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A new concept of a rotating hollow fibre membrane module:impact of rotation on fine-bubble aeration

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ABSTRACT

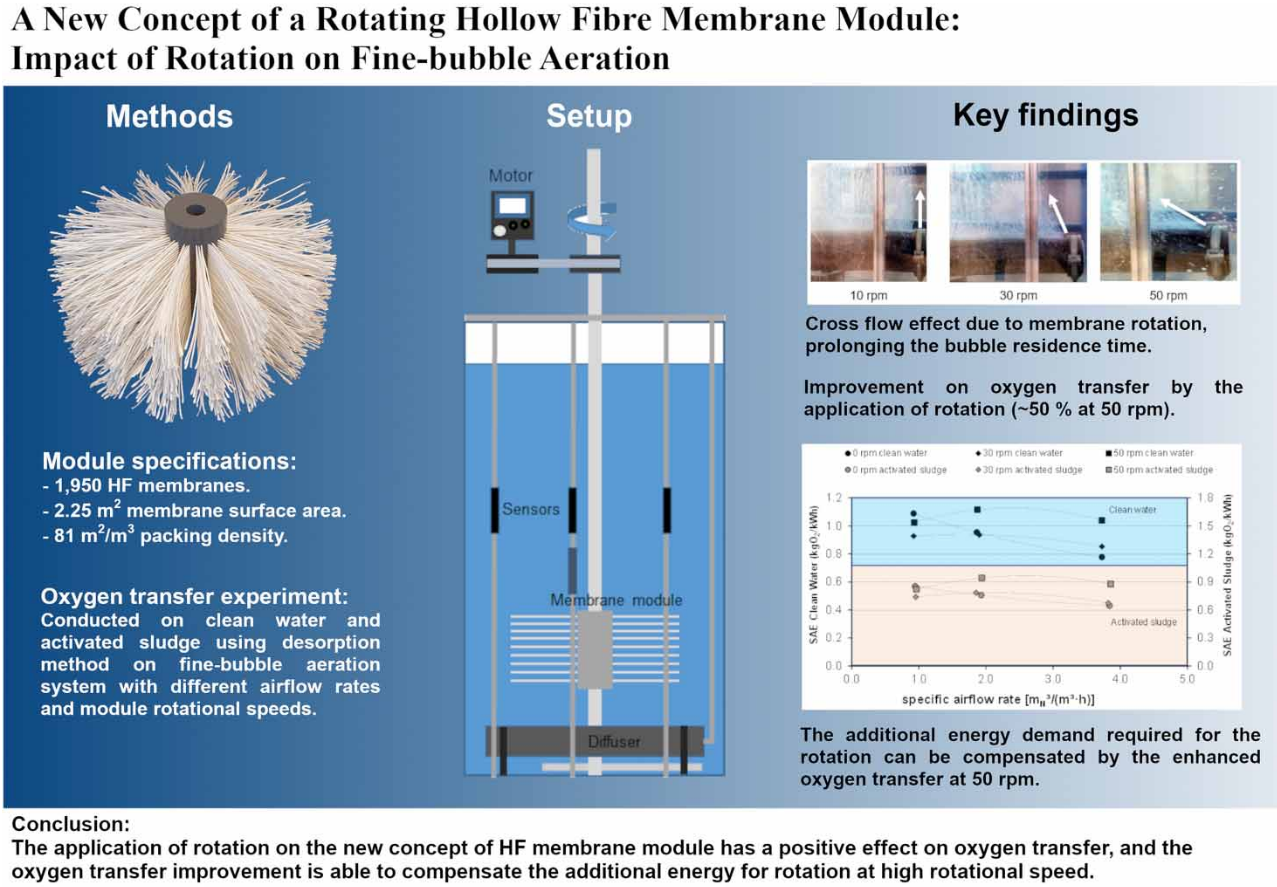
A new concept of a rotating membrane module in a membrane bioreactor (MBR) system was tested for its effect on oxygen transfer in clean water and wastewater. The membrane module consists of horizontally aligned hollow fibres connected to the vertically positioned permeate tube which rotates. The results indicated that oxygen transfer can be improved by up to 50% at the highest applied rotational speed (50 rpm) and that the additional energy demand required for the rotation can be compensated by the enhanced oxygen transfer. However, at the highest rotational speed (50 rpm), the fine bubbles bypassed the MBR module, and, consequently, could not contribute to any cleaning effect. The α-factors at different rotational speeds showed similar results. This indicates that the depletion was caused neither by surfactants nor by viscosity phenomena but rather by the floc/solid holdup of the sludge.

