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Impact of vibration on treatment and filtration performance of membrane bioreactors treating municipal wastewater

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ABSTRACT

Membrane bioreactors (MBRs) are commonly used in municipal and industrial wastewater treatment. However, membrane fouling problem limits the performance of MBRs. The objective of this study was to determine the impact of vibration on membrane fouling. Long-term filtration experiments were conducted to compare treatment and filtration performance of vibrated (magnetically induced) and non-vibrated modules in an MBR treating synthetic municipal wastewater. Results showed that vibration did not have any remarkable effect on treatment performance. However, filtration performance and thus, membrane fouling were significantly affected by the vibration. Magnetically induced vibration system achieved better filtration performance than the non-vibrated module. Cake layer formation found in the magnetically induced vibrating system resulted in low potential for pore clogging. The results suggest that magnetically induced vibration is a promising alternative for reducing membrane fouling problem in MBR systems.

Keywords: Membrane bioreactor; Membrane fouling; Transmembrane pressure; Vibration

1. Introduction

Membrane bioreactor (MBR) systems are widely used for wastewater treatment and water reuse. MBR process is advantageous when compared with conventional activated sludge process since it provides higher sludge concentration in the bioreactor and higher loading rates can be applied with improved effluent quality [1]. The most significant drawback of the MBR technology is membrane fouling that results in an increase in transmembrane pressure (TMP), operational costs and maintenance problems [2] and thus, limits the performance of MBRs [3–5]. Air sparging, crossflow velocity and/or permeate backwashing are frequently used in order to reduce particle deposition over the membrane surface [6,7]. Creating higher shear force over the membrane surface causes lower fouling rate due to the particle back transfer from the surface to the bulk solution. The shear force created on the membrane surface

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prevents particle accumulation and thus, increases critical flux [8–10].

Air sparging has limited flux improvement and has a significant share in the total energy cost [11]. Vibratory shear enhancement is another type of technique used for creating higher shear stress compared with air sparging [10]. These systems may have rotational, transverse and longitudinal vibrations or magnetically induced "push pull" type vibration.

The concept of vibratory motion on membrane surface is mostly known by vibratory shear enhanced processing (VSEP) technology [12] that includes a torsional spring connected with seismic mass to a motor with eccentric weight. The vibration created by this system can have resonant frequencies up to 70 Hz. VSEP and MBR technology may work together, using VSEP module in an external MBR treatment system. Low et al. [13] compared a submerged membrane bioreactor (SMBR) system with an external VSEP MBR system and found that VSEP module achieved 6.8 times higher flux rate than submerged module. Other types of vibration systems used an electric motor with variable speed control in order to adjust frequency and a crank shaft as an oscillatory mechanism in order to adjust amplitude and vibration direction. These types of systems are mostly used for SMBRs and researchers studied different frequencies and amplitudes for the filtration of different sources [8,9,14–16]. Filtration of yeast suspension with a vibrating submerged membrane module was investigated and it was found that keeping the flux well below the critical flux with vibration is advantageous for long-term operation [8]. It is reported that permeate flux can be significantly improved by increasing frequency and amplitude for inorganic bentonite particle filtration with a submerged vibrating membrane module [15]. Gomaa and Rao [14] found that frequency of <25 Hz and amplitude of <0.0015 m can be used to improve the performance of a submerged vibratory flat sheet membrane in yeast suspensions. There is also a novel magnetically induced vibration technology that is used for submerged flat sheet MBR modules [17]. The system includes a magnetically induced vibration engine that is controlled by a controlling device with audio software. Vibration frequencies up to 60 Hz can be adjusted and amplitude is limited to 2 mm at most. The study showed that magnetically induced membrane vibration system can significantly increase critical flux of submerged flat sheet membrane module, and efficiency of the system is confirmed by long-term experiments with proper module arrangement [17]. Pilot scale studies were also performed in order to investigate the impact of vibration on membrane fouling [18,19]. High frequencies up to 583 Hz were applied to vibrated pilot scale hollow fiber module treating synthetic wastewater with an amplitude capacity of 0.3–1 mm by Chatzikonstantinou et al. [18]. According to the results, high frequency vibration resulted in lower TMP in the vibrated system compared with non-vibrated system. Low frequencies of 0.38–0.43 Hz with an amplitude of 44 mm were also tested in a pilot scale reciprocating MBR (rMBR) [19]. Lower TMP values and energy consumption could achieve with the rMBR in comparison with conventional air scouring MBR systems. Studies on vibrating MBR systems applied for aerobic sludge suspensions are limited [13,17–20]. Therefore, further research is needed including long-term experimental studies especially using hollow fiber membranes.

The aim of this paper was to determine the impact of vibration on treatment and filtration performance of submerged hollow fiber MBR treating synthetic municipal wastewater. For this purpose, long-term filtration experiments at subcritical flux were conducted and magnetically induced vibrated module was compared with non-vibrated module in terms of treatment and filtration performances. At the end of each experimental phase, physical and chemical cleaning procedure was applied in sequence, and permeability measurements were conducted to determine the impact of vibration on various membrane fouling mechanisms.

