This article was downloaded by:
On: *25 January 2011*
Access details: *Access Details: Free Access*
Publisher *Taylor & Francis*
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK

Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

Criticality of Flux and Aeration for a Hollow Fiber Membrane Bioreactor

Hector Monclus[a]; Sebastian Zacharias[b]; Ana Santos[b]; Marc Pidou[b]; Simon Judd[b]
[a] Faculty of Sciences, University of Girona, Girona, Spain [b] Center for Water Science, Cranfield University, Cranfield, Bedfordshire, UK

Online publication date: 23 April 2010

To cite this Article Monclus, Hector , Zacharias, Sebastian , Santos, Ana , Pidou, Marc and Judd, Simon(2010) 'Criticality of Flux and Aeration for a Hollow Fiber Membrane Bioreactor', Separation Science and Technology, 45: 7, 956 — 961

To link to this Article: DOI: 10.1080/01496391003666197

URL: http://dx.doi.org/10.1080/01496391003666197

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.informaworld.com/terms-and-conditions-of-access.pdf

This article may be used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

Separation Science and Technology, 45: 956–961, 2010
Copyright © Taylor & Francis Group, LLC
ISSN: 0149-6395 print/1520-5754 online
DOI: 10.1080/01496391003666197

Taylor & Francis
Taylor & Francis Group

Criticality of Flux and Aeration for a Hollow Fiber Membrane Bioreactor

Hector Monclus,[1] Sebastian Zacharias,[2] Ana Santos,[2] Marc Pidou,[2] and Simon Judd[2]
[1]*Faculty of Sciences, University of Girona, Girona, Spain*
[2]*Center for Water Science, Cranfield University, Cranfield, Bedfordshire, UK*

Downloaded At: 08:48 25 January 2011

A three-element microfiltration (MF) hollow fiber (HF) membrane module has been evaluated for treating municipal wastewater by an immersed membrane bioreactor (iMBR) based on a pilot-scale plant. The flux-step method, classically used to identify the critical flux, was compared with an aeration-step method conducted at the identified critical flux of 14.5 $\mathbf{l\,m^{-2}\,h^{-1}}$. It was found that the permeability of the central element was found to be higher, since the air stream imparted to the end elements was dissipated because there is no channel formed by the proximity of the neighboring elements. The aeration-step trials revealed the critical specific aeration demand for both intermittent and continuous aeration regimes to be lower than that applied to the critical flux-step experiments. This implies that the operating conditions identified for critical flux-step experiment are over conservative, corroborating results from previous reports, and that aeration stepping presents a more representative method for identifying sustainable operating conditions.

Keywords aeration; critical flux; fouling; hollow fiber; membrane bioreactor

INTRODUCTION

The immersed membrane bioreactor (iMBR), which combines biological treatment with membrane filtration, has been established for almost two decades (1). The MBR offers a number of advantages over the classical activated sludge process (ASP), including the production of consistently high-quality effluent. The technology can be operated at extended solids retention times (SRTs), thereby reducing the reactor size, increasing the MLSS concentration, and reducing the waste volumes generated due to the decreased sludge yield. However, MBR operation is ultimately constrained by membrane surface fouling (2,3,4) and also membrane channel clogging (5). This leads to a reduction in the permeability of the membranes and demands their frequent physical and chemical cleaning to maintain production. Fouling phenomena are extremely complex in MBRs due to the large number of contributing factors, such as like the nature of the membrane (geometry, material type, pore size, and size distribution, etc.), the biomass (solids concentration, floc size and characteristics, macromolecule concentration, and physicochemistry), and the operating conditions (aeration, sludge age, flux) (6).

Fouling of iMBR membranes in practice is minimized by sub-critical flux operation, through a combination of limiting the flow through the membrane and promoting turbulence by the aeration of the membranes, which acts to scour and/or agitate them (6). Critical flux (J_c) can be broadly defined as the flux, or the flow rate per unit membrane area, below which no deposition of foulants takes place (7). In the "strong" form, J_c is defined as the flux below which the membrane permeability during filtration is the same as that for clean water filtration. It is broadly accepted that this definition is not appropriate to MBRs where membrane fouling takes place even at very low fluxes (8,9).