Key words: membrane bioreactor, oxygen transfer, rotation, α-factor

HIGHLIGHTS

- The novel membrane bioreactor configuration provides a promising result in oxygen transfer experiments.
- With the introduction of 50 rpm rotation, the oxygen transfer was improved by 50%.
- The floc volume was the main driver for oxygen transfer depletion.
- The additional energy demand for rotation can be compensated by the better oxygen transfer efficiency.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The use of membrane bioreactor (MBR) systems becomes a growing interest due to tighter environmental regulations, water scarcity and the rising need of water reuse (Judd 2016; Paul & Jones 2016). The MBR system offers the ability to achieve high nutrient removal efficiency and complete biomass retention at a small footprint (Hoinkis *et al.* 2012; Meng *et al.* 2017). However, MBR systems also suffer from membrane fouling and clogging, which impacts the performance of the system significantly and makes frequent cleaning procedures inevitable. In addition, MBR systems are still considered expensive in comparison to conventional activated sludge (CAS) systems. The average energy consumption of immersed MBRs per m^3 of treated municipal wastewater ranges between 0.8–1.1 kWh/m^3 with the lowest reported value being 0.4 kWh/m^3 (Judd 2011; Krzeminski *et al.* 2017).

For both MBR and CAS systems, aeration is responsible for more than 50% of the energy demand (Judd 2011; Helmi & Gallucci 2020). The overall aeration demand is typically higher for MBR than for CAS systems because the higher sludge concentration (floc/solid holdup) lowers the oxygen transfer rate and an additional air cross flow is required to reduce membrane clogging and fouling (Henkel *et al.* 2011).

Several studies were conducted to improve the performance of MBRs in terms of fouling reduction and aeration efficiency (Judd 2016; Helmi & Gallucci 2020). One possible method is the introduction of a dynamic shear force through rotation (Jaffrin 2008; Wu *et al.* 2008; Jiang *et al.* 2013; Ruigómez *et al.* 2016; Zsirai *et al.* 2016). Rector *et al.* (2006) did experiments on a rotating membrane bioreactor using a hollow fibre (HF) module. They concluded that the rotation of HF membrane modules provides an efficient method of prompting turbulent flow and higher dispersion in an MBR system. Paul & Jones (2016) also showed that rotating MBR systems had better performance than static MBR when both systems were operated under similar conditions.

This paper introduces a novel membrane configuration where horizontally aligned HFs are connected to a vertical permeate tube. The membrane module rotates in the activated sludge reactor. The rotation creates a permanent shear force at the fibre and eliminates the need of a uniformly distributed aeration device below the membrane unit. In comparison to current membrane systems, the fibre length is relatively short (<20 cm), which is expected to improve the backwash and cleaning process significantly.

The study was conducted to investigate the impact of different rotation velocities on oxygen transfer in a CAS plant. Hence a fine bubble aeration system and activated sludge from a nearby conventional activated sludge plant were used. To determine the impact of sludge flocs on aeration performance also clean water tests were performed to evaluate the ratio of sludge to clean water oxygen transfer coefficients (α-factor). Finally, the rotation energy was calculated and put into relationship with the oxygen transfer measurements.

2. MATERIAL AND METHODS

2.1. Membrane prototype

The membrane module (Figure 1) consists of 1,950 HF membranes with one side potted horizontally into the permeate tube and sealed at the other side. The material of HF membrane is polyvinylidene difluoride (PVDF) with the pore size of 0.3 μm. The total surface area of the membrane module is 2.25 m^2, which leads to a packing density of 81 m^2/m^3. Due to the horizontal membrane alignment and the applied rotation, all membranes are in contact with the air bubbles even though only one segment of the membrane prototype is aerated.

2.2. Experimental setup

The measurements were carried out in a transparent tank filled with clean water (softened tap water) and activated sludge with a volume of 1 m^3. The softened water was chosen to prevent any hardness precipitation during the experiments. The activated sludge was obtained from the wastewater treatment plant in Königsbach, Germany (55,000 PE). The experiments were performed in batch mode. No feed or filtrate was added nor taken during the experiment. A Flexnorm 500 diffuser (OTT System GmbH & Co. KG, Langenhagen, Germany) was used as fine bubble air diffuser. The airflow rates and dissolved oxygen (DO) concentrations were measured with a thermal flow sensor TA Di 21.6 GE (Hoentzsch GmbH, Waiblingen-Hegnach, Germany) and three oxygen electrodes (PRONOVA Analysentechnik GmbH & Co., Bad Klosterlausnitz Germany), respectively. In addition, the ambient parameters (air temperature, pressure and partial humidity) were documented through a weather station. Figure 2 shows the setup of the pilot plant.

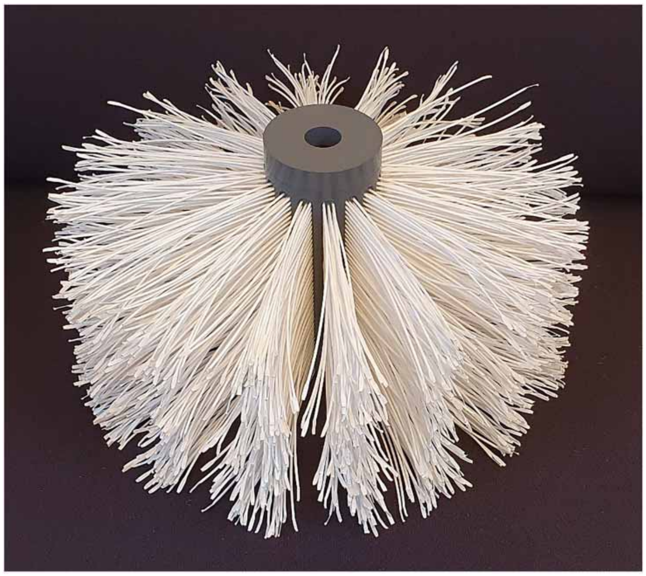


Figure 1 | Rotatable membrane prototype system with 1,950 horizontally aligned hollow fibres.

