A venturi device reduces membrane fouling in a submerged membrane bioreactor
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ABSTRACT
In this study, for the first time, a venturi device was integrated into a submerged membrane bioreactor (MBR) to improve membrane surface cleaning and bioreactor oxygenation. The performances of a blower and the venturi device were compared in terms of membrane fouling and bioreactor oxygenation. Upon comparing membrane fouling, the performances were similar for a low operation flux (18 L/m².h); however, at a medium flux (32 L/m².h), the venturi system operated 3.4 times longer than the blower system, and the final transmembrane pressure was one-third that of the blower system. At the highest flux studied (50 L/m².h), the venturi system operated 5.4 times longer than the blower system. The most notable advantage of using a venturi device was that the dissolved oxygen (DO) concentration of the MBR was in the range of 7 to 8 mg/L at a 3 L/min aeration rate, while the DO concentration of the MBR was inadequate (a maximum of 0.29 mg/L) in the blower system. A clean water oxygenation test at a 3 L/min aeration rate indicated that the standard oxygen transfer rate for the venturi system was 9.5 times higher than that of the blower system.

Key words | aeration, fouling, membrane bioreactor (MBR), venturi device

INTRODUCTION

Membrane bioreactors
A membrane bioreactor (MBR) combines biological treatment and membrane filtration. Using a membrane as a biomass separation tool provides many advantages, including high solids retention, high biomass concentration, and rapid process startup (Pollice et al. 2008). Together with these advantages, there are also some disadvantages. While a high mixed liquor suspended solids 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. Because of the oxygen required for the biomass and the air required to scour the membrane surface, MBRs use intensive aeration, which has high operating costs. The aeration of MBRs has been reported to comprise more than 80% of the operating costs (Gander et al. 2000; Meng et al. 2008). Aeration is commonly performed by air blowers in biological wastewater treatment and is also valid for MBRs. A summary of previous studies on the aeration of submerged MBRs is given below.

Aeration of submerged MBRs for membrane fouling
Aeration-related membrane fouling studies on submerged MBRs have mostly addressed the optimization of the aeration intensity (or aeration rate/membrane area), aeration regime (cyclic/continuous), and bubble size. The aeration intensity was found to influence the membrane fouling rate, but the effect of the aeration intensity on the membrane fouling rate at various fluxes (5–25 L/m².h) could be neglected at high aeration intensities. A sudden transmembrane pressure (TMP) increase was observed when the aeration intensity was reduced from 1.5 to 1.0 m³ per unit membrane area per hour (Johir et al. 2011). Similarly, doubling the air flow scouring on the membrane surface provided a substantial reduction in membrane fouling by extending the filtration duration from 10–50 days to over 200 days (Orantes et al. 2006). Nonetheless, an excessive aeration rate may cause even more fouling. Although increasing the aeration rate from 400 L/h to 800 L/h reduced the cake layer accumulation on the membrane surface, it also caused the breakage of flocs and distribution of colloids and solutes previously adsorbed on the sludge flocs.
in the bulk solution, which resulted in denser cake layer formation and a greater specific cake resistance (Meng et al. 2008). It was observed in another study that the sludge accumulation on the membrane surface decreased with increasing aeration rates (0–25 L/min). However, this effect did not increase linearly with the aeration rate, and the effect was negated when the critical aeration rate was exceeded (Han et al. 2005). Consequently, aeration rates that were lower or higher than the optimum rate promoted a reduction in the permeability of the membrane filtration in the MBRs (Rahimi et al. 2011).

In addition to the aeration rate, the diffuser orifices that sparge air onto the membrane surface were optimized. Mayer et al. (2006) studied the uniform distribution of 10 different aerator devices, including the nozzle, tube, disk and membrane diffusers with orifice diameters ranging from 0.05 to 4 mm. The previous study reported that micro-membrane diffusers supplied the most uniform aeration across the tubular membrane module, but these diffusers were the most complex devices studied. Because there was no filtration, the effectiveness of these devices in reducing membrane fouling was not evaluated. In another configuration, jet loop MBRs, which introduce pressurized air into activated sludge recycle lines, were used to increase the mass transfer of air into the water phase (Kouakou et al. 2005).

In all aeration-related membrane fouling reduction studies with MBRs, a blower or an air compressor was used to supply the air, as demonstrated in the three review papers on membrane fouling reduction in MBRs (Le-Clech et al. 2006; Meng et al. 2009; Drews 2010). However, in a newly adopted technique to aerate wastewater (Dong et al. 2012), the use of a blower or a compressor is eliminated, and instead a venturi device is used for the aeration of activated sludge.

