Asian Institute of Technology
School of Environment, Resources & Development
Environmental Engineering & Management

Final Presentation

Fouling Behavior & Nitrogen Removal in The Aerobic Granulation Membrane Bioreactor

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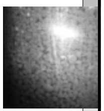
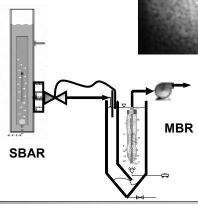
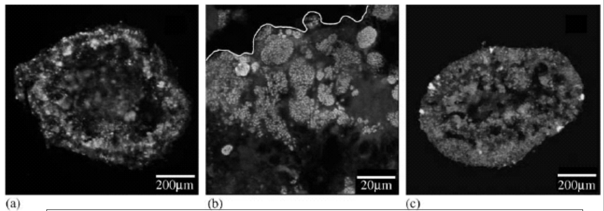




Answers For Examiner's Comments



(a, b) Yellow: ammonia oxidizing bacteria. Red: other bacteria
(c) Yellow: nitrite-oxidizing bacteria. Red: other bacteria

2. The time of aeration appears sufficient to remove C & ammonia but nitrates never appeared in opposite with the appearance of nitrites. Discussion about these phenomena according to size, granule structure and operation time.

- Nitrite-oxidizing bacteria is inhibited (high toxic nitrite) ➔ inhibit nitrate formation.

- Microorganisms (heterotrophs, ammonia-oxidizing, nitrite-oxidizing) exist in 200 μm from surface. Nitrite-oxidizing bacteria is a minor population (Tsunenda et al., 2003).

Answers For Examiner's Comments

3. Biomass concentration in SBAR reached 18 gVSS/L (it could be interesting to differentiate active biomass from volatile biomass compounds

- This method measured volatile biomass (VSS) based on the TOC of mixed sludge conversion factor (Tijhuis et al., 1994).

- VSS = active biomass + cell debris (biomass decay)

- In CAS, active biomass = 85-90% VSS.

- In granular sludge, it is probably lower (long retention of granule) ➔ further study.

4. Discuss the configuration in relation with performances and cost, could such a system be relevant only with an immersion of membranes in a specific zone of setter.

- This solution could reduce number of unit processes and energy.

- Fouling rate of BG-MABR was found higher than that of BG-MBR (0.105 kPa/d and 0.027 kPa/d) (sludge concentration 2 g/L and 4 g/L for MBR and MABR).

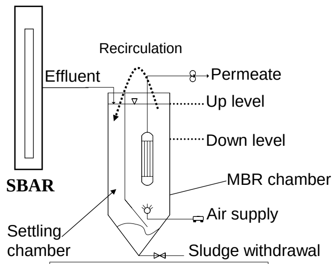
- Specific energy was 0.1, 0.9 & 1.6 kWh/m^3 for aerobic reactor, MBR & BG-MBR.

- OLR: MBR (< 8 kgCOD/m^3.d) and BG-MBR (up to 15) kgCOD/m^3.d.

Answers For Examiner's Comments

- Proposed system is probably compact & less fouling potential compared to BG-MBR & MG-MABR.

- Denitrification can be enhanced with a recirculation from membrane chamber to settling chamber.



Settler-combined MBR

Answers For Examiner's Comments

5. To improve nitrogen removal & granular stability → coupling to form a BG-MBR. This combination induced a partial destruction of granules with appearance of fungi, filaments & decreasing granular bed volume. Author attributes these phenomena to the difficulty of control of optimal SRT (nevertheless, the quick variation of the sludge composition did not correspond to the SRT).

- Granules disintegrated after a certain time of operation (about 300 days).

- Granule breakage occurred due to their long retention in SBAR (filaments & fungus).

- In granulation SBAR, the SRT was calculated by the conventional method as:

SRT = Sludge in reactor/sludge wasted out per day

- SRT calculated for granulation reactor is just a relative definition.

- Sludge washed out (< 10 m/h): light fraction (flocs, small granules, detached particles). Granules retained in reactor

- Actual SRT = 10-15 d to avoid filaments ➔ Perform appropriate sludge removal methods to control actual SRT to enhance granule stability. Periodical sludge removal (a) mixed sludge; (b) top sludge; and (c) bottom sludge.