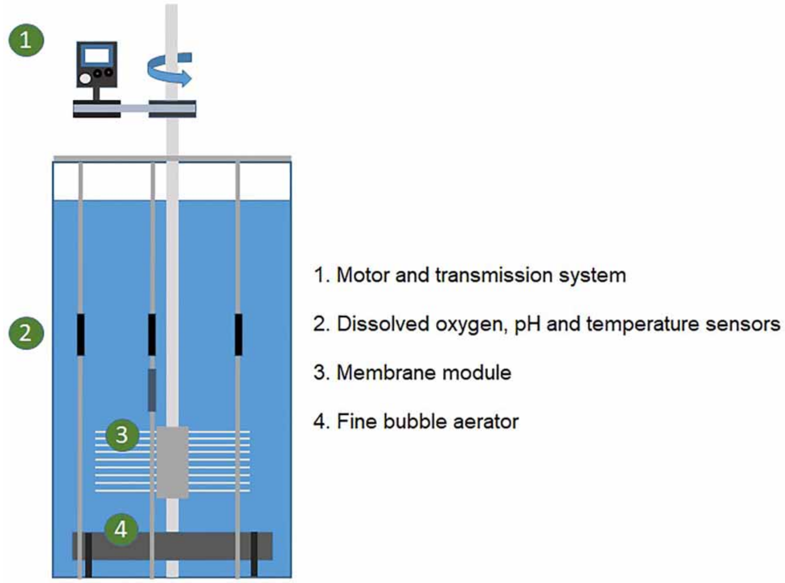


Figure 2 | Setup of the pilot plant of the rotatable membrane prototype system.

2.3. Sludge characteristics

Tables 1 and 2 below show the sludge characteristics and an example of the floc sedimentation test to define the hydrostatic floc volume (HFV) for the activated sludge during the experiment days. After an initial decrease in mixed liquor volatile suspended solids concentration (MLVSS) and HFV during the first 12 hours following activated sludge collection, both values remained relatively stable during experiments, indicating that their impact on the measured oxygen transfer coefficient was stable.

Table 1 | Sludge characteristics for activated sludge experiments at 0 and 50 rpm

Working day	Sampling time	MLSS (g/L)	MLVSS (g/L)	HFV (ml/L)	Conductivity (μS/cm)
1	–	–	–	–	–
	Afternoon	4.50	3.15	180	1,540
2	Morning	3.88	2.71	170	1,555
	Afternoon	3.58	2.47	150	1,563
3	Morning	3.50	2.40	160	1,565
	Afternoon	3.60	2.50	175	1,577
4	Morning	3.70	2.50	175	1,585
	Afternoon	3.60	2.40	175	1,590

Table 2 | Floc sedimentation test for activated sludge experiment

Elapsed time	Volume ratio (mL/L)	
0 h	1,000	
0 h 30 m	300	
16 h 10 m	175	
24 h 0 m	175	(HFV)
39 h 20 m	175	

2.4. Oxygen transfer measurements

As the oxygen concentration in the sludge ranged from 7.2 to 9.9 mg/L and the saturated concentration was up to 10.13 mg/L O_2 during the experiments, the off-gas method was not appropriate in these conditions (Krause *et al.* 2003). Therefore, the desorption method described by Wagner *et al.* (1998) and DWA-M 209 (2007) was chosen for calculating the oxygen transfer coefficient (k_La) value. In this method, the oxygen transfer rate is determined from the decrease in the DO concentration when the water is diffused with normal air. The DO concentration in clean water and in activated sludge was artificially increased above saturated concentration in advance using pure oxygen aeration into the water. Five different rotational speeds (0, 10, 30, 40 and 50 rpm) for clean water and three different rotational speeds (0, 30 and 50 rpm) for activated sludge were tested at three different airflow rates (1, 2, 4 m^3/h). The k_La value was normalized to the standard conditions (k_La_{20}) at a water temperature of 20 °C and an atmospheric pressure of 1,013 hPa, and with the correction factor for a salt concentration of 1 g/L, due to significant differences between the salt content of clean water and wastewater (DWA-M 209 2007).

During activated sludge experiments, it is compulsory to maintain constant respiration rates. This was achieved by aerating the activated sludge for at least 12 hours before the experiment started. This nullified the impact of degradable surfactants on oxygen transfer. Consequently, the results should mainly reflect the impact of activated sludge flocs on oxygen transfer depletion.

2.5. Calculating the α-factor

Three oxygen sensors recorded the change of the oxygen concentration in the sludge at a constant airflow rate and a constant sludge concentration. From these records, the k_La was determined by non-linear regression and an average k_La was calculated. Subsequently, the airflow rate was changed and the procedure was repeated at the same sludge concentration. Three airflow rates were chosen for each experiment series with the same sludge concentration. Afterwards, the three average k_La_{20} values were plotted against the specific airflow rate and trends were defined by polymeric trendlines.