**Venturi device**

A venturi device is created by combining a converging and a diverging cone, as shown in Figure 1. A pressurized fluid enters the converging part and transforms the pressure head into a velocity head, which creates a vacuum at the suction port of the venturi (Baylar & Ozkan 2006). If the suction port is open to the atmosphere, then the air entering the venturi device forms a high-velocity two-phase (air–water mixture) jet at the exit. The design of aeration devices based on the venturi principle has become popular in recent years because venturi aerators possess high air injection efficiencies, which makes the aeration of wastewater treatment systems more effective (Dong et al. 2012). 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 (Englehardt et al. 2013). As another example, for CO2 injection into seawater, the injection efficiency with a venturi was 100% higher than that with a porous stone air diffuser (Du et al. 2012). In practice, venturi devices have applications in areas such as air stripping, the aeration of irrigation water, ozonation, disinfection, oxygenation and odor control for wastewater treatment (Mazzei 2013). The high gas transfer efficiency of the venturi device has great potential for MBR applications.

When integrated into an MBR, the dual effects of a venturi device, namely, the high oxygen transfer efficiency and the air–water mixed jet flow, may relieve some of the disadvantages of the MBR system. However, there is a lack of research in this area. Therefore, the aim of this study is to compare the efficiencies of a blower and a venturi device aeration system in terms of membrane cleaning and bioreactor oxygenation in a submerged MBR.

**MATERIALS AND METHODS**

**Experimental setup, membrane, and venturi device**

A 10 L MBR experimental setup was used in this study. A schematic diagram of the setup is shown in Figure 2(a). Either the blower or 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. In venturi mode, a centrifugal pump circulated the biological suspension of the MBR through the venturi device. Because the pressure was below atmospheric pressure, air entered through the suction port of the venturi. The air discharge was adjusted...
using an air rotameter. The air–water mixture was then directed to the surfaces of the membrane module through a coarse air diffuser. Two Plexiglass panels with the same dimensions as the membrane panel were inserted in front of and behind the membrane panel to account for the wall effect (Figure 2(b)).

The membrane was a flat-sheet polyvinylidene fluoride membrane with a pore size of 0.1 μm. The dimensions (W × H × T) of the membrane panels were 220 × 320 × 6 mm, and the effective membrane area was 0.1 m².

**Influent wastewater, MBR operation and experimental system**

The MBR was fed with synthetic wastewater and the properties are given in Table 1, which was adapted from a previous
The biomass concentration of the MBR was between 5,520 and 6,140 mg/L during the experiments, and the effluent chemical oxygen demand (COD) was between 5 and 15 mg/L. The bioreactor pH, dissolved oxygen (DO) and temperature were 5.91–7.62, 1.0–6.1 mg/L and 24.1–30.5°C, respectively. The bioreactor was operated for 40 days, including the acclimation period before the experiments. No sludge was wasted during this period.

Three different fluxes (low, 18 L/m².h; medium, 32 L/m².h; and high, 50 L/m².h) were used with a constant MBR aeration of 3 L/min to study the performance of each aeration system in terms of the reduction in membrane fouling and bioreactor oxygenation. A separate clean water oxygenation test, the details of which are given below, was performed to determine the standard oxygen transfer rate and standard oxygenation efficiency (SOE) at a 3 L/min aeration rate for both aeration systems. Membrane filtration was performed in continuous mode. When the TMP reached 250 mbar or the operation time reached 6 hours, the experiment was terminated.

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 m³/h; suction intensity, 7.5–10 Nm³/h; and length, 152 mm.

The TMP and membrane fluxes were recorded every 15 minutes. The same membrane panel was used for all of the 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 hours.

### Oxygen transfer in clean water

Standard oxygen transfer rate (SOTR) experiments were performed using the same blower and venturi devices that were used in the MBR, but a 31 L (25 × 25 × 45 cm) clean water tank with four nozzles on the bottom was also used. To deoxygenate the water, 150 mg/L sodium sulphite and 1 mg/L cobalt chloride were used (Dong et al. 2012), and the DO concentration and temperature were recorded every 30 sec. The aeration volume was adjusted to 3 L/min for both the blower and venturi device with an air rotameter.

The oxygen transfer rate is defined as follows (Dong et al. 2012):

\[
\frac{dC}{dt} = K_L a (C_s - C)
\]

where \( C \) is the oxygen concentration in the water (mg/L), \( C_s \) is the saturation concentration of DO (mg/L), \( t \) is the time (h), and \( K_L a \) is the overall mass transfer coefficient (1/h). \( K_L a \) can be defined as the slope of a semi-logarithmic plot of the concentration difference \( C_s - C \) versus time and is converted to a standard temperature of 20°C with the following equation:

\[
(K_L a)_{20} = \frac{(K_L a)_T}{1.024^{(T/20)}}
\]

where \( (K_L a)_{20} \) is the overall mass transfer coefficient at \( T = 20°C \) (1/h), and \( T \) is the water temperature (°C).