Tests performed to identify the critical flux normally take the form of the classical flux-step test, where the flux is incrementally increased at steps of 2–5 $\mathrm{l\,m^{-2}\,h^{-1}}$ (LMH) and for periods of 15–60 minutes and the trans-membrane pressure (TMP) response observed (8,10,11). Many authors report a roughly exponential increase in the rate of increase in TMP (dTMP/dt, usually referred to as the fouling rate) with the applied flux (8,10,11). However, it has also been noted (8) that the measured critical flux is dependent on the step length, along with other factors relating to the sludge quality.

The key contribution to energy demand in submerged systems is the specific aeration demand for membrane scouring, SAD_m, in $\mathrm{Nm^3\,h^{-1}}$ air *per* $\mathrm{m^2}$ membrane area (6). Air is used for biomass floc suspension and circulation, membrane scouring in the case of flat sheet (FS) membranes, and agitation for hollow fiber (HF) membranes. Energy consumption rates as low as 0.62 $\mathrm{kWh\,m^{-3}}$ have been reported on full-scale immersed MBR installations (12) where 41% of the energy consumed was for aeration and comprised 29% for membrane aeration and 12% for process aeration. In the past it has been demonstrated that

Received 1 November 2009; accepted 31 December 2009.
Address correspondence to Simon Judd, Center for Water Science, Cranfield University, Cranfield, Bedfordshire, UK. E-mail: s.j.judd@cranfield.ac.uk

there is a linear relationship between the flux and the aeration rate up to a threshold value beyond which no further increase in permeability takes place (8,11,13). However, no study of critical aeration demand at a fixed flux has been made.

This pilot study aims to determine the critical flux of a microfiltration (MF) HF membrane using the flux-step method. Further, it aims to determine the critical specific aeration demand ($SAD_{m,crit}$), and the impact of SAD_m and aeration regime on membrane fouling.

MATERIALS AND METHODS

The pilot scale rig comprised a 2.5 m^3 bioreactor with a vertically-mounted module fitted with three membrane elements, each providing a surface area of 3.33 m^2. The MF HF membranes were of polyvinylidene fluoride (PVDF) with a pore size of 0.1 μm and were 1.4 mm in external diameter (Table 1). The module was submerged to a depth of 0.5–1.0 m and the permeate was extracted using a peristaltic pump. Transmembrane pressure (TMP) was monitored using pressure sensors connected to a dedicated data logger.

The feed was settled sewage from the Cranfield University Wastewater Treatment Works (Table 2), and samples of sludge and water were taken at regular intervals. The sludge was sampled for the mixed liquor suspended solids (MLSS) and the mixed liquor volatile suspended solids (MLVSS) content, these being determined by Standard Methods 2540D and 2540E respectively (14). Similarly, standard methods were used to measure the chemical oxygen demand (COD), ammonia (NH_4^+), nitrogen oxide

TABLE 1
Membrane and module specification

Description	Value
Type	HF MF
Membrane material	PVDF
Pore size, mm	0.1
Internal fiber diameter, mm	0.9
External fiber diameter, mm	1.4
Fiber length, mm	1500
Dimensions of fiber bundle (LxWxH), mm	169 × 40 × 1620
Dimensions of module (LxWxH), mm	400 × 300 × 2140
Number of fiber per bundle	517
Fiber separation, mm	1
Bundle separation, mm	20
Packing density, $m^2\,m^{-3}$	293
Bundle area, m^2	3.33
Total effective membrane surface area, m^2	10

TABLE 2
Wastewater characteristics

Parameter	Value
COD, $mg\,l^{-1}$	290
(NH_4^+), $mg\,l^{-1}$	35
(NO_x^-), $mg\,l^{-1}$	0.3
pH	7.6
SVI, $ml\,g^{-1}$	116

compounds (NO_x), and sludge volume index (SVI). The MLSS concentration was held at between 7–9 $g\,l^{-1}$ throughout the trial, and tests were performed on the three elements individually.