This procedure was performed in clean water and activated sludge. Finally, the comparison between the k_La_{20} value of activated sludge and clean water defined as the α-factor was calculated by dividing the trendline equation at a certain sludge concentration by the equation obtained during the clean water experiment. As x-variable, the three applied specific airflow rates were inserted into the equation and as a result, three α-factors were received for each sludge concentration. This modus operandi was applied since it was not possible to have identical airflow rates for each experiment series. Humidity, air pressure, air temperature and the air blower influenced the airflow rate, which was transformed to standard conditions.

2.6. Calculating the energy demand

The energy consumption was calculated from the electrical demand of the blower and the reading from the rotational device. The blower energy consumption followed the equation introduced by the blower manufacturer: Power (W)$=35\times$volume flow. According to the reading from the rotational device, it consumed 16.52 W at 30 rpm and 17.27 W at 50 rpm.

3. RESULTS AND DISCUSSIONS

3.1. Clean water experiments

The results in clean water showed that both specific airflow rates and the rotational speeds of the membrane prototype influenced the k_La_{20} value in direct proportion, see Figure 3.

The oxygen transfer rate rises steadily because with increasing airflow rate, the gas holdup increases. As the airflow rates increase, the efficiency decreases slightly due to the creation of bigger bubbles at the flexible orifice and bubble coalescence nearby the diffuser, which is typical of membrane diffusers (Painmanakul *et al.* 2004). Most likely, the effect of coalescence is additionally favoured through the contact of the bubbles with the rotating membrane module, which acts like a barrier for the uprising bubbles and facilitates the collision of the bubbles. As the bubble size was not investigated in this study, there is no final proof of this assumption.

Furthermore, the rotation of the membrane module leads to an improvement in oxygen transfer, as shown in Table 3. With the exception of the 10 rpm experiment, every increase of the rotational speed by 10 rpm raised the oxygen transfer by roughly 10%. The biggest improvement was achieved at the highest specific airflow rate of 4 $m^3/(m^3 \cdot h)$ and 50 rpm with an increase in k_La_{20} of 52% compared to the experiment without rotation. With increasing airflow rate, the improvement

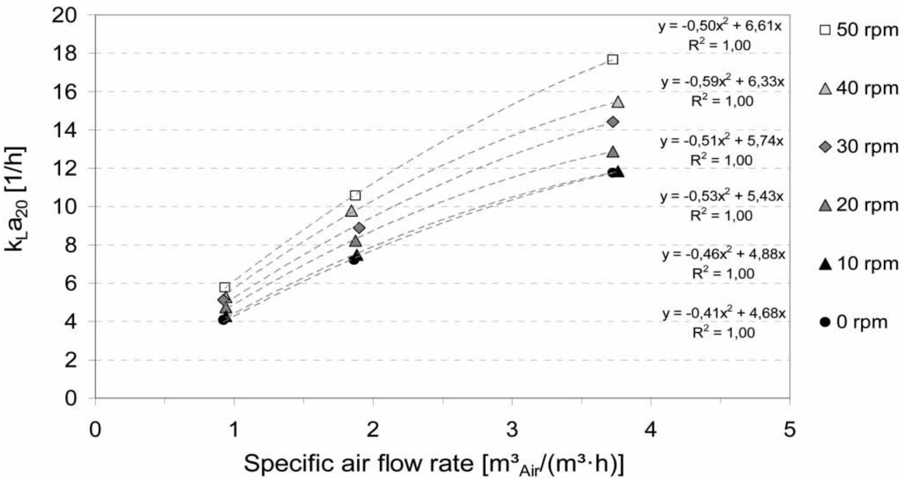


Figure 3 | The obtained standard oxygen transfer coefficient values by different specific airflow rates and rotational speeds for fine bubble aeration in clean water experiments.

Table 3 | Improvement of standard oxygen transfer coefficient values due to different rotational speeds for fine bubble aeration in clean water experiments

	k_La_{20} value improvement in comparison to no membrane rotation (%)			
	At specific airflow rates			
Rotational speeds (rpm)	1 m³/m³.h	2 m³/m³.h	4 m³/m³.h	Average improvement
10	4%	3%	0%	2%
20	15%	13%	9%	12%
30	22%	22%	22%	22%
40	34%	33%	31%	33%
50	43%	45%	52%	47%

in oxygen transfer rate decreased slightly for the same rotational speed except for the experiment at 50 rpm where it increased from 43% to 52%.

