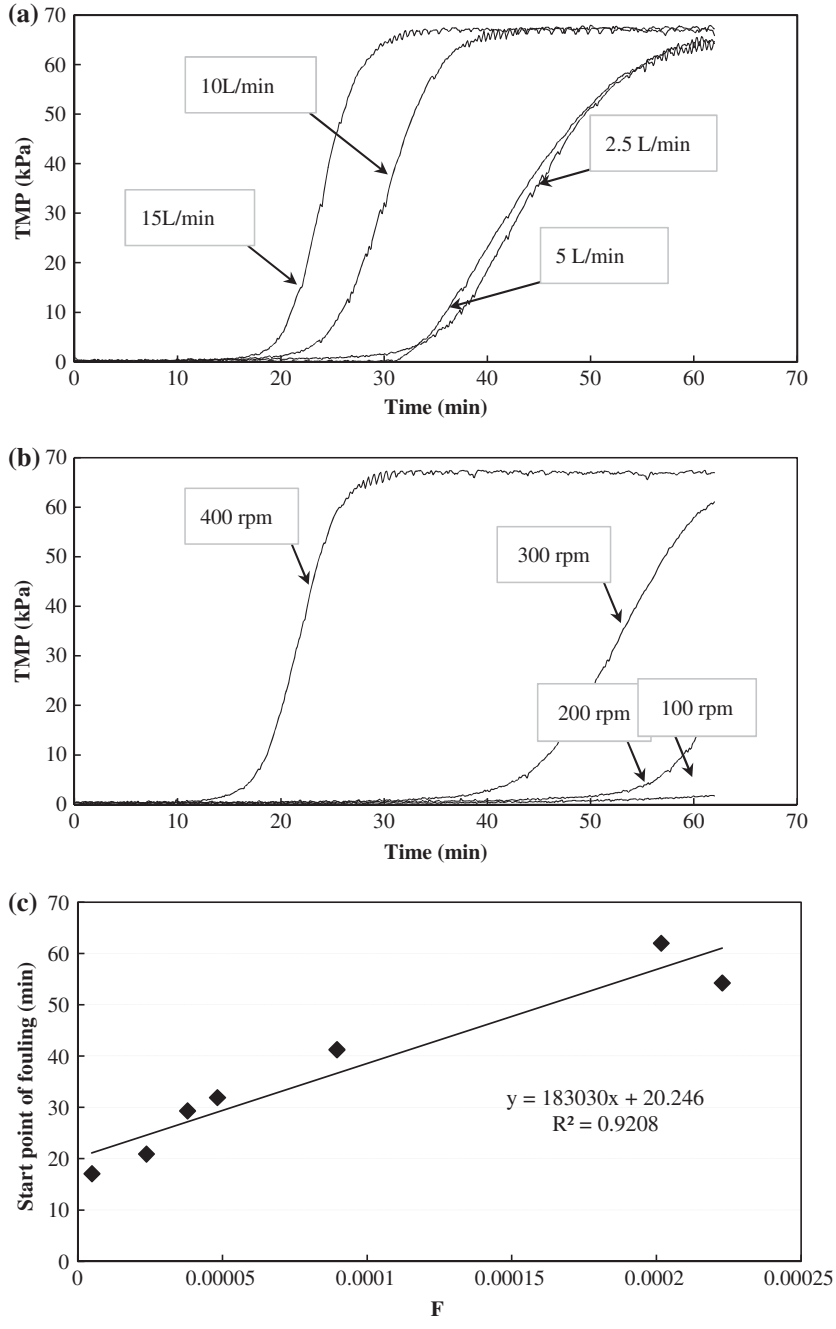

Fig. 7. Transmembrane pressure (TMP) during the formation of DMs formed by (a) aeration, (b) agitation, and (c) relationship between *F* and starting point of fouling.

size of sludge, and thickness of DMs decline by increasing aeration rate and agitation speed, and the tendency of DMs to get fouled increases subsequently.