Two types of test were performed: flux-step and aeration-step. The classical flux-step method was similar to that reported previously (8,11,15). Flux steps were performed at 15 minute intervals at steps of ~5 LMH up to a maximum flux of around 25 LMH. The flux-step experiment was used initially to determine the critical flux of all three elements individually. For this trial the elements were operated without relaxation and with continuous aeration at a SAD_m of 0.48 $Nm^3\,m^{-2}\,h^{-1}$. The second flux-step experiment was performed on the central element alone with relaxation (9 minutes permeation with 1 minute of relaxation) and with intermittent aeration (10 s on/10 s off at a SAD_m of 0.24 $Nm^3\,m^{-2}\,h^{-1}$. In both cases the critical flux was assumed to be the flux at which the fouling rate, dTMP/dt, exceeded a threshold of 0.5 mbar min^{-1}.

Aeration-step experiments were used to determine the $SAD_{m,crit}$ of the membranes under conditions of intermittent and continuous aeration. During this test, the permeation regime was cyclic (15 min on/1 min relaxation) at a constant flux of around 14.5 LMH. Each SAD_m step was duplicated, such that each step comprised 30 minutes of permeate extraction in total. The same limiting fouling rate as previously (0.5 mbar min^{-1}) was applied to determine $SAD_{m,crit}$. A standard maintenance clean, or chemically-enhanced backflush (CEB), was employed prior to each test; a 500 mg l^{-1} hypochlorite solution was applied at 5 backflush pulses of 15 seconds duration and a flux of ~55 $l\,m^{-2}\,h^{-1}$, with around 5 minutes of relaxation time between pulses.

RESULTS

Critical Flux Test

Element Comparison

The fouling rate at a constant SAD_m of 0.48 $Nm^3\,m^{-2}\,h^{-1}$ for all individual elements followed the expected exponential relationship with flux (Fig. 1), corroborating previously reported correlations (8,11,15), but with no clear inflection at the assumed critical flux J_c. Critical flux was thus arbitrarily taken as the flux corresponding to a

Downloaded At: 08:48 25 January 2011

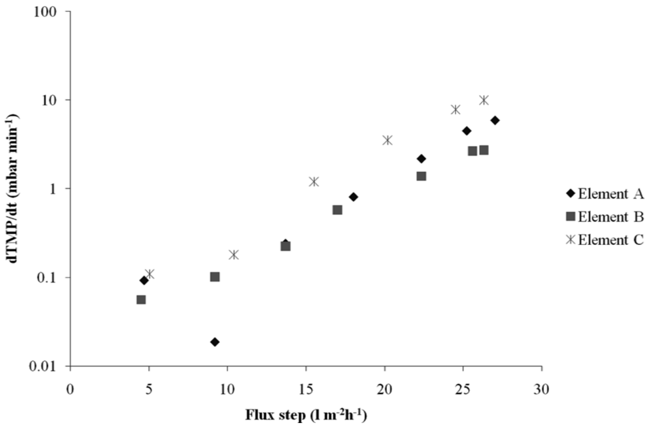

FIG. 1. Trend of fouling rate, dTMP/dt for each individual element; continuous aeration without relaxation (at a SAD_m of 0.48 $Nm^3\,m^{-2}\,h^{-1}$).

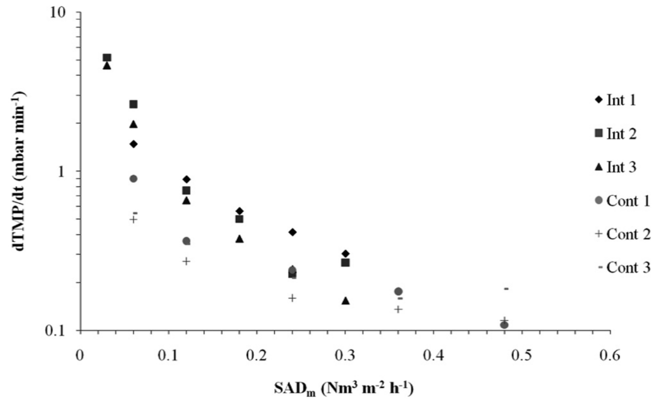

FIG. 3. Comparison of effect of intermittent and continuous aeration regimes on fouling rate (constant flux of $14.5\,l\,m^{-2}\,h^{-1}$).

fouling rate of $0.5\,mbar\,min^{-1}$. Accordingly, the critical flux values of Elements A and B were $16.6\,l\,m^{-2}\,h^{-1}$ and $17.0\,l\,m^{-2}\,h^{-1}$ respectively, while it was slightly lower for element C at $12.6\,l\,m^{-2}\,h^{-1}$. At its peak the permeability of the central element was ~30% more than the element A and ~65% more than element C. Comparing the fouling rates of the three elements revealed that, with the exception of one anomalous result, the central element had consistently lower fouling rates.