The following observations of the effect of rotation of the membrane module were made:

- At a rotational speed of 10 rpm, no effect on bubble formation at the orifice was visible. The bubbles rose straight to the top of the reactor. With increasing rotational speed, this pattern changed. Figure 4 shows that at a rotational speed of 30 rpm, the increased fluid force led to an angular raise of the bubbles, which was even more pronounced at 50 rpm. The increased fluid flow force at the orifice stimulated a faster bubble detachment and clearly changed the bubble raise behaviour. Both effects had a positive impact on oxygen transfer because the interfacial area and the residence time of the bubbles were increased.
- A second effect was visible at the level of the membrane device. At 0 and 10 rpm, the bubble entered the membrane device and little to no effect on the bubble rising behaviour was visible. With increasing rotational speed, the bubbles experienced an additional horizontal acceleration which led to an increase in the bubble residence time and improved oxygen transfer. However, at a high rotational speed (50 rpm), the effect of horizontal acceleration during bubble formation became the determining factor, so the majority of bubbles did not rise through the membrane device but bypassed the module. On this account, the enhancement of k_La_{20} with increasing airflow rate at 50 rpm was caused by the reduction of coalescence phenomena triggered by the rotating membrane module. This effect should not prevent the primary intention of crossflow aeration to provide sufficient shear forces to membrane fibres to reduce fouling/clogging of the module. So far the question is open whether the higher rotational speed can compensate/offset the need for an additional air crossflow to suppress fouling and clogging of the module.

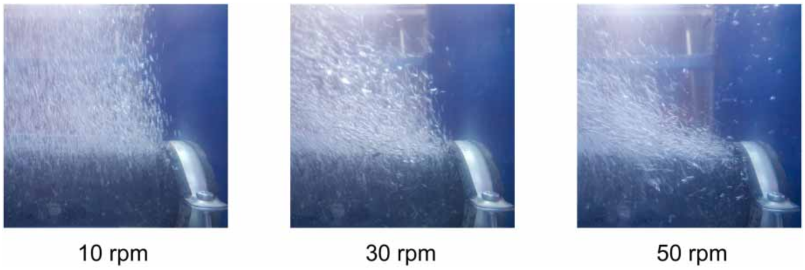


Figure 4 | The effect of cross flow at fine bubble aeration for 1 m^3/h.

3.2. Activated sludge experiments

Additional experiments were performed to investigate the effect of the rotating membrane module on oxygen transfer in activated sludge from a municipal wastewater treatment plant.

Similarly to the results obtained in clean water, the results of the oxygen transfer experiments for activated sludge at 0, 30 and 50 rpm also showed that k_La_{20} values improved in direct proportion as both specific airflow rates and the rotational speeds increased (Figure 5). Similar improvement rates caused by rotation as in clean water were measured as well (Table 4) due to the same dependencies provided in the activated sludge system.

Table 5 shows the obtained α-factors at different specific airflow rates. The α-factors ranged from 0.77 to 0.81, almost independently from rotational speeds and specific airflow rates.

A slight increase with rotational speed can be observed for specific airflow rates of 1 and 2 $m^3/(m^3{\cdot}h)$, while with 4 $m^3/(m^3{\cdot}h)$, no connection to rotational speed was detected. This observation suggests that the effect that was responsible for the decrease in oxygen transfer by around 20% in activated sludge must act nearly independently from the rotational speed and the applied airflow rate.

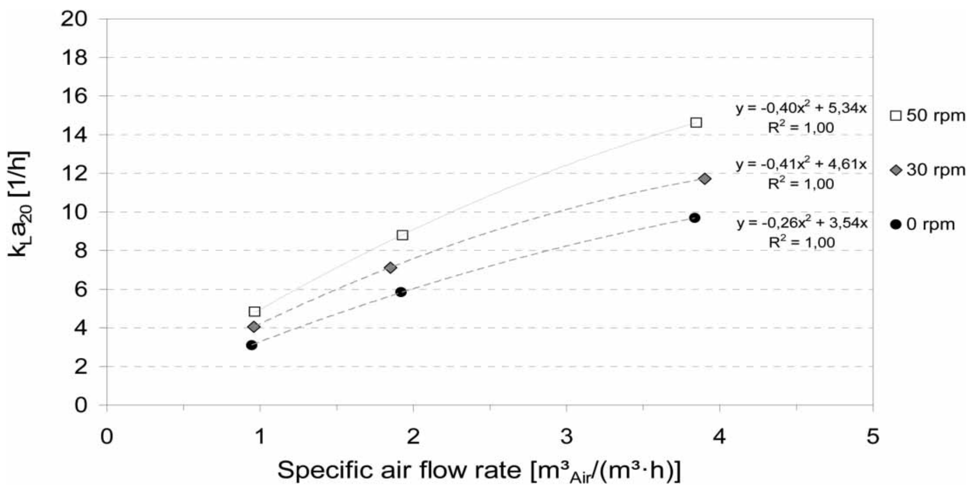


Figure 5 | Standard oxygen transfer coefficient values for fine bubble aeration in activated sludge experiments.

Table 4 | Improvement of standard oxygen transfer coefficient values due to different rotational speeds for fine bubble aeration in activated sludge experiments

	αk_La_{20} value improvement in comparison to no membrane rotation (%)			
	At specific airflow rates			
Rotational speeds (rpm)	1 $m^3/m^3{\cdot}h$	2 $m^3/m^3{\cdot}h$	4 $m^3/m^3{\cdot}h$	Average improvement
30	28%	25%	19%	24%
50	51%	50%	50%	50%

Table 5 | The obtained α-factors for fine bubble aeration

HFV (mL/L)	MLSS (g/L)	MLVSS (g/L)	Rotational speed (rpm)	α-factor at specific airflow rate 1 $m^3/(m^3 \cdot h)$	2 $m^3/(m^3 \cdot h)$	4 $m^3/(m^3 \cdot h)$
175	3.6	2.4	0	0.77	0.78	0.82
175	4.3	2.7	30	0.80	0.80	0.80
150	3.9	2.5	50	0.81	0.81	0.81

