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A comparison of a blower and a Venturi aeration system in a submerged membrane bioreactor

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ABSTRACT

A novel aeration method for submerged membrane bioreactors (MBR) was developed in this study. This method uses a Venturi injector to supply the air to the MBR. Short term experiments were performed to determine the technical applicability of integrating a venturi device into a submerged MBR. A flat–sheet, 0.1–µm polyvinylidene fluoride membrane was used to operate the MBR. Real wastewater taken from Diyarbakir Municipal Wastewater Treatment Plant was used as feed. Membrane fouling was evaluated under three different fluxes (18, 32, and 50 L/m^2 · h) and 3 L/min aeration rate for both blower- and venturi-aerated MBR systems. Transmembrane pressure (TMP), chemical oxygen demand (COD), mixed liquor suspended solids, mixed liquor volatile suspended solids, pH, dissolved oxygen, and temperature were measured in the experimental setup. The COD removal rate was between 75–92% for blower system and 85–87% for venturi system. Effluent NH_4–N concentration was between 0.0–14.7 mg/L for blower system and 0.0–0.7 for venturi system. While the effluent NO_3–N was between 3.1–27.4 mg/L for blower system, it was 33.3–37.8 mg/L for venturi system. At 3 L/min aeration rate, the dissolved oxygen concentration in MBR was between 0.42–3.43 mg/L for blower–aerated system and between 6.43–7.07 mg/L for venturi–aerated system. TMP development at different fluxes in blower and venturi systems showed that integration of a venturi device with a submerged MBR improved filtration capacity significantly. The rate of TMP increase in blower–aerated system was higher than that of venturi–aerated system at the same aeration rate of 3 L/min for both systems. At the highest filtration flux tested (50 L/m^2 · h), venturi–aerated system operated three times longer than the blower system.

Keywords: Membrane bioreactor (MBR); Aeration; Venturi device; Membrane fouling; Wastewater treatment

1. Introduction

A membrane bioreactor (MBR) combines biological treatment and membrane filtration that uses membrane as a biomass separation tool. Wastewater treatment systems that use membrane processes are becoming a serious alternative to traditional wastewater treatment systems because of allowing many advantages including high solids retention, high biomass concentration, rapid process startup and reuse and recycle of wastewater [1]. Together with these advantages, there are also some disadvantages. While a high MLSS concentration causes problems in terms of oxygenation, the high solids removal rate causes the retentate to accumulate on the membrane surface, which creates membrane fouling.

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1.1. Aeration of MBRs

Both to satisfy the oxygen needed for bacteria and the air needed for membrane surface cleaning, aeration is used intensively in membrane bioreactors (MBRs). Due to intensive aeration, the aeration of MBRs has been reported to comprise more than 80% of the operating costs [2,3]. In MBRs, especially for submerged configurations, since other biological aeration techniques, such as mechanical surface aerators, are not much suitable, aeration is mostly performed with air blowers or compressors connected to a diffuser system. However, the characteristics of the air bubbles used for biological aeration and those used for membrane surface cleaning contradict each other. Fine bubble aeration (2–5 mm) is generally used for biomass aeration because of the enhanced oxygen transfer, while coarse bubble aeration (6–10 mm) is usually carried out for membrane surface cleaning due to shear forces created [4]. In other words, fine bubble aeration promotes higher oxygen transfer with a higher energy requirement when compared to coarse bubble aeration. On the other hand, coarse bubble aeration promotes better membrane surface scouring with less oxygen transfer efficiency when compared to fine bubble aeration [4]. Data from manufacturers and from literature study indicated 3–10% and 1–3% oxygen transfer efficiencies for fine and coarse bubble diffusers, respectively. Also, approximate costs of £40 per diffuser for fine bubble systems and £15 per diffuser for coarse bubble systems reported [4].

Therefore, a compromise should be found between fine and coarse bubble diffuser systems. An optimization of air flow was performed in a submerged MBR using two chambers, one for biomass oxygenation with fine bubble diffusers (aerobic chamber) and the other for membrane surface scouring with coarse bubble diffuser system (membrane chamber). Optimum conditions were found at dissolved oxygen (DO) set-point of 0.5 mg/L for aerobic chamber and membrane specific aeration demand of 1 m/h for membrane chamber. By this optimization, a total flow reduction of 42% was achieved (75% energy reduction) without compromising nutrient removal efficiencies [5].