Central Element Tests

The flux-step experiment was duplicated for the central element. Cyclic permeation was introduced (9 min on/1 min relaxation) along with intermittent aeration (10 s on/10 s off) at an overall SAD_m of $0.24\,Nm^3\,m^{-2}\,h^{-1}$, and the fouling rate measured as before (Fig. 2). Under these conditions, the J_c of the central element was estimated to be around $14.7 \pm 0.5\,l\,m^{-2}\,h^{-1}$. It was also observed that at higher flux, the fouling rate of the element

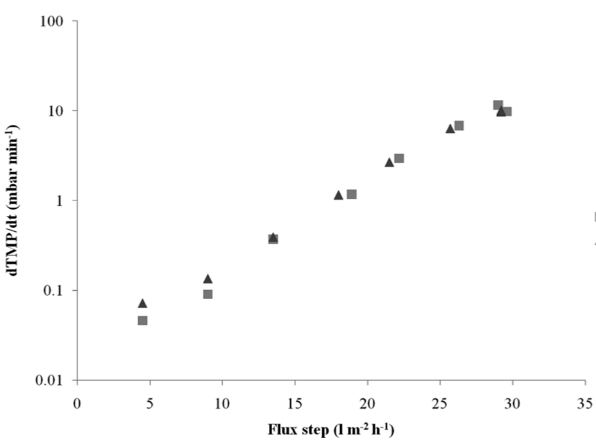

FIG. 2. Trend of fouling rate, dTMP/dt for central element; intermittent aeration with relaxation (at a SAD_m of $0.24\,Nm^3\,m^{-2}\,h^{-1}$).

was slightly lower under continuous aeration operation than for intermittent operation.

Critical Aeration Demand

Two separate studies were conducted to determine $SAD_{m,crit}$ of the central element operating with intermittent and continuous aeration. The membrane was operated at a constant flux of $14.5\,l\,m^{-2}\,h^{-1}$, with cyclic permeation (15 min on/1 min relaxation) for both the studies. The aeration-step experiment was performed to determine $SAD_{m,crit}$ of the central element under conditions of intermittent aeration (10 s on/10 s off). A correlation of fouling rate with SAD_m between 0.03 and $0.3\,Nm^3\,m^{-2}\,h^{-1}$ (Fig. 3) revealed a $SAD_{m,crit}$ of $0.19 \pm 0.01\,Nm^3\,m^{-2}\,h^{-1}$. The second aeration-step experiment performed to determine $SAD_{m,crit}$ of the same central element with continuous aeration, stepping SAD_m from 0.06 to $0.6\,Nm^3\,m^{-2}\,h^{-1}$, revealed $SAD_{m,crit}$ to be in the range $0.06 \pm 0.05\,Nm^3\,m^{-2}\,h^{-1}$ (Fig. 3). The critical aeration studies thus reveal $SAD_{m,crit}$ for intermittent aeration to be higher than that for continuous aeration $SAD_{m,crit}$, implying that the latter is more energetically efficient.

DISCUSSION

Effect of Aeration on Membrane Permeability

Fouling control and flux enhancement of biomass filtration membranes using aeration has been extensively studied (8,11,13). Research reveals the effectiveness of aeration to depend on the design of the aerator (coarse/fine bubble) and module (HF or tubular membrane diameter, packing density, module spacing, etc.) (16,17).

The initial flux-step experiment performed to determine the critical flux of the individual elements revealed that while the exponential relationship between the fouling rate and flux was similar for all three elements, the exponent value being around 0.1 for fouling rate expressed in mbar min^{-1} and flux in $l\,m^{-2}\,h^{-1}$, the permeability of the central

Downloaded At: 08:48 25 January 2011

Downloaded At: 08:48 25 January 2011

element was higher than that of the outer elements. The presence of the membrane elements on either side of the central element meant that its channels were formed to direct the air bubbles past the membrane fibers and prevent their dissipation into the bulk liquor. It is well known that a channel or spacing within a submerged membrane module has an important effect on the hydraulic performance of the system (17). Since elements in an MBR are predominantly in the center of the stack, for example, manufacturer data of the GE Zenon ZeeWeed® 500 d module indicates that more than only 5% of all elements are at the outside of the stack, it is more reasonable to base studies on the central element than the external ones.