Germain *et al.* (2005) and Krause (2005) argued that one effect that impacts oxygen transfer depletion in activated sludge could be attributed to the increase in apparent viscosity. With this assumption, an improvement in the α-factor with increasing rotational speed can be expected. Because activated sludge is described as a non-Newtonian pseudoplastic fluid (Rosenberger 2003; Yang *et al.* 2009), an increasing shear stress should have decreased the apparent viscosity of the sludge and thus improved the α-factor significantly. Such an effect could not be observed during experiment series with the rotatable membrane module system.

Several other authors (Wagner & Pöpel 1996; Rosso *et al.* 2006; Garrido-Baserba *et al.* 2020) argued that dissolved organic matter such as surfactants mainly contribute to the depletion of the α-factor in activated sludge. As in the case of apparent viscosity, a positive impact of rotation on the alpha factors can be expected if surfactants are the major contributors to the decrease observed. The higher turbulence introduced by the rotation, which clearly led to an improvement in oxygen transfer should have also increased the surface renewal rate of the bubbles and as such decreased the effect of surfactants significantly. Again, such an effect could not be observed during experiment series with the rotatable membrane module system, particularly because the activated sludge was stabilized before the oxygen transfer tests.

Another factor that influences oxygen transfer in a three-phase system is the floc/solid holdup (Deckwer 1992; Mena *et al.* 2005; Henkel *et al.* 2011). Already van der Kroon (1968) demonstrated that aluminium hydroxide and activated sludge flocs steadily decreased oxygen transfer with increasing concentration. Henkel (2010) demonstrated that despite different reactor configurations (bubble column, airlift reactor), diffuser systems (fine bubble, coarse bubble, combination of both) and sludges/slurries of different origins (e.g. iron hydroxide flocs, municipal activated sludge, greywater activated sludge), the α-factor showed similar values if the floc volume was used as comparative parameter. Because the different rotational velocities did not show a significant impact on the obtained α-factors, the floc volume seems to be the main driver of oxygen transfer depletion according to present study. The rotational speed indeed impacted the bubble formation and gas holdup, which lead to an increase in oxygen transfer compared to the results obtained without rotation, but it did not impact the reduction of the interfacial area of the bubble caused by the sludge flocs.

3.3. Analysis of energy demand

To investigate if the energy demand required by the rotation of the membranes could be compensated by the improved oxygen transfer rate, the standard aeration efficiency (SAE) was plotted against the specific airflow rates as shown in Figure 6.

Except for clean water experiments at the lowest airflow rate, the SAE was equal to or higher than the experiments without membrane module rotation. An improvement of 24% at 2 $m^3/(m^3 \cdot h)$ and 36% at 4 $m^3/(m^3 \cdot h)$ was achieved at a rotational speed of 50 rpm if matched against the activated sludge results at 0 rpm. Consequently, the additional energy required for rotation was overcompensated by the improved oxygen transfer efficiency in the activated sludge experiments.

4. CONCLUSIONS

A set of experiments was conducted with a new rotating type of membrane module suitable for membrane bioreactor applications to study its effect on oxygen transfer and energy consumption. The rotation of the membrane module showed the following effects:

- oxygen transfer was significantly improved by the application of rotation (~50% at 50 rpm),
- the rates of improvement in oxygen transfer for clean water and activated sludge were similar,
- the α-factors showed comparable values for all experiments independent of the rotational speed,

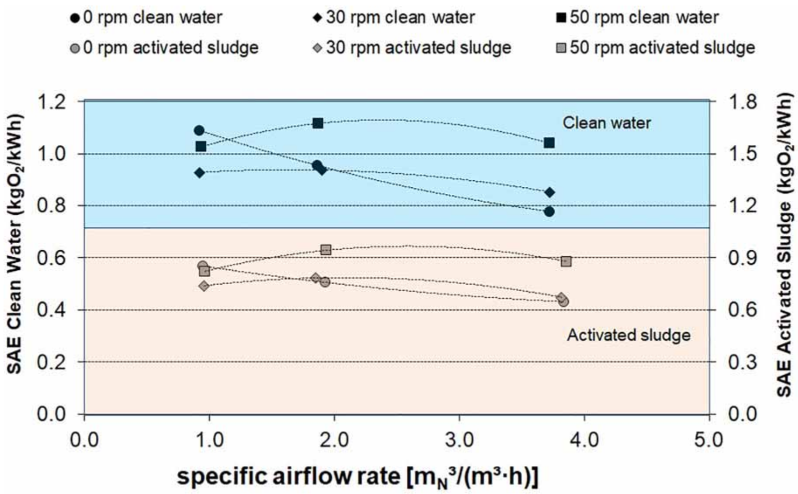


Figure 6 | Standard aeration efficiency at different specific airflow rates and rotational speeds.