Instead of using both a fine and a coarse bubble aeration in two different chambers for MBR operation, a system that is capable of providing both high oxygen transfer efficiency and high membrane surface cleaning efficiency at the same time can reduce MBR operation costs significantly. Although jet aeration systems such as the VO_2 and Vitox systems have been successfully retrofitted to upgrade biological treatment plants to meet increased loads and even tightening legislation [6] the integration of a venturi device into an MBR has not been studied in a configuration that can be extended to full-scale applications in submerged MBR system. The working principle of a venturi device is summarized below.

1.2. Venturi device

A venturi device is formed by combining a converging and a diverging two tubes (Fig. 1.). When a fluid is circulated through a venturi device, under certain conditions, a negative pressure (vacuum) is formed at its throat portion and air is sucked if a port on it is open to the atmosphere.

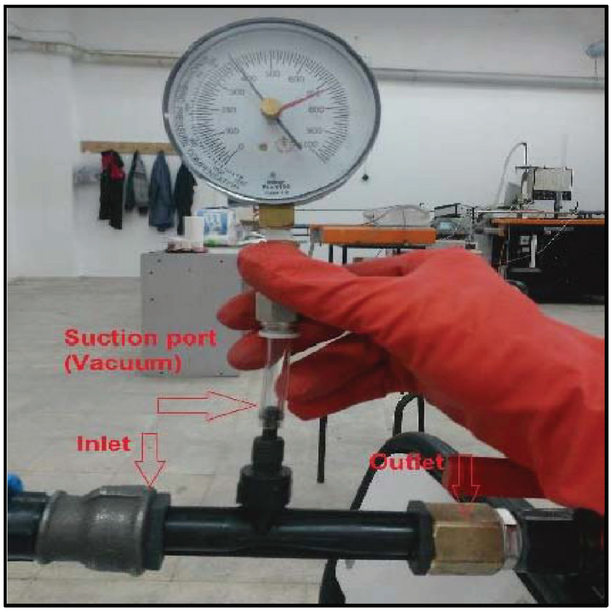

Fig. 1. Venturi device.

The air–water mixture then exits the venturi in the shape of a jet. Highly turbulent conditions at the throat portion of the venturi device enable very high gas transfer efficiencies. For example, while the typical mass transfer efficiency of ozone by bubble diffusers is 10–15%, a venturi injector system may achieve 90% transfer efficiency [7]. As another example, for CO_2 injection into seawater, the injection efficiency with a venturi was 100% higher than that with a porous stone air diffuser [8] In practice, venturi devices have applications in are as such as air stripping, the aeration of irrigation water, ozonation, disinfection, oxygenation and odor control for wastewater treatment [9]. The high gas transfer efficiency of the venturi device has great potential for MBR applications.

The use of a venturi device have two potential advantages over the use of a blower for aeration in submerged MBRs. The first one is that high gas transfer efficiency is especially useful for MBRs where high mixed liquor suspended solids (MLSS) concentrations up to 15 g/L is used. The second one is that a certain amount of shear is required to scour the membrane surface to limit membrane fouling. The high–velocity air water mixed jet exiting the venturi device can ensure the highly turbulent environment on the membrane surface for a better membrane surface scouring.

Therefore, the aim of this study was to investigate the technical applicability of integrating a venturi device into a submerged MBR to satisfy both biomass oxygenation and membrane surface aeration simultaneously.

2. Material and methods

2.1. Experimental setup, membrane, and venturi device

In the study a 10-L membrane bioreactor was used. Schematic diagram of the setup is shown in Fig. 2. Both the