Answers For Examiner's Comments

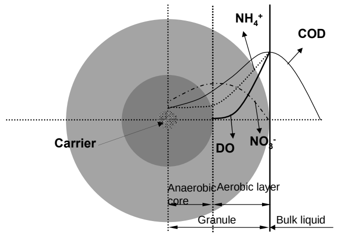
6. Result pointed out that the difficulty to achieve adequate nitrogen removal probably link to the opposite conditions imposed by granulation and anoxic reduction of NOx when NLR is too high. (A simulation with ASM model could indicate the adequate time of aeration and non aeration to remove nitrogen and its conformity with granular bed stability). Author should take some interest to ASM model to identify the necessary time of aerobic/anoxic periods and the mass transfer through the granule to remove nitrogen and compare the results to the optimal conditions to maintain the structures of granule.

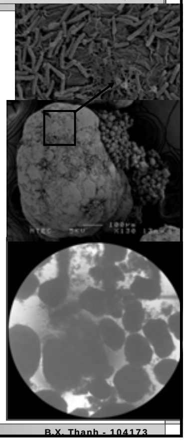
- For the proposed objectives, it needs to measure specific kinetic data, mass transfer constants, mass transfer coefficients and active biomass for granule at various NLR, OLR which have not planned in this research ➔ These objectives to be performed in the future research.

7. Some corrections in chapter 3 ➔ has been corrected in the final version of Dissert.

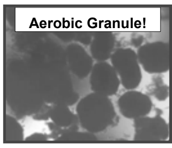
Background: Aerobic Granule

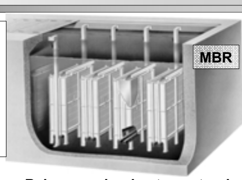
- Size: 0.5–9.0 mm ➔ Simultaneous nitrification/denitrification;
- Excellent settling ability (20-110 m/h, SVI = 18 mL/g)
- Tolerate temperature range (8-55ºC) *(De Kreuk et al., 2005)*;
- Microbial diversity;
- Remove phenol (3.8 kg/m³.day) *(Tay et al., 2005)* and nitrilotriacetic (NTA) *(Nancharaiah et al., 2006)*



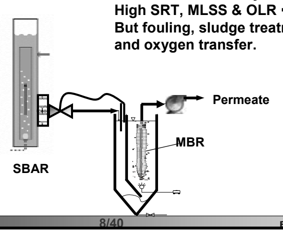


Rationale: Aerobic Granulation MBR





Being popular due to cost reduction
Water reuse and recycling;
High SRT, MLSS & OLR ➔ less footprint;
But fouling, sludge treatment, and oxygen transfer.

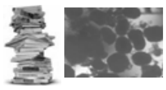


Objectives of Study

1. Study on organic removal and simultaneous nitrification denitrification of aerobic granule and its stability in SBAR;

2. Characterize the fouling behavior of an external submerged MBR treating granulation SBAR effluent (BG-MBR) ;

3. Study on granule stability and fouling propensity of the Continuous Granulation MBR (CG-MBR) at various organic loading rate (OLR);



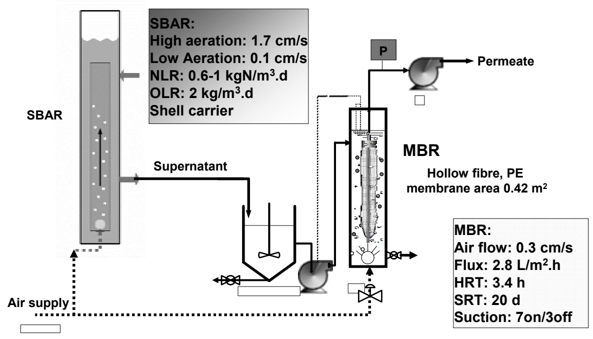
Overall Experimental Plan

Aerobic Granulation MBR

- Phase I a (*AIT*): Batch granulation MBR (BG-MBR)
  - SBAR → Settler → MBR
  - + C, N removal
  - + Granule characterization
  - + Granule stability
  - + Fouling behavior
- Phase I b (*INSA*)*: SBAR
  - + Effect of aeration rates (*conventional vs granulation*)
  - + Effect of anoxic/aerobic condition on sludge/effluent of SBAR
- Phase II (*AIT*): Continuous granulation MBR (CG-MBR)
  - + Granule stability;
  - + Effect of OLR on fouling, N removal