- an energy comparison indicates that the additional energy demand for rotation can be compensated by the better oxygen transfer efficiency,
- at the highest rotational speed (50 rpm), the rotation induced such high shear forces to the bubble formation that the majority of bubbles bypassed the membrane module,
- compared to full-scale systems using fine bubble aeration, the SAE was low (<1,2 kgO_2/kWh vs. 4 kgO_2/kWh), which can be attributed to the pilot-scale blower and motor for rotation. Consequently, a transfer of these results to full-scale applications is not feasible and requires further investigations.

The proposed membrane module design encourages the possible reduction of total membrane area needed in comparison to existing membrane design available in the market. According to Lo *et al.* (2015), who studied cost estimation for small membrane bioreactor, the membrane cost contributes to approximately 50–64% to total capital expenditure (CAPEX). Therefore, if the proposed membrane module design can reduce the total membrane area needed by 50%, it has potential to reduce total CAPEX by approximately 30%.

Furthermore, the challenge for a wider use of MBR technology is its integration into an existing CAS system without major modification. The membrane module design in present study shows high feasibility to meet these expectations. Further experiments include the testing of the rotating module under process conditions (filtration, cleaning, fouling behaviour) and the study of the impact of rotation to a coarse bubble aeration system at high sludge concentrations.

AUTHOR CONTRIBUTION STATEMENT

Fathul Mahdariza: Conceptualization, Methodology, Investigation, Data Curation, Writing, Review and Editing; Ignacio Domingo Rimoldi: Conceptualization, Methodology, Investigation; Jochen Henkel: Conceptualization, Methodology, Validation, Writing, Review and Editing; Tobias Morck: Conceptualization, Methodology, Validation, Supervision, Writing, Review and Editing

COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

Deckwer, W.-D. 1992 *Bubble Column Reactors*. Wiley. Available from: http://www.loc.gov/catdir/description/wiley033/91011879.html

DWA-M 209 2007 *Messung der Sauerstoffzufuhr von Belüftungseinrichtungen in Belebungsanlagen in Reinwasser und in belebtem Schlamm [Measurement of the Oxygen Supply of Aeration Devices in Activated Sludge Plants in Pure Water and in Activated Sludge] (Apr. 2007). DWA-Regelwerk Merkblatt: M 209*. DWA.

Garrido-Baserba, M., Rosso, D. [Diego]., Odize, V., Rahman, A., van Winckel, T., Novak, J. T., Al-Omari, A., Murthy, S., Stenstrom, M. K. [Michael K.]. & de Clippeleir, H. 2020 Increasing oxygen transfer efficiency through sorption enhancing strategies. *Water Research* **183**, 116086. https://doi.org/10.1016/j.watres.2020.116086.

Germain, E., Stephenson, T. & Pearce, P. 2005 Biomass characteristics and membrane aeration: toward a better understanding of membrane fouling in submerged membrane bioreactors (MBRs). *Biotechnology and Bioengineering* **90** (3), 316–322. https://doi.org/10.1002/bit.20411

Helmi, A. & Gallucci, F. 2020 Latest developments in membrane (bio)reactors. *Processes* **8** (10), 1239. https://doi.org/10.3390/pr8101239

Henkel, J. 2010 *Oxygen Transfer Phenomena in Activated Sludge [Dissertation]. TU Darmstadt*, Darmstadt. Available from: https://tuprints.ulb.tu-darmstadt.de/id/eprint/3008

Henkel, J., Siembida-Lösch, B. & Wagner, M. [Martin] 2011 Floc volume effects in suspensions and its relevance for wastewater engineering. *Environmental Science & Technology* **45** (20), 8788–8793. https://doi.org/10.1021/es201772w.

Hoinkis, J., Deowan, S. A., Panten, V., Figoli, A., Huang, R. R. & Drioli, E. 2012 Membrane bioreactor (MBR) technology – a promising approach for industrial water reuse. *Procedia Engineering* **33**, 234–241. https://doi.org/10.1016/j.proeng.2012.01.1199

Jaffrin, M. Y. 2008 Dynamic shear-enhanced membrane filtration: a review of rotating disks, rotating membranes and vibrating systems. *Journal of Membrane Science* **324** (1–2), 7–25. https://doi.org/10.1016/j.memsci.2008.06.050

Jiang, T., Zhang, H., Yang, F. [Fenglin]., Gao, D. & Du, H. 2013 Relationships between mechanically induced hydrodynamics and membrane fouling in a novel rotating membrane bioreactor. *Desalination and Water Treatment* **51** (13–15), 2850–2861. https://doi.org/10.1080/19443994.2012.750794

Judd, S. [Simon]. 2011 *The MBR Book: Principles and Applications of Membrane Bioreactors for Water and Wastewater Treatment/Edited by Simon Judd, Claire Judd (2nd ed.)*. Elsevier.

Judd, S. J. 2016 The status of industrial and municipal effluent treatment with membrane bioreactor technology. *Chemical Engineering Journal* **305**, 37–45. https://doi.org/10.1016/j.cej.2015.08.141

Krause, S. [Stefan]. 2005 *Untersuchungen zum Energiebedarf von Membranbelebungsanlagen [Investigations into the energy requirements of membrane systems]*. Zugl.: Darmstadt, Techn. Univ., Diss, 2005 (Schriftenreihe WAR WAR-166). Darmstadt.