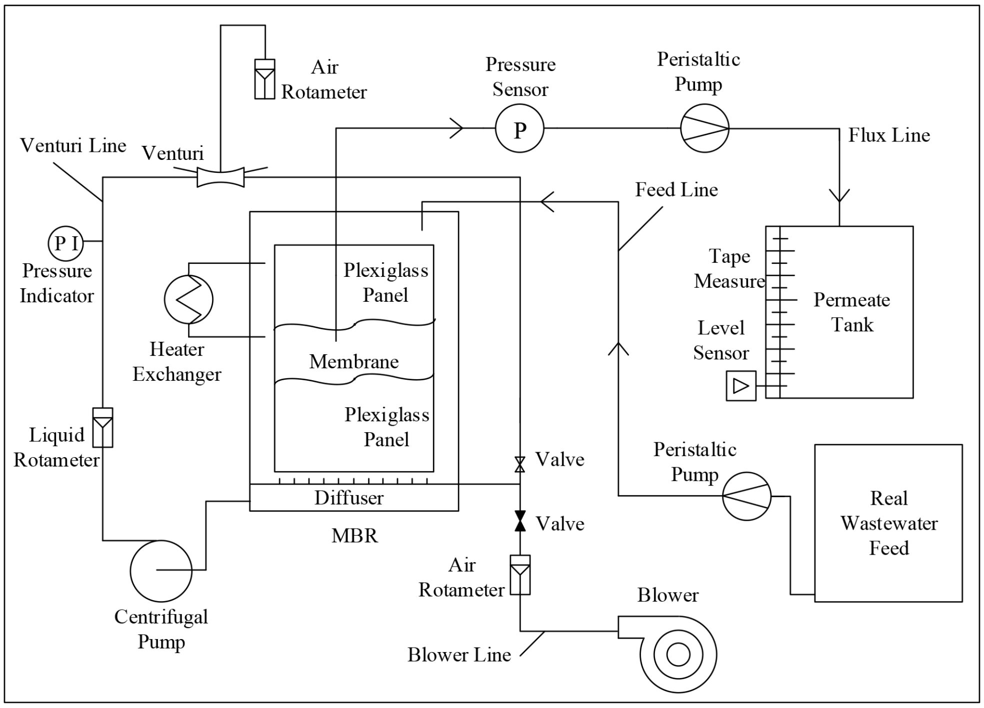

Fig. 2. Schematic diagram of the experimental setup.

blower and the venturi aeration system can be operated by adjusting the valves on the respective lines. When the blower was operating, the valve on the venturi line was closed, and vice versa. In blower mode, the required air for the MBR was provided by the blower and directed to the surfaces of the membrane module through a coarse air diffuser. In venturi mode, a centrifugal pump circulated the biological suspension of the MBR through the venturi device. Because of the low pressure below atmospheric pressure, air entered through the suction port of the venturi device. The air discharge was adjusted with an air rotameter. The air–water mixture was then directed to the surfaces of the membrane module through the same coarse air diffuser system used for blower aeration.

The membrane module was inserted between two plexi glass panels with the same dimensions as the membrane panel to account for the wall effect. The dimensions (W × H × T) of the membrane panels were 220 × 320 × 6 mm. Other membrane properties are given in Table 1. The transmembrane pressure (TMP) was recorded by a pressure sensor on the suction line. The membrane flux was calculated from the data taken from a level sensor on the permeate storage tank. The same membrane was used for all experiments. Before each experiment, the membrane was chemically cleaned by soaking it in a solution containing 4 g/L NaOCl and 1 g/L NaOH for 2 h.

Table 1
Properties of the membrane module used in MBR

Property	Value
Membrane module	SINAP–10–PVDF
Effective area, m^2	0.1
Weight, kg	0.4
Pore diameter, µm	0.1
Aeration volume, L/min. panel	6
pH	3–12
Effluent turbidity, NTU	1.0
Effluent SS, mg/L	1

The properties of the venturi device (type A25152) as given by the manufacturer (Guangzhou Quanju Co., Guangzhou, China) are as follows: inlet–outlet diameter, 3/4 inch; gas inlet diameter, 1/4 inch; input water pressure, 0.25–0.5 MPa; water flow, 1–3 m^3/h; suction intensity, 7.5–10 Nm^3/h; and length, 152 mm. A drawing of a venturi device similar to that used in this study is shown in Fig. 3. [10].

2.2. Sludge and wastewater characteristics

The sludge taken from the recycle line to the aeration basin of Gaziantep Municipal Advanced Biological Wastewater Treatment Plant was used as vaccine sludge for the MBR.

The MBR was fed with the real wastewater taken from the Diyarbakir Municipal Advanced Biological Wastewater Treatment Plant. Characteristics of the wastewater are given in Table 2. The wastewater was taken twice a week and placed in coolers in order to keep the temperature around 4 °C.