### RESULTS AND DISCUSSION

#### Membrane fouling studies

There was a negligible TMP rise at low flux (18 L/m².h) for both the blower and venturi aeration systems, as shown in Figure 3. There was no reduction in flux for either aeration
system at the low flux, as shown in Figure 4. While the pH was in the same range of 7.0–7.5 for both aeration systems, a 5 °C difference was observed, as shown in Figure 5. Because a circulation pump was used in the venturi device system, the temperature of the MBR tended to increase with time, but it was kept constant at 30 °C with a tap water cooling system. This 5 °C difference between the two aeration systems did not affect the fouling results because, as shown in Figure 3, there was no difference in the TMP development of the two systems. However, a temperature correction factor was not used to report the TMP results at the same temperature for the two systems. A temperature increase due to circulation pump usage was also reported in some previous studies using a jet loop reactor (JLR) to aerobically treat brewery and winery wastewaters. For example, the temperatures of JLRs used for brewery (Bloor et al. 1998) and winery (Petruccioli et al. 2002) wastewater treatment were between 35 and 39 °C.

At a low flux (18 L/m².h) and a 3 L/min aeration rate, the biggest difference between the blower and venturi systems was observed for the DO concentration of the MBR, as shown in Figure 6. While the DO concentration was...
between 0.18 and 0.29 mg/L for the blower system, it was in the range of 7.21–7.86 mg/L for the venturi system. Although we did not find a direct comparison between a blower and a venturi aeration system used in activated sludge aeration, studies on jet aeration systems, which are similar to venturi gasification systems, showed higher gas transfer efficiencies than conventional diffuser systems. For example, in a JLR aerobically treating a high strength winery wastewater, DO was always greater than 30% of the saturation when the loading rate was between 0.4 and 5.9 kg COD/m$^3$.d (Petruccioli et al. 2002). A high DO transfer efficiency in a JLR also enabled high COD loading rates up to 50 kg COD/m$^3$.d (Bloor et al. 1995). In another study, a venturi device provided an ozone transfer rate that was six times higher for secondary effluent disinfection (Englehardt et al. 2013). Additionally, the CO$_2$ transfer rate to seawater was reported to be two times higher than that of a porous stone air diffuser (Du et al. 2012).

This large difference in aeration efficiency between the venturi and blower aeration systems was because of the higher gas transfer rate of the venturi device compared to that of the blower system. The higher gas transfer in the venturi system was the result of the highly turbulent conditions in the throat portion of the venturi device. Because the turbulence increased the air–water contact surface, the mass transfer of the air increased proportionally. Therefore, when integrated with a venturi device, lower aeration rates can be used to sustain MBR operation. For example, in a patented, commercial MBR system (Memjet® MBR, Memcor, Siemens), although it was difficult to find information on the internet about how the technology was used; it seems that compressed air was injected with activated sludge in the form of a jet, which is a technique similar to the one used in some JLR configurations. It was claimed that a higher membrane packing density was permitted, along with specific aeration demand (SAD$_{m}$) values below 0.3 Nm$^3$/h.m$^2$ membrane area, while SAD$_{m}$ changes in the range of 0.34–0.75 Nm$^3$/h.m$^2$ were permitted for Kubota modules (Judd 2006).

As the flux increased from low (18 L/m$^2$.h) to medium (32 L/m$^2$.h) values, a difference in TMP was observed between the blower and venturi systems. As shown in Figure 3, the TMP reached its final permitted value of 250 mbar after operating for 106 minutes in the blower system, while it only reached 93.3 mbar at the maximum operating time of 360 minutes in the venturi system. This shows that the venturi system retards membrane fouling at the medium flux (32 L/m$^2$.h). A similar result was observed in a previous study that compared the performances of a high rate compact reactor, a type of JLR, combined with membrane filtration (MHCR) and a conventional MBR under the constant flux of 15 L/m$^2$.h (Yeon et al. 2005). The TMP of a conventional MBR, which was aerated by a blower at a 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.

At the medium flux target (32 L/m$^2$.h), a minor decrease was observed in the blower system, and the venturi system sustained the target flux during the entire operation period (Figure 4). The improved reduction in membrane fouling by the venturi device relative to that of the blower system can be attributed to the high-velocity air–water mixture jet.