Krause, S., Cornel, P. & Wagner, M. 2003 Comparison of different oxygen transfer testing procedures in full-scale membrane bioreactors. *Water Science and Technology: A Journal of the International Association on Water Pollution Research* **47** (12), 169–176. https://doi.org/10.2166/wst.2003.0643

Krzeminski, P., Leverette, L., Malamis, S. & Katsou, E. 2017 Membrane bioreactors – a review on recent developments in energy reduction, fouling control, novel configurations, LCA and market prospects. *Journal of Membrane Science* **527**, 207–227. https://doi.org/10.1016/j.memsci.2016.12.010

Lo, C. H., McAdam, E. & Judd, S. 2015 The cost of a small membrane bioreactor. *Water Science and Technology : A Journal of the International Association on Water Pollution Research* **72** (10), 1739–1746. https://doi.org/10.2166/wst.2015.394

Mena, P. C., Ruzicka, M. C., Rocha, F. A., Teixeira, J. A. & Drahoš, J. 2005 Effect of solids on homogeneous–heterogeneous flow regime transition in bubble columns. *Chemical Engineering Science* **60** (22), 6013–6026. https://doi.org/10.1016/j.ces.2005.04.020

Meng, F., Zhang, S., Oh, Y., Zhou, Z., Shin, H.-S. & Chae, S.-R. 2017 Fouling in membrane bioreactors: an updated review. *Water Research* **114**, 151–180. https://doi.org/10.1016/j.watres.2017.02.006

Painmanakul, P., Loubiere, K., Hebrard, G. & Buffiere, P. 2004 Study of different membrane spargers used in waste water treatment: characterisation and performance. *Chemical Engineering and Processing: Process Intensification* **43** (11), 1347–1359. https://doi.org/10.1016/j.cep.2003.09.009

Paul, P. & Jones, F. A. 2016 Advanced wastewater treatment engineering-investigating membrane fouling in both rotational and static membrane bioreactor systems using empirical modelling. *International Journal of Environmental Research and Public Health* **13**, 1. https://doi.org/10.3390/ijerph13010100

Rector, T. J., Garland, J. L. & Starr, S. O. 2006 Dispersion characteristics of a rotating hollow fiber membrane bioreactor: effects of module packing density and rotational frequency. *Journal of Membrane Science* **278** (1–2), 144–150. https://doi.org/10.1016/j.memsci.2005.10.050

Rosenberger, S. 2003 *Charakterisierung von belebtem Schlamm in Membranbelebungsreaktoren zur Abwasserreinigung [Characterization of Activated Sludge in Membrane Bioreactors for Wastewater Treatment]*. Zugl.: Berlin, Techn. Univ., Diss., 2003 (Als Ms. gedr). *Fortschritt-Berichte VDI Reihe 3, Verfahrenstechnik: Vol. 769*. VDI-Verl.

Rosso, D., Larson, L. E. & Stenstrom, M. K. 2006 Surfactant effects on alpha factors in full-scale wastewater aeration systems. *Water Science and Technology: A Journal of the International Association on Water Pollution Research* **54** (10), 143–153. https://doi.org/10.2166/wst.2006.768

Ruigómez, I., Vera, L., González, E. & Rodríguez-Sevilla, J. 2016 Pilot plant study of a new rotating hollow fibre membrane module for improved performance of an anaerobic submerged MBR. *Journal of Membrane Science* **514**, 105–113. https://doi.org/10.1016/j.memsci.2016.04.061

van der Kroon, G. T. M. 1968 The influence of suspended solids on the rate of oxygen transfer in aqueous solutions. *Water Research* **2** (1), 26–30. https://doi.org/10.1016/0043-1354(68)90151-6

Wagner, M. R. & Pöpel, H. J. 1996 Surface active agents and their influence on oxygen transfer. *Water Science and Technology : A Journal of the International Association on Water Pollution Research* **34**, 3–4. https://doi.org/10.1016/0273-1223(96)00580-X

Wagner, M. R., Pöpel, H. J. & Kalte, P. 1998 Pure oxygen desorption method – a new and cost-effective method for the determination of oxygen transfer rates in clean water. *Water Science and Technology : A Journal of the International Association on Water Pollution Research* **38**, 3. https://doi.org/10.1016/S0273-1223(98)00454-5

Wu, G., Cui, L. & Xu, Y. 2008 A novel submerged rotating membrane bioreactor and reversible membrane fouling control. *Desalination* **228** (1–3), 255–262. https://doi.org/10.1016/j.desal.2007.10.014

Yang, F. [Fei], Bick, A., Shandalov, S., Brenner, A. & Oron, G. 2009 Yield stress and rheological characteristics of activated sludge in an airlift membrane bioreactor. *Journal of Membrane Science* **334** (1-2), 83–90. https://doi.org/10.1016/j.memsci.2009.02.022

Zsirai, T., Qiblawey, H., A-Marri, M. J. & Judd, S. 2016 The impact of mechanical shear on membrane flux and energy demand. *Journal of Membrane Science* **516**, 56–63. https://doi.org/10.1016/j.memsci.2016.06.010

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