2. Materials and methods

2.1. Wastewater source

Synthetic municipal wastewater was used as substrate in this study. The composition of the substrate was slightly modified from the synthetic wastewater composition given by Koseoglu-Imer et al. [21]. The composition of the synthetic wastewater and the main characteristics of the wastewater are shown in Table 1 [22].

2.2. Sludge source

The bioreactor was inoculated with return activated sludge from a full scale wastewater treatment plant treating municipal wastewater. Characterization of the seed sludge is given in Table 2.

Table 1
Composition and characterization of the synthetic wastewater

Composition	
Chemicals	Values (mg/L)
Glucose, mg/L	715
Urea, mg/L	85
KH_2PO_4, mg/L	70
$(NH_4)_2SO_4$, mg/L	70
$MgSO_4.7H_2O$, mg/L	70
Na_2CO_3, mg/L	145
NaCl, mg/L	70
$CaCl_2.2H_2O$, mg/L	15
Characterization	
Parameters	Values (mean ± standard deviation)
Chemical oxygen demand (COD), mg/L	540 ± 44
Soluble COD, mg/L	450 ± 45
Total suspended solids (TSS), mg/L	250 ± 35
Total Kjeldahl nitrogen (TKN), mg/L	55 ± 6
Total phosphorus (TP), mg/L	11.9 ± 0.8
pH	7.5 ± 0.1
Turbidity, NTU	115 ± 10

2.3. Membrane modules and vibration system

Reinforced polyvinylidene difluoride (PVDF) hollow fiber membranes with a length of 17.5 cm and a mean pore size of 0.04 µm were used in each laboratory scale membrane module. Total membrane surface area was 500 cm^2. A Plexiglas inner tube with four holes in the center of each module was used for air scouring. Permeate was collected from the top of the module. Schematic of the MBR system can be seen in Fig. 1. A new batch of reinforced PVDF hollow fiber membrane was used in the membrane modules for each phase of the study.

Magnetically induced vibration system was used as the vibration source. A control module without vibration was used for comparison. Magnetically induced vibrated module is hereafter referred to as vibrated module.

Frequency range of the vibration system could be changed between 20 and 150 Hz. Amplitude was 0.01 mm. Four oscillation springs were used for the vibration chassis.

Two I-BEAM VT200 transducers were used as a magnetic vibrator, which was driven by an audio amplifier at 200 W electrical power. The desired frequency was generated by a computer audio software. The magnetic vibration system was made of aluminum plates and steel supports. Four springs were screwed on the lower aluminum table which were used to prevent the biological tank from vibrations. Schematic view of the vibration system is given in Fig. 2.

Table 2
Characterization of the seed sludge

Parameter	Value (mean ± standard deviation)
COD, mg/L	114,890 ± 64
Total solids (TS), mg/L	27,000 ± 1,585
Volatile solids (VS), mg/L	15,920 ± 840
TSS, mg/L	13,585 ± 380
Volatile suspended solids (VSS), mg/L	8,490 ± 311
VSS/TSS	0.62 ± 0.01
pH	6.9

2.4. Experimental setup

The MBR system was designed to allow testing of two different module types at the same time. Modules were located in the same reactor. The schematic view of MBR system is provided in Fig. 1.

An external diaphragm pressure gauge (Keller, Model 23E) was used to measure the vacuum pressure of each module. Permeate of each module was collected in vessels which were located on digital balances in order to determine flux. Two permeate pumps (Longer Pump BT-100) were used (one pump for each module) in the MBR system. Flux was adjusted

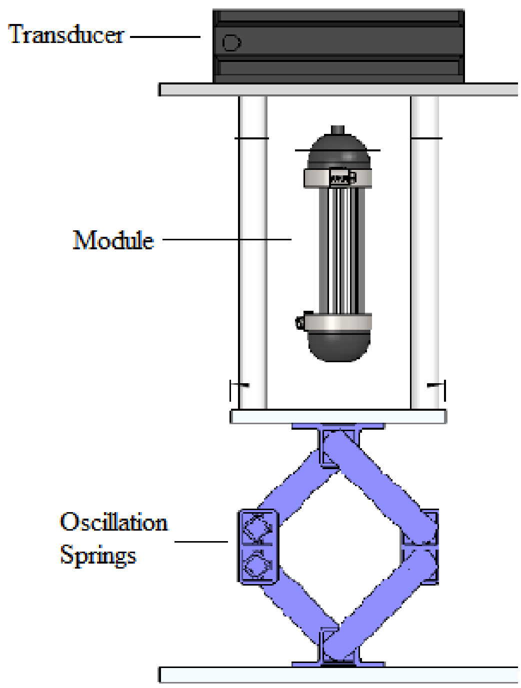

Fig. 2. Flow chart of the lab scale MBR system.