The flux-step experiments indicated J_c values to be somewhat lower than those reported for other pilot scale studies on municipal feedwater (Table 3). In the past several different methods have been adopted to interpret J_c. Bouhabila et al. (18), determined J_c from correlation of TMP with J and interpreted J_c as being the flux at which there is a sudden increase in TMP. This was refined by Le-Clech et al. (8), and subsequently by Guglielmi et al. (11), who defined J_c as the maximum flux at which the permeability (K) was greater than 90% of K_0, K_0 being the permeability measured at the first flux-step. More recently, Bottino et al. (15) defined J_c as the J at which $dTMP/dt \geq 0.5\,\text{mbar}\,\text{min}^{-1}$, a very simple definition based on practical considerations though insufficiently conservative, given that it equates to a fouling rate of 0.72 bar a day.

Critical Aeration Rate

It has been recognized for some time that a threshold membrane aeration rate exists above which no further suppression of fouling takes place (14). This trend has since been corroborated by a number of authors (8,11,18) and formed the basis for empirically modelling aeration energy demand (19). However, this key threshold value—denoted as the critical aeration demand $SAD_{m,crit}$ in this study—is evidently system dependent (Table 3), varying with the membrane element design and, presumably, the process operating conditions.

From the results it can be observed that for the same limiting fouling rate of $0.5\,\text{mbar}\,\text{min}^{-1}$ the $SAD_{m,crit}$ ($0.19 \pm 0.01\,\text{Nm}^3\,\text{m}^{-2}\,\text{h}^{-1}$) for the intermittent aeration regime is lower than the aeration rate of $0.24\,\text{Nm}^3\,\text{m}^{-2}\,\text{h}^{-1}$ employed for the critical flux-step experiment. Similarly the $SAD_{m,crit}$ of $0.06 \pm 0.05\,\text{Nm}^3\,\text{m}^{-2}\,\text{h}^{-1}$ used for continuous aeration regime is much lower than the $0.24\,\text{Nm}^3\,\text{m}^{-2}\,\text{h}^{-1}$ aeration rate used for the critical flux-step experiment. The operating conditions identified on the basis of the critical flux-step experiment thus appear to be over conservative.

Previous studies performed on GE Zenon HF membranes have assumed that intermittent aeration can be used to effectively control fouling and improve membrane permeability (11,12,22,23). Pilot and full-scale trials have been recently conducted to determine the effect of decreased intermittent aeration on permeability (12,24). Garcés et al. (12) evaluated the impact of a 50% reduction in aeration rate through the established aeration regime of 10''/10'' (10 s on, 10 s off) against two other aeration regimes of 10''/30'' and 10''/10'' with 50% less air. The results at low and medium fluxes (under $50\,\text{l}\,\text{m}^{-2}\,\text{h}^{-1}$) revealed that under either condition of 50% aeration, there was no significant difference in TMP behavior when compared to the established aeration regime. This result indicates that reduced aeration through intermittent application is more efficient than continuous aeration, a result corroborated by the study of Tao et al. (24), but contrary to the results from the current study. This may be a facet of the rather unusual sludge, which had a very high SVI and was not readily filterable, encountered in the current study.

TABLE 3
Critical flux studies

System	Membrane	Feed	J_c ($\text{l}\,\text{m}^{-2}\,\text{h}^{-1}$)	MLSS ($\text{g}\,\text{l}^{-1}$)	SAD_m ($\text{Nm}^3\,\text{m}^{-2}\,\text{h}^{-1}$)	Reference
iMBR (LS[a])	HF	Real	10.3 12.1 13.3	8	9	15
iMBR (PS[b])	HF	Real	30	10	0.5	11
iMBR (PS)	FS	Real	31	7.7	0.35	20
iMBR (PS)	FS	Real	31.2	20	0.88	21
iMBR (LS)	HF	Real	25	8.2	25	18
iMBR (PS)	HF	Real	30	8.2	3.6	
iMBR (PS)	MT	Real	58	8	0.87	8
iMBR (PS)	HF	Real	14.5	8	0.24	Current study

[a]LS – Lab scale.
[b]PS – Pilot scale.