Different factors such as mean particle size of sludge, dry weight of DM per unit area of filter media, and SMP content of sludge can affect the fouling propensity of DMs. In this section, a dimensionless index is introduced which is helpful in predicting the time when the DMs start getting highly fouled. This index is calculated according to the following equation:

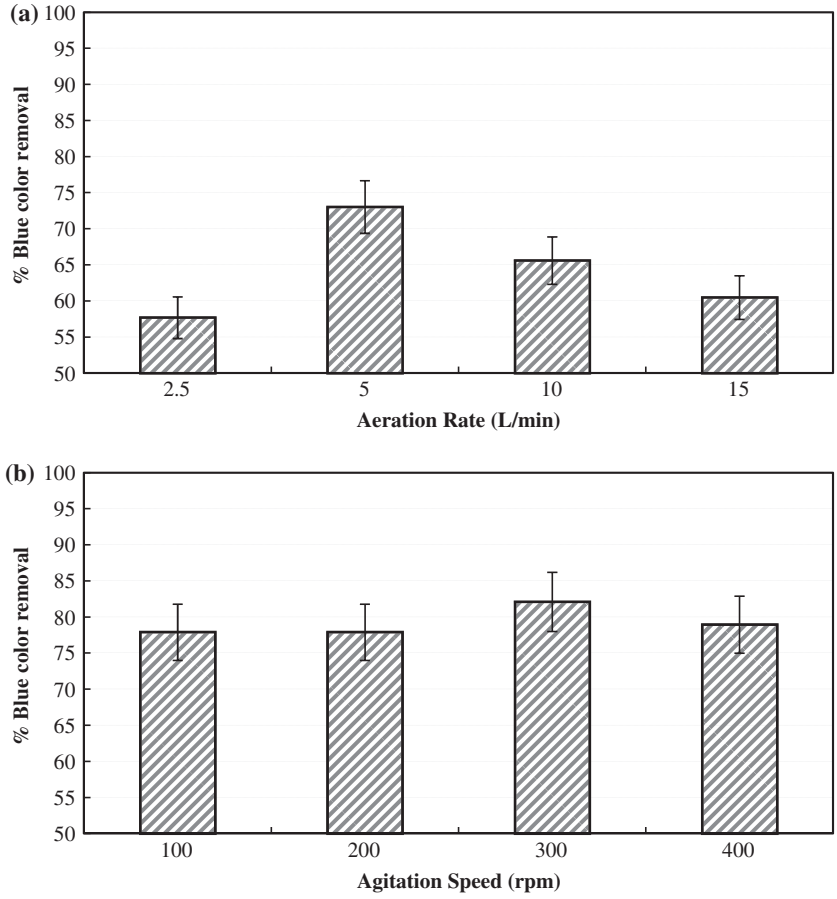

Fig. 8. Rejection of blue pigment by DMs formed by (a) aeration and (b) agitation.

Table 1
Comparison of aeration and agitation effects on sludge characteristics and filtration properties of DM (summary of results)

	Aeration rate (L/min)				Agitation speed (rpm)			
	2.5	5	10	15	100	200	300	400
Protein (mg/L)	13.450	13.600	14.720	25.270	2.308	4.454	5.454	7.090
Polysaccharide (mg/L)	7.570	6.800	5.917	6.380	2.308	0.052	0.052	0.503
Mean diameter (μm)	49.93	39.16	36.35	29.87	49.13	44.41	38.35	36.16
Dry weight of DM/filter area (g/cm^2)	0.0398	0.0385	0.0178	0.0046	0.0462	0.0446	0.0189	0.0139
Effluent turbidity (NTU)	34	14	30	34	13	10	0[a]	28
Start point of severe fouling (min)	29.33	31.92	20.92	17.08	62	54.25	41.25	17.50
Blue color removal (%)	57.67	73.02	65.58	60.46	77.89	77.89	82.10	78.94

[a]Under range of the spectrophotometer detection.

$$F = \frac{(\text{Dry weight of DM/Area of filter medium})}{(\text{Mean particle size of sludge})(\text{SMP concentration})} = \frac{M_A}{d_m \times \text{SMP}} \quad (3)$$

Fig. 7(c) shows the linear relationship and equation between F and starting point of fouling of the DMs. The positive slope indicates that by increasing F the starting point increases, which indicates that the DM gets fouled in a longer period of operation.