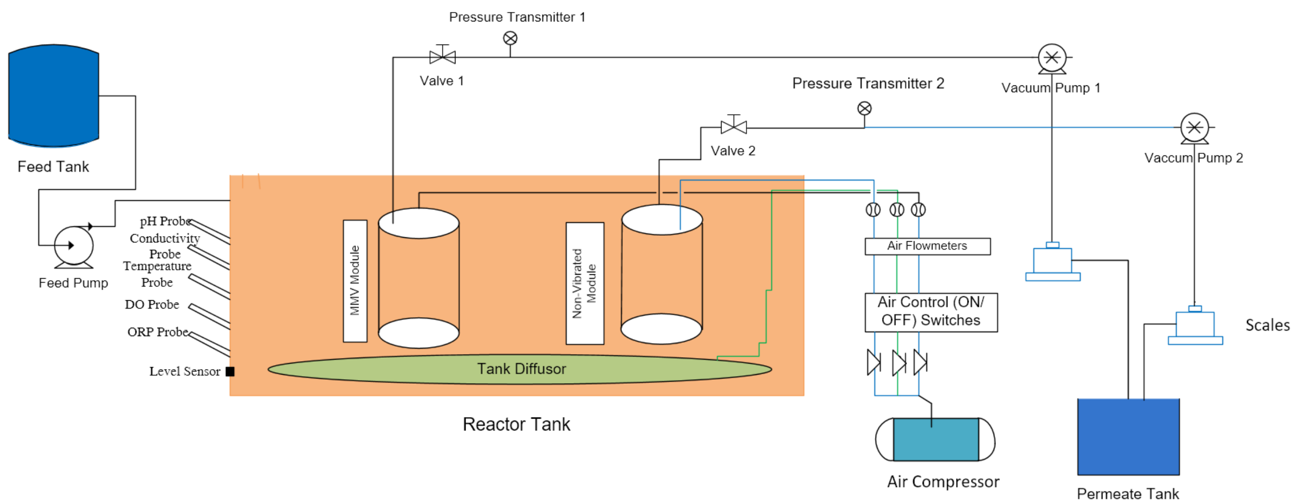

Fig. 1. Schematic view of the magnetically induced vibration system used in the study.

by the permeate pumps. One peristaltic feed pump was used to feed synthetic municipal wastewater to the MBR. To keep the sludge height at the same level in the MBR tank, a level sensor (Ifm, PL2658) was used. pH (Olean PH5500), temperature (1XPT1000, P/N120T158-033), dissolved oxygen (Hamilton ARC, P/N 355219/1514), conductivity (Olean CON5500) and oxygen reduction potential (ORP) (Olean ORP5500) were measured by sensors located in the tank. The laboratory scale MBR unit was operated under aerobic conditions. Dry air was supplied by central compressor system. Airflow was controlled by a rotameter (Aalborg Model P). MBR system was controlled by a supervisory control and data acquisition system.

2.5. Experimental procedure

Operational conditions of three phases applied in the study were presented in Table 3. Average mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) concentrations were 6,445 and 4,090 mg/L, respectively, in Phase 1. There is a decline in average MLSS and MLVSS concentrations in Phase 2. Decrease in MLSS concentration during Phase 2 was related to the dilution effect as a result of backwashing with tap water. Phase 3, in which average MLSS concentration was 7,672 mg/L, was included to verify whether the impact of vibration on filtration performance during Phase 1 was reproducible. Frequency and amplitude of vibrated module were kept constant (3 Hz and 0.01 mm) in each phase. Modules were operated at the same subcritical flux determined by the critical flux tests.

2.6. Analytical methods

2.6.1. Analysis

Analysis of feed, sludge and permeate samples was performed in order to evaluate the performance of MBR. Chemical oxygen demand (COD), total solids, volatile solids, total suspended solids (TSS), volatile suspended solids, total phosphorus (TP), total nitrogen (TN), nitrite and nitrate concentrations were measured according to Standard Methods [23]. Soluble COD samples were filtered through 0.45 μm membrane filter prior to measurement. The turbidity was measured with a portable turbidity meter (2100Q, Hach, USA).

Sludge particle size distribution (PSD) was determined by laser diffraction method by using a Zetasizer (Nano S series, Malvern Instruments, UK) with a measurement range from 0.3 nm to 10 μm. Each sample was measured in triplicates.

2.6.2. Critical flux determination

The critical flux was determined using a flux-step method [24,25]. The method consists of cycles of 15 min permeation step followed by 1 min of backwashing. The initial flux was 2 L/m^2 h with a gradual increase of 2 L/m^2 h up to the critical flux. The flux below which there is no flux decline and no fouling was observed over time is defined as critical flux [26,27]. For each step, TMP was recorded with 30 s time intervals and plotted against flux values to obtain the critical flux.