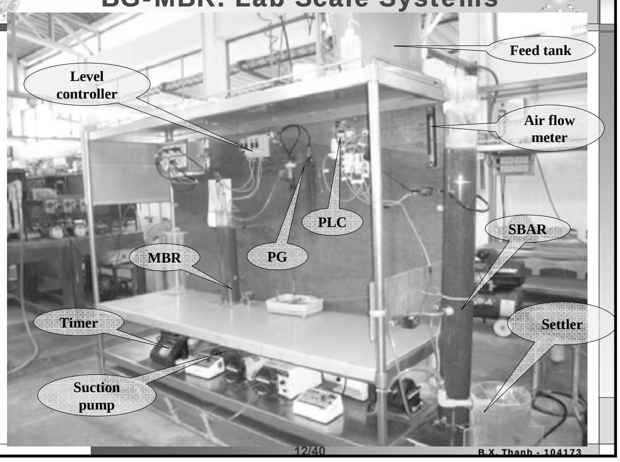
**INSA = Institut National des Sciences Appliquées, Toulouse, France*

Batch Granulation MBR (BG-MBR): Phase Ia

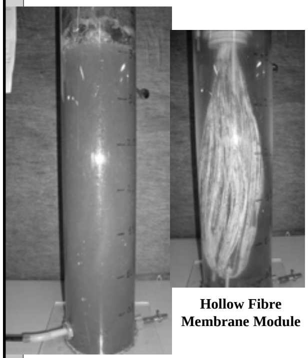


Cycle (4 hrs)	Feeding	High Aeration	Low Aeration	Settling	Withdrawal
Time (min)	6	198	30	3	3

BG-MBR: Lab Scale Systems



MBR & Measured Parameters



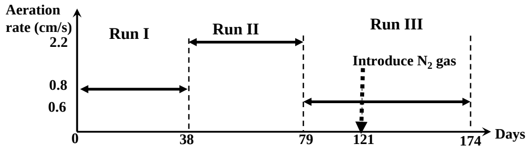
External Submerged MBR

Soluble parameters:
- TOC, Nitrogen species
- EPS (PS, PN)
- UVA254, SUVA (= UVA254/DOC)
- Size Exclusion Chromatography (SEC-EEM)
- Hydrophobicity

Sludge parameters:
- MLVSS/MLSS
- SVI
- Capillary Suction Time (CST)
- Microscopic Observation
- Specific oxygen uptake rate (SOUR)

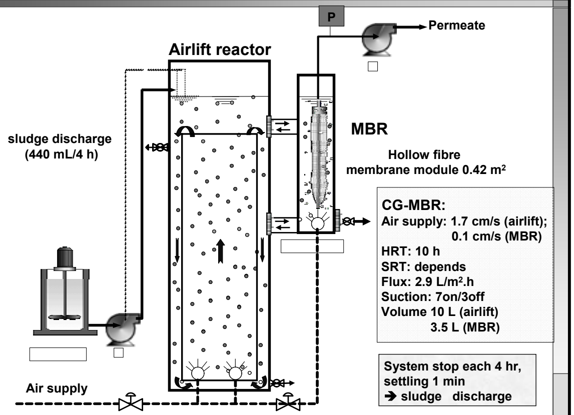
Membrane fouling parameters:
- Modified Fouling Index (MFI) (SS, CL, SL)
- Trans-membrane pressure (TMP)
- Critical flux
- Particle Size Distribution (PSD)
- Resistance/Resistance rate

Effect of Aeration Rates and Anoxic growth on SBAR effluent– Phase I b



Operating conditions:
- SBAR: V = 17 L, H = 1.07 m, D = 0.15 m
- OLR: 2.0-2.3 kgCOD/m^3.d;
- Batch: 6 h; 8 L/batch;
- Cycle: Feeding: 30 min; Reaction: 4h30min; Settling: 30 min; Discharge: 30min
- SRT: automatic washout;