![Figure 5](https://iwaponline.com/wst/article-pdf/74/1/147/459657/wst074010147.pdf) | Temperature change in MBR at low (18 L/m$^2$.h) flux.

![Figure 6](https://iwaponline.com/wst/article-pdf/74/1/147/459657/wst074010147.pdf) | DO concentration in MBR at low (18 L/m$^2$.h) flux.
that was efficiently directed towards the membrane surface. No matter at what angle the air exits, leaving the diffuser orifices it immediately flowed in the vertical direction on a random path. Conversely, the high-velocity mixed jet flow from the venturi device can effectively be directed toward the membrane surface, which will effectively scour the membrane surface. Although we did not provide supplementary media to show the difference between the mixed jet coming from the venturi and the air coming from a blower system, the random vertical motion of the latter can be easily observed in a basic installation. For medium flux, there was no significant difference between the two systems in terms of pH and temperature, but a large difference was observed for the DO concentration of the MBR (data not shown).

At the highest flux (50 L/m².h) tested in this study, the blower system operated for only 24 minutes when it reached the final TMP of 250 mbar, and the venturi system operated for 129 minutes, which was more than five times longer (Figure 3). As shown in Figure 4, there was a large reduction in the membrane flux for both aeration systems at the high flux (50 L/m².h). This shows that the high flux was not sustainable for the blower and venturi aeration systems.

Oxygen transfer parameters of the blower and venturi systems

To determine the SOTR and SOE of the blower and venturi aeration systems, a clean water test was performed. As shown in Figure 7(a), the venturi system reached the saturation concentration faster than the blower system. For example, to reach a 7 mg/L DO concentration in the tank, the blower system required more than 30 minutes and the venturi system needed less than 5 minutes. The values of the SOTR and SOE are shown in Table 2. The overall oxygen transfer coefficient \( K_{L,a} \) and SOTR of the venturi system are 9.5 times higher than those of the blower system at a standard temperature of 20 °C. In addition, the SOE, which was normalized by the pump power, was also higher (4.33 times) in the venturi system. In a previous study (Bloor et al. 1995), the oxygen transfer efficiency of a JLR was measured by a clean water test. Using a nozzle configuration with a 12 mm
diameter and 6 mm air tube, a maximum oxygen transfer coefficient \( K_{La} \) of 157.9/h was obtained at 20 °C. As shown in Table 2, a \( K_{La} \) of 26.88/h was found for the venturi system in our study. The reason for the smaller \( K_{La} \) found in our study was that we adjusted the air suction rate to 3 L/min with a rotameter to make a comparison between the blower and the venturi aeration systems at the same aeration rate. So we did not fully use the capacity of the venturi device, while in the previous study, the aeration rate was 22 L/min. Also the volume of the clean water tank in our study was 31 L, while it was 20.3 L in the previous study. In another study (Farizoglu & Uzuner et al.) that used an air compressor to supply air to a JLR at a 10 L/min aeration rate, increasing \( K_{La} \) values ranging from 102 to 164/h were obtained for increasing liquid phase velocities of 20–80 m/s. It was reported that approximately 100 times higher \( K_{La} \) values were obtained in the JLR configuration compared to a conventional reactor system.

Oxygen transfer efficiencies for a different combination of fine bubble diffuser and coarse bubble crossflow aeration devices were measured in two different reactors (Reactor A with coarse bubble crossflow, reactor A with fine bubble crossflow, reactor B with fine bubble aeration, and reactor B with fine bubble aeration + coarse bubble crossflow) to calculate \( \varepsilon \)-factors in an MBR-treated synthetic greywater (Henkel et al. 2009). With clean water tests, a minimum and a maximum oxygen transfer rate of approximately 18 and 65 g O₂/m³.h were obtained for fine bubble diffuser + coarse bubble crossflow reactor B and fine bubble crossflow reactor A, respectively, at an aeration rate of approximately 80 L/min. In the current study with a 3 L/min aeration rate, 16.5 and 157 g O₂/m³.h oxygen transfer rates were obtained for the blower and venturi aeration systems, respectively, which can be calculated from Table 2 for a 31 L aeration tank. This shows that venturi aeration has better performance than the conventional aeration systems used in submerged MBRs in terms of oxygen transfer efficiency.