2.6.3. Filtration resistance

In the end of each experimental step, fouled membranes were tested by a series of cleaning procedures to evaluate different fouling resistances. The Darcy equation, shown by Eq. (1) was used to obtain individual resistances.

$$R_T = \frac{\text{TMP}}{\eta \cdot J} = R_{\text{intrinsic}} + R_{\text{removable}} + R_{\text{irreversible}} + R_{\text{irrecoverable}} \quad (1)$$

where J is the flux as m^3/(m^2 s), TMP is the transmembrane pressure as Pa, η is the dynamic viscosity of water as Pa s. R_T is the total membrane filtration resistance (1/m) which consisted of the intrinsic membrane resistance ($R_{\text{intrinsic}}$), the resistance due to cake layer formation ($R_{\text{removable}}$), the resistance due to pore-clogging ($R_{\text{irreversible}}$) and irrecoverable resistance which cannot be recovered chemically and physically ($R_{\text{irrecoverable}}$). The resistances were determined as follows: (1) before starting the long-term experiment, $R_{\text{intrinsic}}$ was calculated by filtration of deionized water through the

Table 3
Operational conditions

Operational conditions	Phase 1	Phase 2	Phase 3
Magnetically induced vibration frequency (Hz)	30	30	30
Air scouring rate (sL/min)	8	8	8
MLSS (mg/L)	8,615	6,088	7,672
MLVSS (mg/L)	5,460	3,915	4,993
Flux (L/m^2 h)	25	25	25
Hydraulic retention time (HRT) (h)	12	12	12
Sludge age (SRT) (day)	∞	∞	∞
Dissolved oxygen (DO) (mg/L)	4.9 ± 0.5	6.7 ± 0.8	7.8 ± 0.7
Conductivity (μS/cm)	403 ± 23	502 ± 27	624 ± 71
Temperature (°C)	22 ± 2	21 ± 1	20 ± 1
ORP (mV)	220 ± 13	235 ± 19	201 ± 15
pH	6.5 ± 0.3	7.2 ± 0.2	7 ± 0.3
Filtration period (s)	570 (in every 600 s)	570 (in every 600 s)	570 (in every 600 s)
Backwashing period (s)	30 (in every 600 s)	30 (in every 600 s)	30 (in every 600 s)

virgin membrane. (2) R_T was determined by measuring the permeate flux of deionized water passing through the fouled membrane at the end of operation period. (3) The fouled membrane surface was flushed with tap water in order to remove cake layer. After flushing, determined filtration resistance was equal to ($R_{intrinsic} + R_{irreversible} + R_{irrecoverable}$). Subtracting the value of ($R_{intrinsic} + R_{irreversible} + R_{irrecoverable}$) from total membrane resistance, $R_{removable}$ was calculated. (4) Subsequently, $R_{irrecoverable}$ was determined by applying a chemical cleaning method [28] that was used to remove a strong matrix of solutes associated with pore narrowing or pore blocking. (5) $R_{irreversible}$ was calculated based on Eq. (1).

3. Results and discussion

3.1. Treatment performance

Average MLSS and MLVSS concentrations in the bioreactor were 7,150 ± 1,140 and 4,600 ± 700 mg/L, respectively. An average MLVSS/MLSS ratio of about 65% ± 2% was obtained in the bioreactor (Fig. 3). MLSS concentrations were lower during Phase 2 in comparison with Phases 1 and 3. PSD of the sludge in the MBR (Fig. 4) was measured in the MBR during three phases. Average particle sizes (D50) were 44, 38 and 35 µm in Phases 1, 2 and 3, respectively. Trends in PSDs were very similar, which indicated that vibrated module did not cause any effect on PSD of sludge throughout the whole experimental study. Seed sludge used at the beginning of the Phase 1 was the main reason for higher PSD values at Phase 1.

Fig. 5 presents average permeate COD concentrations obtained from two different types of modules. COD removal efficiency of over 95% was achieved under all tested conditions and phases. Average COD removal efficiencies were very similar for each module during each phase, indicating that the presence of vibration did not have any remarkable effect on treatment performance. Fig. 6 shows turbidity and TSS concentrations in the permeate for each membrane module. Average TSS concentrations in the permeate were below 10 mg/L for each membrane module. Permeate turbidities were also below 1 NTU for two modules. TSS and turbidity removal efficiencies of over 98% were obtained in each system regardless of vibration. The permeate characteristics were also comparatively evaluated in terms of PSD (data not shown). From PSD results, an average particle size of 483 and 458 nm were measured for non-vibrated and vibrated module.

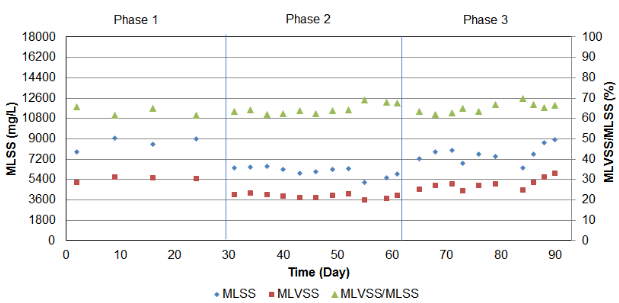

Fig. 3. MLSS and MLVSS concentrations in the MBR at different stages.