2.3. Analysis and measurement of conventional parameters

HQ40D Hach portable multi-meter was used to measure pH, temperature and dissolved oxygen concentration in the MBR. Hach test kits were used for chemical oxy-

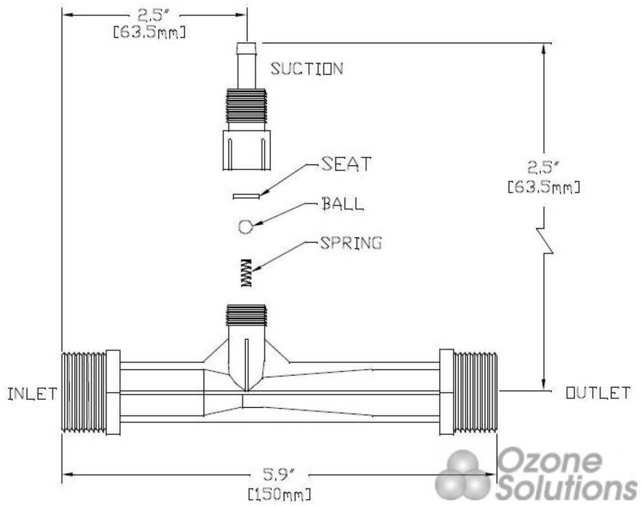

Fig. 3.. Configuration of a venturi device [10].

Table 2
Wastewater characteristics

Parameter	Minimum (mg/L)	Maximum (mg/L)	Average (mg/L)
COD	280	458	334
NH_4^+–N	25.6	48.6	40.6
PO_4^{3-}–P	4.1	9.8	6.4

gen demand (COD), NH_4–N, NO_3–N and PO_4–P analyses. Mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) were measured according to the standard methods [11]. Since we did not see significant fluctuations in some trials (data not shown), we did one measurement for each parameter of COD, PO_4–P, NH_4–N, and NO_3–N using Hach-Lange test kits. However, because real wastewater was used in the study, depending on the composition of wastewater used, somewhat different values might have been observed.

2.4. MBR operation and the experimental studies

The MBR system operated continuously more than 90 d in filtration (10 min)/relaxation (1 min) mode at a constant flux of 18 L/m$^2\cdot$ h in the usual manner. In the usual manner, the system was operated periodically with blower and venturi aeration devices to keep the biomass acclimated to the both operating conditions. No sludge was intentionally wasted during the MBR operation. In usual operation at a flux of 18 L/m$^2\cdot$ h, the hydraulic retention time (HRT) of the MBR was 5.6 h. During this period the pH, DO, MLSS, MLVSS, and temperature changed between 6.5–8.5, 0.34–7.42, 2.5–8.5 g/L, 1.4–7.1 g/L, and 15–37 ºC, respectively. However, for the comparative study of the blower and venturi aeration systems, the conditions were changed to the experimental values for a maximum of 6 h for each test, then the operation returned to the usual manner. To compare the efficiencies of the venturi and blower aeration systems in terms of bioreactor oxygenation and membrane fouling reduction, the MBR was operated under different fluxes (18, 32, and 50 L/m$^2\cdot$ h) at 3 L/min aeration rate for both the venturi and blower systems. At the fluxes of 32 and 50 L/m$^2\cdot$ h, the HRT of the system corresponded to 3.1 and 2.0 h, respectively. The test was terminated when the transmembrane pressure (TMP) reached 250 mbar or the operation time reached six hours. Effluent COD, NH_4–N, NO_3–N, and PO_4–P was measured to compare the treatment efficiencies of the two aeration systems.

3. Results and discussions

3.1. Effects of the Venturi aeration system on treatment efficiency

There was no significant difference between the blower and the Venturi systems in terms of chemical oxygen demand (COD) removal efficiency as shown from Table 3. However, Venturi system achieved more stable COD removal efficiencies. While the COD removal efficiency of the blower system was between 75–92%, it was in the range of 85–87% in the Venturi system. As it is seen from Table 4, while there was no difference between the two systems in terms of effluent PO_4–P concentration, Venturi system performed better nitrification than the blower system because quite high values of NO_3–N concentration was measured in the effluent of Venturi system at fluxes of 32 and 50 L/m$^2\cdot$ h.