### Effects of the venturi aeration system on treatment efficiency

The use of a venturi device for the aeration of the MBR did not affect the treatment performance. As shown in Table 3, the total and soluble COD removal performances were in the range of 94% to 95% after 6 hours of operating the venturi aeration system. The values of the total and soluble COD in the MBR supernatant after 6 hours of venturi operation also showed that there was no negative effect on the MBR from using the venturi device in terms of the COD removal efficiency. Table 3 shows that the soluble COD in the MBR supernatant was quite low (25.5 mg/L), which indicated that there was no COD accumulation in the MBR due to venturi aeration. Using a JLR system to aerobically treat high strength brewery wastewater, 97% of the COD removal was obtained with a 50 kg COD/m³.d loading rate (Bloor et al. 1995).

A minor disruption in the floc structure of the MBR was observed after 6 hours of venturi aeration. As shown in Figure 8, the MBR supernatant (centrifuged at 2,000 rpm for 2 minutes) after 6 hours of venturi aeration was more turbid than that of the blower system. However, when the system was subsequently treated with the blower aeration system, the floc structure reverted to its normal appearance (as shown in Figure 8(a)) in 1 hour. This result shows that the disruption in the floc structure in the venturi system

### Table 2 | Oxygen transfer parameters for blower and venturi systems

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Blower</th>
<th>Venturi</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_{La} ) Blower (25 °C) (1/h)</td>
<td>3.17</td>
<td></td>
</tr>
<tr>
<td>( K_{La} ) Venturi (26 °C) (1/h)</td>
<td>30.99</td>
<td></td>
</tr>
<tr>
<td>( K_{La} ) (20 °C) (1/h)</td>
<td>2.82</td>
<td>26.88</td>
</tr>
<tr>
<td>SOTR (kg O₂/h)</td>
<td>0.00051</td>
<td>0.00488</td>
</tr>
<tr>
<td>Pump power (kW)</td>
<td>0.2</td>
<td>0.37</td>
</tr>
<tr>
<td>SOE (kg O₂/kW.h)</td>
<td>0.003</td>
<td>0.013</td>
</tr>
</tbody>
</table>

### Table 3 | COD removal efficiency and COD of MBR supernatant after 6 hours of operating the venturi aeration system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent mass (mg/day)</th>
<th>Influent concentration (mg/L)</th>
<th>Effluent mass (mg/day)</th>
<th>Effluent concentration (mg/L)</th>
<th>Removal efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total COD</td>
<td>9980</td>
<td>231</td>
<td>488.2</td>
<td>11.3</td>
<td>95.1</td>
</tr>
<tr>
<td>Soluble COD</td>
<td>1765</td>
<td>204.3</td>
<td>488.2</td>
<td>11.3</td>
<td>94.5</td>
</tr>
<tr>
<td>Total MBR supernatant COD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soluble MBR supernatant COD</td>
<td></td>
<td></td>
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</tbody>
</table>
was temporary. In addition, as shown in Table 3, the total MBR supernatant COD after 6 hours of operating the venturi aeration system was 330 mg/L. If 1.42 mg COD/mg TSS (total suspended solids) was assumed, then the TSS concentration in the supernatant could be 232 mg/L, which indicated that a very low fraction of the MBR flocs were disrupted. Similar to the turbid supernatant observed in our MBR, a cloudy effluent was also previously reported in a JLR treating high strength brewery wastewater (Bloor et al. 1995). High shear force conditions at the nozzle and a high organic loading rate (50 kg COD/m³.d) in the JLR caused the absence of protozoa and filamentous bacteria, and the treated effluent to be characterized by high concentrations, 200–350 mg/L, of free motile bacteria.

In another study, cavitations caused by the venturi effect were used to reduce MBR sludge production. It was reported that nozzle-cavitation treatment had no negative effects on MBR treatment performance because the COD removal efficiency and nitrification did not change after the introduction of cavitation (Hirooka et al. 2009).

CONCLUSION

This study aimed to compare blower and venturi aeration systems in terms of membrane fouling and bioreactor oxygenation in a submerged MBR system. The following conclusions can be drawn from the results obtained in this study:

1. The air requirement for a submerged MBR can be reduced significantly by integrating a venturi device for aeration. Because aeration is the highest cost for submerged MBR operation, venturi aeration can reduce the operating costs of submerged MBR systems.

2. The high-velocity air–water mixture at the exit of the venturi device, when directed toward the membrane surfaces by a diffuser system, can retard membrane fouling at medium/high fluxes.

Although it was not included in the current study, there may be an additional benefit for integrating a venturi device with a submerged MBR. Because a vacuum (suction pressure) was generated in the throat portion, a venturi device can also be used to draw permeates from the membrane, which eliminated the need for a permeate pump. By modifying a submerged MBR, two venturi devices can be used in parallel on the circulation line, one for aeration and the other for permeate drawing.

ACKNOWLEDGEMENTS

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