Significant removal efficiencies were not achieved for TN and TP parameters during the study (data not shown). However, concentrations of nitrate in the permeate of vibrated and non-vibrated module were 29.8 ± 11.0 and 27.6 ± 7.4, respectively. These results showed that nitrification

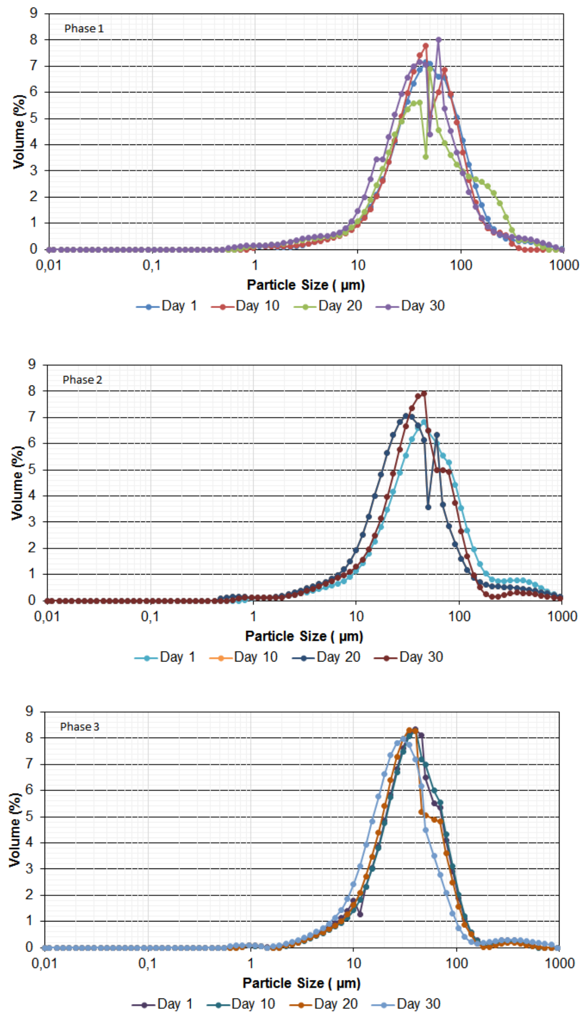

Fig. 4. PSDs of the sludge at different phases.

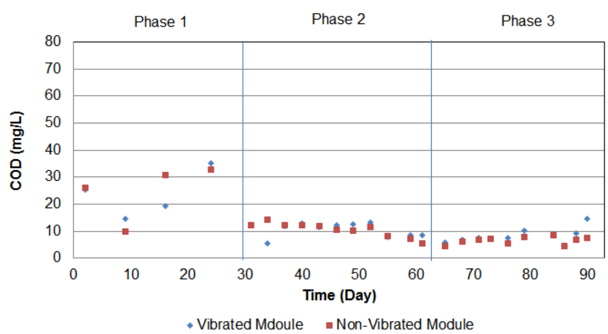

Fig. 5. Average COD concentrations in the permeate at different phases.

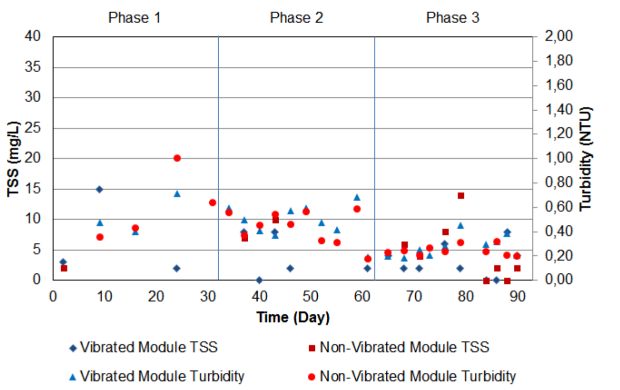

Fig. 6. Turbidity levels and TSS concentration in the permeate at different phases.

process occurred in the MBR during the study. However, effective nitrogen removal was not achieved in this study because denitrification did not take place due to limitation of anoxic conditions by continuous oxygen supply to the MBRs. An effective nitrogen removal can be achieved if MBR tanks are designed properly to allow anoxic conditions, which was not the case in the present study.

3.2. Critical flux tests

For each system, a critical flux could be distinguished based on the sudden TMP increase at a certain flux. Following the flux-step method, the critical fluxes were found to be 29.1 and 31.9 L/m^2 h for vibrated and non-vibrated module (data not shown). There was no significant difference in critical fluxes for each system since all tests were performed without vibration in order to present the characteristics of the seed sludge. However, critical flux tests were also applied under vibration. Difference was not observed in critical fluxes between the vibrated and non-vibrated modules. According to the result of these tests, operational flux was selected as 25 L/m^2 h that was below the critical fluxes obtained for each system.