Better nitrification observed in the Venturi system can be attributed to the higher oxygen transfer efficiencies observed in this aeration system. As it is seen from Table 5, at the same aeration rate of 3 L/min Venturi system performed higher oxygen transfer efficiencies irrespective of the flux tested. With the same aeration rate of 3 L/min, 1.91, 4.3, and 15.3 times greater DO concentrations were observed in the Venturi system when compared to the blower system at 18, 32, and 50 L/m$^2\cdot$ h fluxes, respectively. This shows that Venturi aeration system always ensured better oxygen transfer rates than conventional diffuser systems.

3.2. Membrane fouling studies

As it seen from Fig. 4(a), a significant difference was observed in terms of membrane fouling between the blower and the Venturi aeration systems at 18 L/m$^2\cdot$ h targeted permeate flux. While the TMP was nearly constant at around 20 mbar during 6 h of operation in the Venturi system, it increased to 180 mbar in the blower system at the end of operation. This shows that the Venturi system retards membrane fouling significantly at the low flux (18 L/m$^2\cdot$ h). A similar result was observed in a previous study that compared the performances of a high rate compact reactor, a type of jet-loop reactor, combined with membrane filtration (MHCR) and a blower-aerated MBR under the constant flux of 15 L/m$^2\cdot$ h [12]. The TMP of the blower-aerated MBR, which was aerated at 4 L/min aeration rate, reached 30 kPa in 1.5 h, whereas the increase in TMP for the MHCR was negligible over 6 h of operation. The improved membrane cleaning performance in the MHCR configuration was attributed to the bubbles and the turbulence generated by a liquid jet in the MHCR. Regarding to the permeate flux, while the difference

Table 3
Concentrations and removal efficiencies of COD in MBR at different fluxes

Aeration system and rate	Flux (L/m^2h)	COD concentration (mg/L)			F/M	COD removal efficiency (%)
		Influent	MBR	Effluent		
	18	324	75.2	25.6	0.35	92
Blower 3 L/min	32	308	85.1	60.8	0.63	80
	50	307	77.6	75.4	1.20	75
	18	458	74.9	59.7	0.23	87
Venturi 3 L/min	32	301	59.9	44.7	0.44	85
	50	388	75.1	51.8	1.04	87

Table 4
Influent and effluent concentrations of phosphorus, ammonia, and nitrate in blower and venturi systems together with MLSS and MLVSS concentration in MBR at different fluxes

Aeration system	Flux (L/m^2h)	MLSS (mg/L)	MLVSS (mg/L)	PO_4–P (mg/L)		NH_4–N (mg/L)		NO_3–N (mg/L)
				Influent	Effluent	Influent	Effluent	Effluent
	18	4020	3620	4.6	3.5	25.6	0.0	27.4
Blower	32	3760	3040	5.9	3.9	38.7	3.9	9.4
	50	3080	2900	5.2	4.1	39.9	14.7	3.1
	18	8460	7140	5.9	3.9	> 47	0.0	33.3
Venturi	32	5280	4220	9.7	4.1	> 47	0.1	37.8
	50	4460	3820	Err.	5.5	> 47	0.7	34.0

Table 5
DO concentration in MBR depending at different aeration systems and varying targeted permeate fluxes

Aeration system	Targeted permeate flux ($L/m^2 \cdot h$)		
	18	32	50
Blower (mg/L)	3.49	1.66	0.42
Venturi (mg/L)	6.68	7.07	6.43

was negligible before 3 h, the difference in fluxes of the both systems tended to increase thereafter as shown in Fig. 5. (a). However, it was not possible to reach the targeted flux of 18 L/m^2.h in the both systems due to membrane fouling.

When the targeted flux was increased to 32 $L/m^2 \cdot h$ the TMPs of the blower and the Venturi systems reached to 240 mbar and 160 mbar, respectively, at the maximum operation time of 360 min as shown in Fig. 4(b).

The difference in the fluxes of the two systems became more clear at the targeted flux of 32 $L/m^2 \cdot h$. As shown in Fig. 5(b), while the flux of the Venturi system was nearly constant at around 26 $L/m^2 \cdot h$, that of the blower system decreased to 12 $L/m^2 \cdot h$ at the maximum operating time of 360 min.

At the highest flux (50 $L/m^2 \cdot h$) tested in this study, the blower system operated for 120 min when it reached the final TMP of 250 mbar, and the Venturi system operated for 360 min, which was three times longer (Fig. 4(c)). As shown in Fig. 5(c), there was a large reduction in the membrane flux for both aeration systems at the highest flux tested (50 $L/m^2 \cdot h$). This shows that the flux of 50 $L/m^2 \cdot h$ was not sustainable for the blower and Venturi aeration systems.