Downloaded At: 08:48 25 January 2011

CONCLUSIONS

A pilot-scale trial was conducted to assess the performance of a hollow fiber membrane. The outcomes from the J_c and $SAD_{m,crit}$ correlations are as follows:

- Initial flux-step trials on the three individual membranes revealed the permeability of the two outer membrane elements to be lower than that of the central element, indicating that tests are most representative if conducted on the central element rather than the three-element module.
- The J_c of the central element ($14.51\,m^{-2}\,h^{-1}$) was low in comparison to other pilot-scale trials of HF membranes operated under similar conditions and similarly challenged with municipal effluent.
- The aeration-step method revealed that for constant flux operation there was a $SAD_{m,crit}$ value below which a significant increase in membrane fouling arose, analogous to the critical flux trends. $SAD_{m,crit}$ can thus be used to optimize the aeration rate for submerged HF membrane systems.
- The $SAD_{m,crit}$ for both intermittent and continuous aeration regimes was lower than the aeration rate used to identify the critical flux through flux-step experiments. This implies that the operating conditions identified for critical flux-step experiment are conservative.
- The aeration-step trials under the two different aeration regimes revealed that for any given SAD_m, continuous aeration is more effective at controlling the fouling rate intermittent aeration, which is counter-intuitive and contrary to industrial practice. Further trials need to be carried out on full-scale installations to verify these counter-intuitive findings.
- The $SAD_{m,crit}$ value ($0.19\,Nm^3\,m^{-2}\,h^{-1}$) for the central element, is slightly less than the mean values of SAD_m ($0.25\,Nm^3\,m^{-2}\,h^{-1}$) recommended by the supplier, and also less than data reported for a number of full and pilot-scale applications (19).

The results suggest that the measurement of $SAD_{m,crit}$ by aeration stepping offers a more appropriate method for identifying the optimal operating conditions of an MBR, particularly for most full-scale plants where operation is invariably below the critical flux.

SYMBOLS AND ABBREVIATIONS

CEB	Chemically enhanced backflush
COD	Chemical oxygen demand
dTMP/dt	Fouling rate
HF	Hollow fiber
HRT	Hydraulic retention time
Imbr	Immersed membrane bioreactor
J	Flux
J_c	Critical flux
J_{sust}	Sustainable flux
MBR	Membrane bioreactor
MF	Microfiltration
MLSS	Mixed liquor suspended solids
MLVSS	Mixed liquor volatile suspended solids
$(NH_4^-)-N$	Ammonia nitrogen
$(NO_3^-)-N$	Nitrous oxide nitrogen
PVDF	Polyvinylidene fluoride
SAD_m	Specific aeration demand
$SAD_{m,crit}$	Critical specific aeration demand
SRT	Solids retention time
SVI	Sludge volume index