3.3. Filtration performance

Fig. 7 shows TMP profiles measured during the experimental study for two modules during three phases. The differences in TMP trends clearly observed after a certain period of operational time. It is clear that magnetically induced vibrating MBR has lower TMP values in comparison with non-vibrated control module throughout three phases. Vibrated module prevented pore blocking on the hollow fiber membrane surface and provided lower fouling rates compared with non-vibrated module during each phase. Therefore, pore blocking might be more severe in non-vibrated module in comparison with vibrated module. Li et al. [15] also found that the vibrated module fouling rate decreased compared with non-vibrated module.

3.4. Cleaning tests

Following each experimental phase, cleaning tests were applied to membrane modules in order to determine the

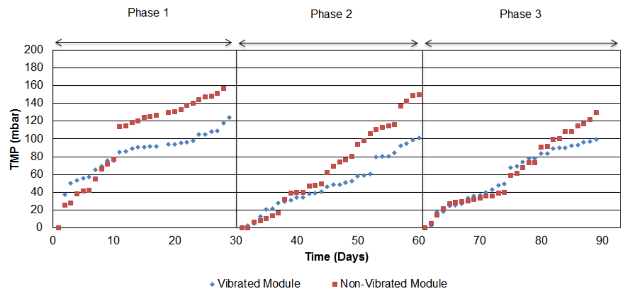

Fig. 7. TMP profiles for each module at different phases.

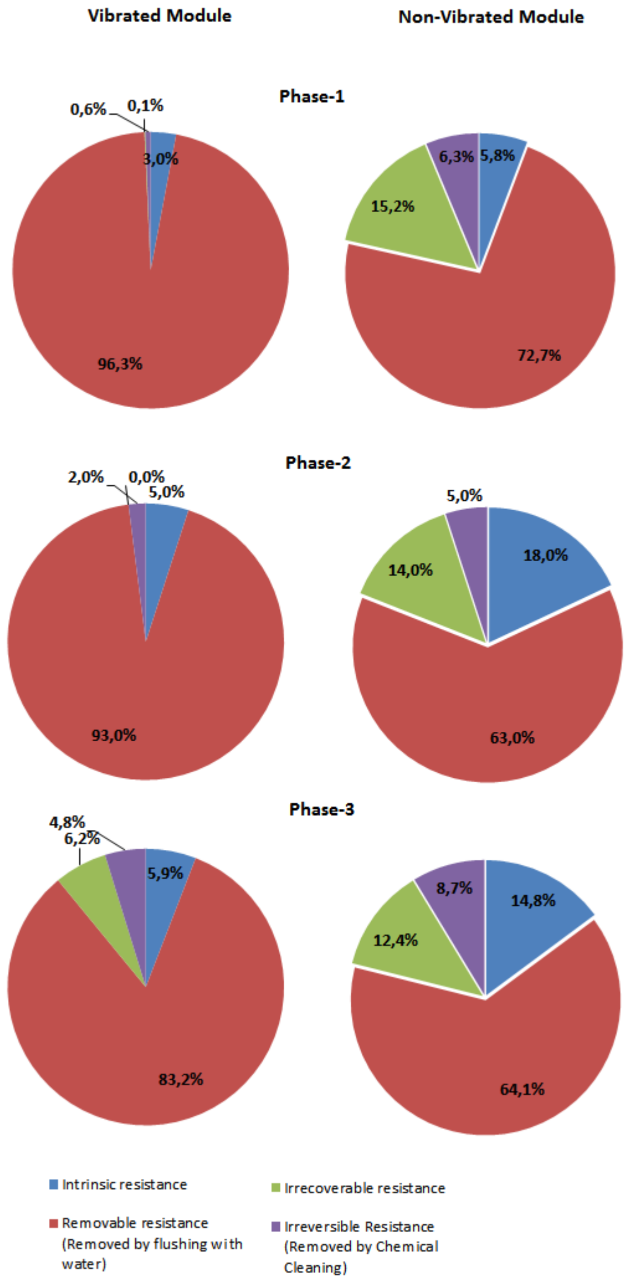

Fig. 8. Contribution of different resistances to R_Ts for each system at different phases.