As the results of this study indicates, using a Venturi device, the advantage of a coarse bubble diffuser and that of a fine bubble diffuser can be combined to supply the required aeration in a MBR. However, although Venturi devices are commercially [13–15] used in wastewater aeration systems, an economic analysis should be done to determine if the use of Venturi aeration is feasible in MBR aeration in full-scale systems. Nevertheless, the lab-scale study reported here was not suitable for making such an economical comparison between blower and Venturi aeration systems due to small bioreactor volume, inappropriate blower and centrifugal pump powers for such a small-volume reactor, and operating conditions, such as high fluxes and short-term filtration period, used. Instead of a lab-scale reactor, an economic analysis may be more meaningful in a pilot scale study using at least 1.5–2.0 m^3 aeration tank and using a blower and a centrifugal pump which have the same capacity.

4. Conclusions

A novel aeration method for submerged MBRs that uses a Venturi injector to supply the necessary aeration in to the MBR was developed in this study. The following conclusions can be drawn from this study;

The highly turbulent air–water mixture jet that exited the Venturi device reduced membrane fouling due to more effective surface scouring than the conventional coarse bubble aeration by the blower system as inferred from TMP and

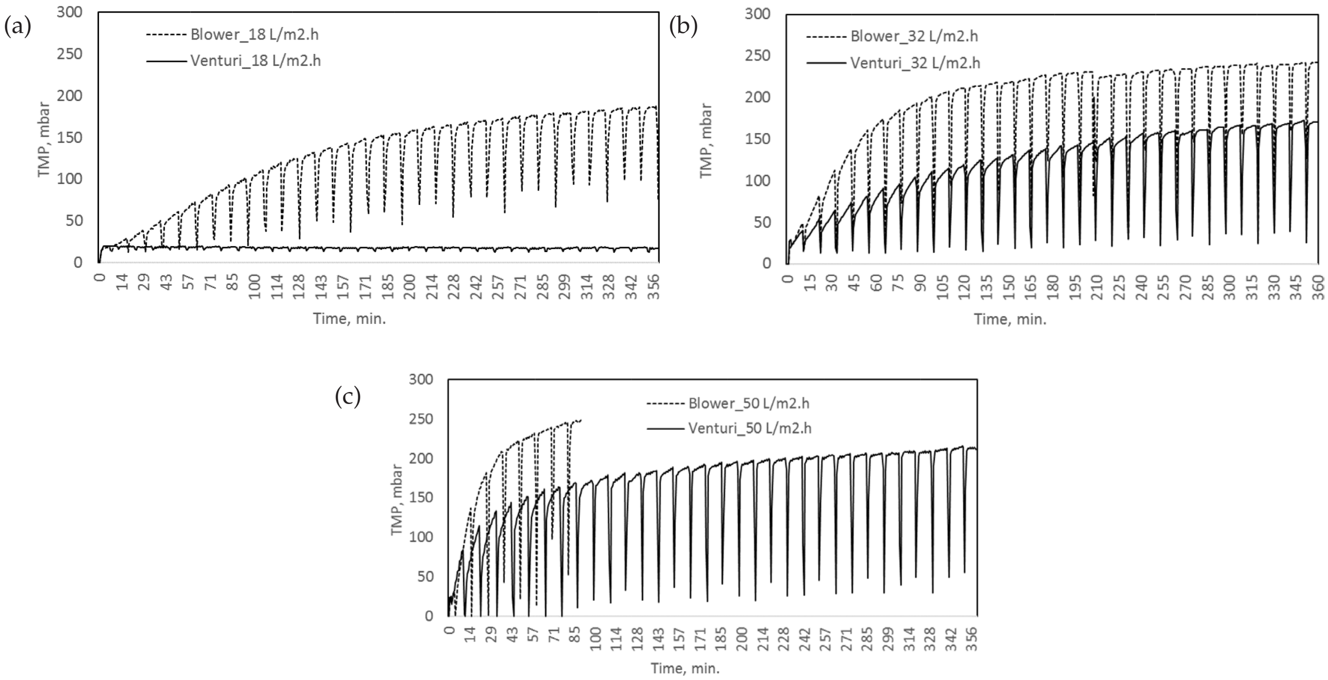

Fig. 4. The TMP development of blower and Venturi aeration systems at target fluxes of (a) 18 L/m²h, (b) 32 L/m²h, and (c) 50 L/m²h.