REFERENCES

1. Stephenson, T.; Judd, S.; Jefferson, B.; Brindle, K. (2000) *Membrane Bioreactors for Wastewater Treatment*; IWA Publishing: London.
2. Wang, X.; Li, X.; Huang, X. (2007) Membrane fouling in a submerged membrane bioreactor (SMBR): Characterisation of the sludge cake and its high filtration resistance. *Separation and Purification Technology*, 52 (3): 439.
3. Chu, H.P.; Li, X. (2005) Membrane fouling in a membrane bioreactor (MBR): Sludge cake formation and fouling characteristics. *Biotechnology and Bioengineering*, 90 (3): 323.
4. Choi, H.; Zhang, K.; Dionysiou, D.D.; Oerther, D.B.; Sorial, G.A. (2005) Effect of permeate flux and tangential flow on membrane fouling for wastewater treatment. *Separation and Purification Technology*, 45 (1): 68.
5. Judd, S. (2008) The status of membrane bioreactor technology. *Trends in Biotechnology*, 26 (2): 109.
6. Judd, S. (2006) *The MBR Book: Principles and Applications of Membrane Bioreactors in Water and Wastewater Ttreatment*, 1st Ed.; Elsevier: Oxford, UK.
7. Field, R.W.; Wu, D.; Howell, J.A.; Gupta, B.B. (1995) Critical flux concept for microfiltration fouling. *Journal of Membrane Science*, 100 (3): 259.
8. Le Clech, P.; Jefferson, B.; Chang, I.S.; Judd, S.J. (2003) Critical flux determination by the flux-step method in a submerged membrane bioreactor. *Journal of Membrane Science*, 227 (1–2): 81.
9. Cho, B.D.; Fane, A.G. (2002) Fouling transients in nominally sub-critical flux operation of a membrane bioreactor. *Journal of Membrane Science*, 209 (2): 391.
10. Howell, J.A.; Chua, H.C.; Arnot, T.C. (2004) In situ manipulation of critical flux in a submerged membrane bioreactor using variable aeration rates, and effects of membrane history. *Journal of Membrane Science*, 242 (1–2): 13.
11. Guglielmi, G.; Chiarani, D.; Judd, S.J.; Andreottola, G. (2007) Flux criticality and sustainability in a hollow fibre submerged membrane bioreactor for municipal wastewater treatment. *Journal of Membrane Science*, 289 (1–2): 241.
12. Garcés, A.; De Wilde, W.; Thoeye, C.; De Gueldre, G. (2007) Operational cost optimisation of MBR Schilde. Proceedings of the 4th IWA International Membranes Conference, Membranes for Water and Wastewater Treatment; 15–17 May 2007, Harrogate, UK.
13. Ueda, T.; Hata, K.; Kikuoka, Y.; Seino, O. (1997) Effects of aeration on suction pressure in a submerged membrane bioreactor. *Water Research*, 31 (3): 489.

14. American Public Health Association (APHA) (1998) *Standard Methods for the Examination of Water and Wastewater*, 20th Ed.; American Water Works Association and Water Pollution Control Federation: Washington, DC.
15. Bottino, A.; Capannelli, G.; Comite, A.; Mangano, R. (2009) Critical flux in submerged membrane bioreactors for municipal wastewater treatment. *Desalination*, 245 (1–3): 748.
16. Chan, C.C.V.; Bérubé, P.R.; Hall, E.R. (2007) Shear profiles inside gas sparged submerged hollow fiber membrane modules. *Journal of Membrane Science*, 297 (1–2): 104.
17. Cui, Z.F.; Chang, S.; Fane, A.G. (2003) The use of gas bubbling to enhance membrane processes. *Journal of Membrane Science*, 221 (1–2): 1.
18. Bouhabila, E.H.; Ben Aïm, R.; Buisson, H. (1998) Microfiltration of activated sludge using submerged membrane with air bubbling (application to wastewater treatment). *Desalination*, 118 (1–3): 315.
19. Verrecht, B.; Judd, S.; Guglielmi, G.; Brepols, C.; Mulder, J.W. (2008) An aeration energy model for an immersed membrane bioreactor. *Water Research*, 42 (19): 4761.
20. Guglielmi, G.; Saroj, D.P.; Chiarani, D.; Andreottola, G. (2007) Sub-critical fouling in a membrane bioreactor for municipal wastewater treatment: Experimental investigation and mathematical modelling. *Water Research*, 41 (17): 3903.
21. Guglielmi, G.; Chiarani, D.; Saroj, D.P.; Andreottola, G. (2008) Impact of chemical cleaning and air-sparging on the critical and sustainable flux in a flat sheet membrane bioreactor for municipal wastewater treatment. *Water Science and Technology*, 57 (12): 1873.
22. DeCarolis Jr., J.F.; Adham, S. (2007) Performance investigation of membrane bioreactor systems during municipal wastewater reclamation. *Water Environment Research*, 79 (13): 2536.
23. Fatone, F.; Battistoni, P.; Pavan, P.; Cecchi, F. (2007) Operation and maintenance of full-scale municipal membrane biological reactors: A detailed overview on a case study. *Industrial and Engineering Chemistry Research*, 46 (21): 6688.
24. Tao, G.; Kekre, K.; Oo, M.-H.; Viswanath, B.; Lew, C.-H.; Kan, L.-M.; Seah, H. (2009). Large scale membrane bioreactor plant design (retrofit) and optimisation. Proceedings of the 5th IWA Membrane Technology Conference; 1–3 September, Beijing, China.

Downloaded At: 08:48 25 January 2011