Table 4
Comparison of the frequency and amplitude values of the references and our study

Frequency range (Hz)	Amplitude range (mm)	Oscillation type	Reference
Fixed 30	Fixed 100	Longitudinal	Low et al. [13]
0–30	0.2, 0.7, 1.175		Beier et al. [8]
0–15	0–12		Li et al. [15]
0–10	Fixed 40		Genkin et al. [9]
5, 10, 15, 18, 20, 25	3, 12, 20, 30		Gomaa and Rao [14]
0–10	0–28 with 4 mm intervals	Transverse	Li et al. [10]
3.5–50	0.5–5		Kola et al. [16]
0–35	Fixed 2.5	Transversal liquid movement	Kola et al. [16]
0.5	Fixed 180° back and forth movement	Cross-rotational	Low et al. [13]
70	19–32	VSEP Series L	Low et al. [13]
60	Max 2	Magnetically induced	Bilad et al. [17]
30	0.01	Magnetically induced	This study

contributions of different resistances to total filtration resistance (R_T) (Fig. 8). For all experimental phases, intrinsic resistance ($R_{intrinsic}$) and the resistance caused by pore clogging ($R_{irreversible}$) were found lower compared with the cake layer resistance ($R_{removable}$). Cake layer resistances accounted for most of the R_T, 96%, 93% and 83% of the R_T in Phases 1, 2 and 3, respectively, for the vibrated module. Irreversible fouling was less significant since it only represented around 1%, 2% and 5% of the total resistance, indicating the feasibility and importance of the fouling control by minimizing pore clogging. As shown in Fig. 8, $R_{removable}$ was lower in the non-vibrated module, giving rise to $R_{irreversible}$ and $R_{irrecoverable}$, in comparison with the vibrated module. This result is consistent with the TMP pattern in Fig. 7. The increase in irreversible fouling indicated more pore blocking, which is a drawback of extending the membrane operation period. Besides, the highest $R_{irrecoverable}$ observed at Phase 1 resulted in highest TMP values. However, contribution of resistances for the non-vibrated module and vibrated module were similar during three phases since the vibrational conditions were kept constant during each stage.

Overall, the results indicated that membrane fouling and filtration performance were significantly affected by vibration system. Cake layer formation might occur on the membrane surface in the magnetically induced vibrating system resulted in lower potential for pore clogging. In the non-vibrated module, the foulants can easily penetrate inside the membrane pores and resulted in higher potential for pore clogging. For the vibrated module, lower contributions of pore clogging were observed since magnetic vibration prevented pore clogging. As can be seen in Fig. 8, removable resistance that can be called as cake layer formation was easily removed by flushing with water. That means the looseness of the cake on the magnetically vibrated module was higher compared with non-vibrated module. This also explains why irreversible resistance was also low for the magnetically vibrated module since the loose cake layer on the membrane surface also prevented further clogging of the pores. Instead of destructive vibration force, low frequency and amplitude values were used in this study not to deteriorate the cake layer formation. Table 4 shows the comparison of the frequency and amplitude values of vibrations systems reported in the literature.

In Table 4, the frequency and amplitude value of this study were lowest compared with other references. Most of the studies were conducted with synthetic organic and inorganic solutions to model MBR activated sludge. The shear rate for our vibration frequency and amplitude was found to be 21 s^{-1} based on time mean average surface shear rate equation [8]. The shear rate gradually increases as frequency and/or amplitude increases. This continuous low shear rate applied by magnetically induced vibration system created loose cake layer on the membrane surface in long-term experiments.

4. Conclusions

In this study, two different MBR systems (magnetically induced vibration and non-vibrated module) were investigated to determine the impact of vibration on both treatment and filtration performance. The results showed that lower TMP profile and thus higher filtration performance were achieved by magnetically induced vibration module in comparison with non-vibrated module. Treatment performance for each module was comparable. Magnetic vibration was effective on fouling and TMP trend for long-term operation. Cleaning tests showed that magnetically induced vibrating system resulted in lower pore clogging. Overall, based on the findings of this study, magnetically induced vibration system can be regarded as a promising alternative for reducing membrane fouling in MBR systems.

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References

[1] C. Visvanathan, R. Ben Aim, K. Parameshwaran, Membrane separation bioreactors for wastewater treatment, Crit. Rev. Environ. Sci. Technol., 30 (2000) 1–48.