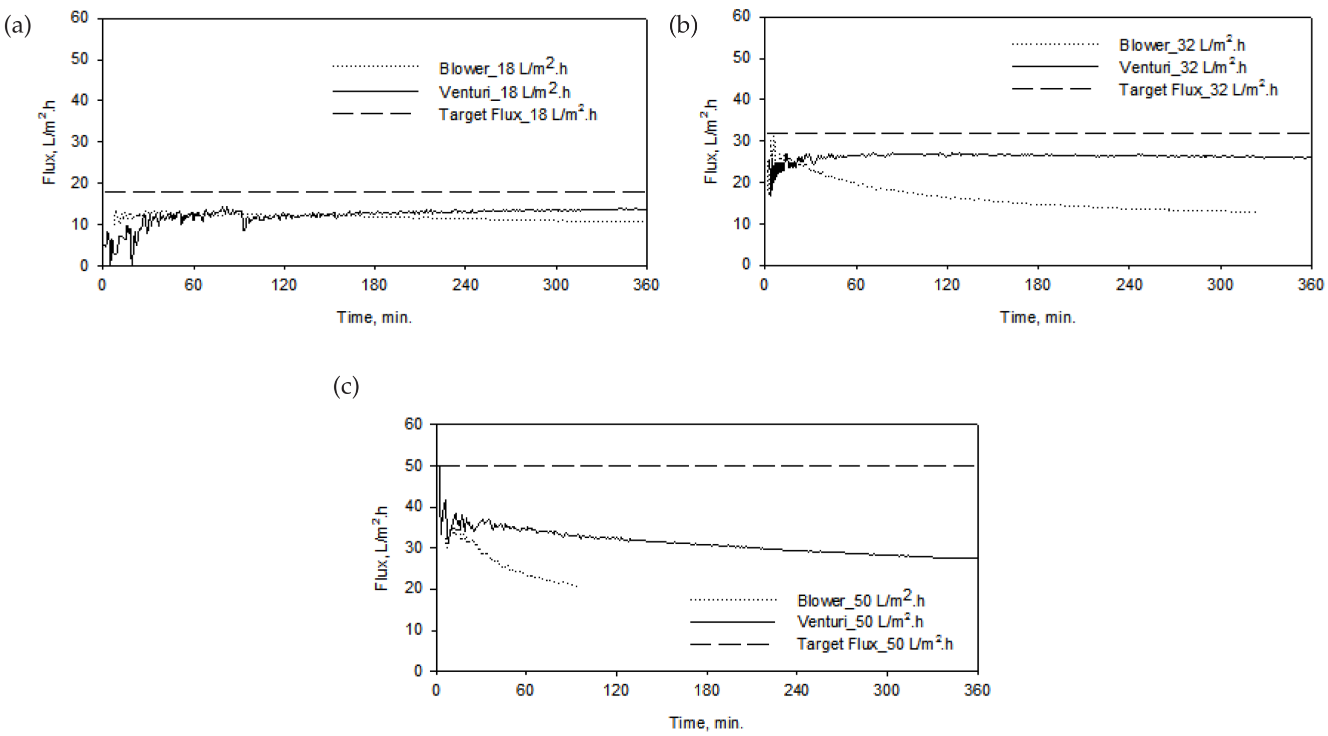

Fig. 5. The flux change of blower and Venturi aeration systems at target fluxes of (a) 18 L/m²h, (b) 32 L/m²h, and (c) 50 L/m²h.

flux measurements. The target membrane flux could not be sustained in both blower and Venturi aeration systems irrespective of the flux tested, however, Venturi system exhibited more stable flux which was closer to the target flux at low (18 L/m² · h) and medium (32 L/m² · h) flux.

Venturi aeration system enabled very high dissolved oxygen concentration in MBR compared to the conventional coarse bubble diffuser with the blower system.

Despite similar COD removal rates, better nitrification occurred in the Venturi system than that in the blower system, which also showed the greater oxygen transfer efficiency of Venturi aeration system.

Although this study shows the technical applicability of incorporating a Venturi device to an MBR, an economic analysis should be made in a future pilot-scale study to justify the possible use of such a system in full-scale applications.

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