3.2.4. Capability of DMs in rejecting the blue pigment

Dye-rejection test is a technique to compare the pore size of conventional membranes [34]. Similarly, this method was applied to qualitatively compare the pore size of DMs formed in this study. Fig. 8 demonstrates the blue pigment rejection capacity of DMs formed under different aeration rates and agitation speeds. The results showed that membranes formed under agitation could reject the pigment better than those formed under aeration method. Also, membranes formed under the aeration rate of 5 L/min and agitation speed of 300 rpm showed a better rejection capability among aeration rates and agitation speeds, respectively. These findings are in accordance with the effluent turbidity results.

In order to make it possible to easily compare the results obtained by applying two methods of mixing for DMs formation, all findings have been summarized in Table 1.

It is acceptable that physical conditions in a large bioreactor can never exactly duplicate those in a smaller one however geometric similarity is maintained. A stirred tank can be scaled up based on constant power input, constant liquid circulation rate inside the vessel (pumping rate of impeller per unit volume), constant shear at impeller tip, and constant Reynolds number. Since all these scaleup criteria are dependent on agitation speed and impeller diameter, fixing these two parameters fixes all the above quantities. Constant power input implies constant OTR, constant Re implies geometrically similar flow patterns, constant agitation speed gives constant mixing time and constant tip speed gives constant shear [35]. Furthermore, in bubble columns, design of sparger and gas flow rate determines gas superficial velocity which is a key factor in calculation of the Reynolds number and liquid circulation rate [36]. Therefore, the results of this study seem to be satisfactory to systems scaled up.

4. Conclusions

This study investigated how hydrodynamics created by aeration and agitation affect the sludge characteristics and separation properties of DMs. Results obtained from applying four aeration rates and four agitation speeds showed that types of mixing flow and mixing intensity have great effects on sludge properties as well as DMs formed in the MBR. Increasing aeration rate and agitation speed resulted in the presence of a higher concentration of protein in the supernatant due to cell lysis. However, the concentration of polysaccharides did not change significantly, as a result of being utilized by endogenous microorganisms in the absence of other carbon sources. Aeration as a mixing mechanism has an optimum value. Below the optimal condition, there may be no suitable mixing in the bioreactor to form a uniform DM. Moreover, above the optimum aeration rate a very huge tension causes a remarkable reduction in sludge particle size and thickness of DM and subsequently low quality of effluent and high tendency of fouling are obtained.

Similar to aeration rate, agitation speed has an optimum value under which the DM should be formed to have the highest efficiency in the DM formation and performance. Increasing agitation speed results in reduction of DMs thickness and mean particle size of sludge. This causes higher tendency of fouling. DMs formed under 300 rpm were able to reduce turbidity and reject blue pigments better than the other membranes. In addition, more uniform DMs were formed by the flow pattern created by the agitation which provided better performance in terms of turbidity removal and the blue dye rejection. Less fouling propensity in these membranes is another advantage of using this technique.

Acknowledgement

Authors thank Dr Farshid Pajoum Shariati for his great support and useful comments.

Nomenclature

DM	—	dynamic membrane
d_m	—	mean particle size (μm)
DMBR	—	dynamic membrane bioreactor
DO	—	dissolved oxygen
EPS	—	extracellular polymeric substances
eEPS	—	extractable extracellular polymeric substances
F_g	—	aeration rate (L/min)
M_A	—	dry weight of DM/area of filter media (g/cm^2)
MBR	—	membrane bioreactor
MLSS	—	mixed liquor suspended solid
N	—	agitation speed (rpm)
PT	—	protein concentration (mg/L)
PS	—	polysaccharide concentration (mg/L)
SFDM	—	self-forming dynamic membrane
SMP	—	soluble microbial product (mg/L)
SS	—	suspended solids
TMP	—	trans-membrane pressure

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