[2] T. Mukai, K. Takimoto, T. Kohno, M. Okada, Ultrafiltration behaviour of extracellular and metabolic products in activated sludge system with UF separation process, Water Res., 34 (2000) 902–908.
[3] S.J. Judd, A review of fouling of membrane bioreactors in sewage treatment, Water Sci. Technol., 49 (2004) 229–235.
[4] J. Wu, F. Chen, X. Huang, W. Geng, X. Wen, Using inorganic coagulants to control membrane fouling in a submerged membrane bioreactor, Desalination, 197 (2006) 124–136.
[5] X.M. Wang, X.Y. Li, X. Huang, Membrane fouling in a submerged membrane bioreactor (SMBR): characterisation of the sludge cake and its high filtration resistance, Sep. Purif. Technol., 52 (2007) 439–445.
[6] M.Y. Jaffrin, Dynamic shear-enhanced membrane filtration: a review of rotating disks, rotating membranes and vibrating systems, J. Membr. Sci., 324 (2008) 7–25.
[7] L. Xia, A.W.-K. Law, A.G. Fane, Hydrodynamic effects of air sparging on hollow fiber membranes in a bubble column reactor, Water Res., 47 (2013) 3762–3772.
[8] S.P. Beier, M. Guerra, A. Garde, G. Jonsson, Dynamic microfiltration with a vibrating hollow fiber membrane module: filtration of yeast suspensions, J. Membr. Sci., 281 (2006) 281–287.
[9] G. Genkin, T.D. Waite, A.G. Fane, S. Chang, The effect of vibration and coagulant addition on the filtration performance of submerged hollow fibre membranes, J. Membr. Sci., 281 (2006) 726–734.
[10] T. Li, A.W.K. Law, A.G. Fane, Submerged hollow fibre membrane filtration with transverse and longitudinal vibrations, J. Membr. Sci., 455 (2014) 83–91.
[11] S. Judd, C. Judd, The MBR Book: Principles and Applications of Membrane Bioreactors for Water and Wastewater Treatment, 2nd ed., 2011.
[12] B. Culkin, A.D. Armando, N.L. Inter, New separation system extends the use of membranes, Filtr. Sep., 29 (1992) 376–378.
[13] S.C. Low, H.H. Juan, L.K. Siong, A combined VSEP and membrane bioreactor system, Desalination, 183 (2005) 353–362.
[14] H.G. Gomaa, S. Rao, Analysis of flux enhancement at oscillating flat surface membranes, J. Membr. Sci., 374 (2011) 59–66.
[15] T. Li, A.W.K. Law, M. Cetin, A.G. Fane, Fouling control of submerged hollow fibre membranes by vibrations, J. Membr. Sci., 427 (2013) 230–239.
[16] A. Kola, Y. Ye, P. Le-Clech, V. Chen, Transverse vibration as novel membrane fouling mitigation strategy in anaerobic membrane bioreactor applications, J. Membr. Sci., 455 (2014) 320–329.
[17] M.R. Bilad, G. Mezohegyi, P. Declerck, I.F.J. Vankelecom, Novel magnetically induced membrane vibration (MMV) for fouling control in membrane bioreactors, Water Res., 46 (2012) 63–72.
[18] K. Chatzikonstantinou, N. Tzamtzis, A. Pappa, S. Liodakis, Membrane fouling control using high-frequency power vibration, in an SMBR pilot system—preliminary studies, Desal. Wat. Treat., 57 (2016) 11550–11560.
[19] J. Ho, S. Smith, J. Patamasank, P. Tontcheva, G.D. Kim, H.K. Roh, Pilot demonstration of energy-efficient membrane bioreactor (MBR) using reciprocating submerged membrane, Water Environ. Res., 87 (2015) 266–273.
[20] X. Qiao, Z. Zhang, J. Yu, X. Ye, Performance characteristics of a hybrid membrane pilot-scale plant for oilfield-produced wastewater, Desalination, 225 (2008) 113–122.
[21] D.Y. Koseoglu-Imer, N. Dizge, A. Karagunduz, B. Keskinler, Influence of membrane fouling reducers (MFRs) on filterability of disperse mixed liquor of jet loop bioreactors, Bioresour. Technol., 102 (2011) 6843–6849.
[22] M. Agtas, M.E. Ersahin, H. Ozgun, I. Koyuncu, Impact of module design on the performance of membrane bioreactors treating municipal wastewater, Sep. Sci. Technol., 51 (2016) 836–844.
[23] American Public Health Association, American Water Works Association, Water Environment Federation, Standard Methods for the Examination of Water and Wastewater, 2005.
[24] I. Chang, P. Le Clech, B. Jefferson, Membrane fouling in membrane bioreactors for wastewater treatment, J. Environ. Eng., 128 (2002) 1018–1030.
[25] P. Le Clech, B. Jefferson, I.S. Chang, S.J. Judd, Critical flux determination by the flux-step method in a submerged membrane bioreactor, J. Membr. Sci., 227 (2003) 81–93.
[26] R.W. Field, D. Wu, J.A. Howell, B.B. Gupta, Critical flux concept for microfiltration fouling, J. Membr. Sci., 100 (1995) 259–272.
[27] H. Ozgun, M.E. Ersahin, S. Erdem, B. Atay, B. Kose, R. Kaya, M. Altinbas, S. Sayili, P. Hoshan, D. Atay, E. Eren, C. Kinaci, I. Koyuncu, Effects of the pre-treatment alternatives on the treatment of oil-gas field produced water by nanofiltration and reverse osmosis membranes, J. Chem. Technol. Biotechnol., 88 (2013) 1576–1583.
[28] H. Ozgun, Y. Tao, M.E. Ersahin, Z. Zhou, J.B. Gimenez, H. Spanjers, J.B. van Lier, Impact of temperature on feed-flow characteristics and filtration performance of an upflow anaerobic sludge blanket coupled ultrafiltration membrane treating municipal wastewater, Water Res., 83 (2015) 71–83.