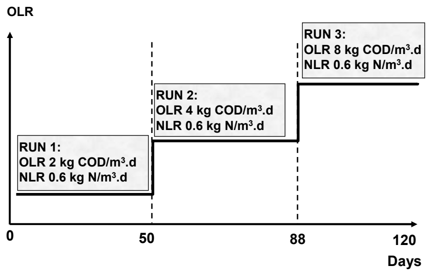
Continuous Granulation MBR (CG-MBR): Phase II



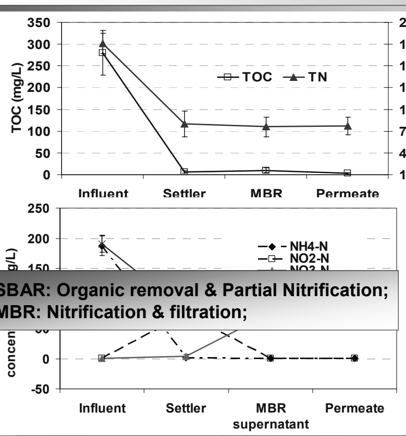
CG-MBR:
Air supply: 1.7 cm/s (airlift); 0.1 cm/s (MBR)
HRT: 10 h
SRT: depends
Flux: 2.9 L/m^2.h
Suction: 7on/3off
Volume 10 L (airlift) 3.5 L (MBR)

System stop each 4 hr, settling 1 min
➔ sludge discharge

Operating Conditions: CG-MBR



BG-MBR Performance: Phase Ia



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SBAR: Organic removal & Partial Nitrification;
MBR: Nitrification & filtration;

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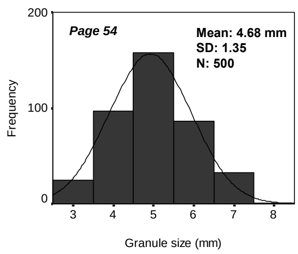
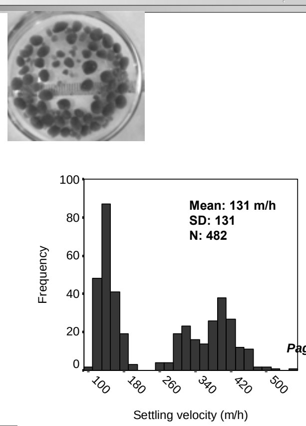
Granule Characteristics in SBAR (Phase Ia)





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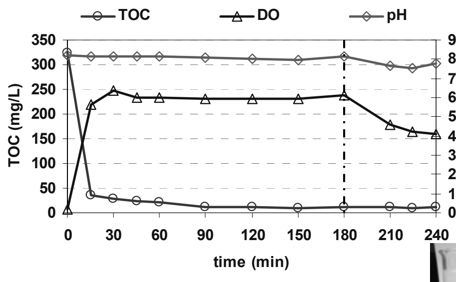
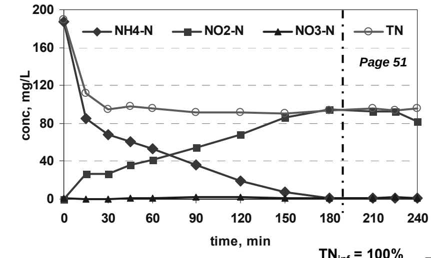
Good settling (AS: < 10 m/h);
High density & compact

SBAR Performance – Organic Removal



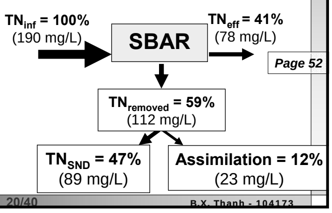
pH = 8.0 ± 0.2; DO = 4.0 – 7.8 mg/L;
Organic matters are removed fast in 30 min (97.7 ± 1.4 %);

SBAR Performance – Nitrogen Removal



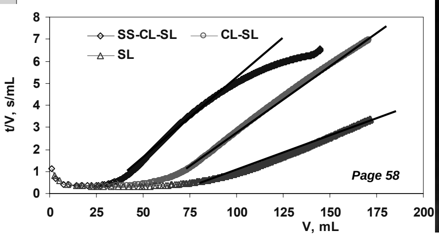
+ Dynamic balance: NH_4-N reduces ➔ NO_2, NO_3 ➔ N_2 generated!

+TN removal 59% (SND= 47%, 22.2 mgN/L.h or 1.76 gN/gVSS.h);



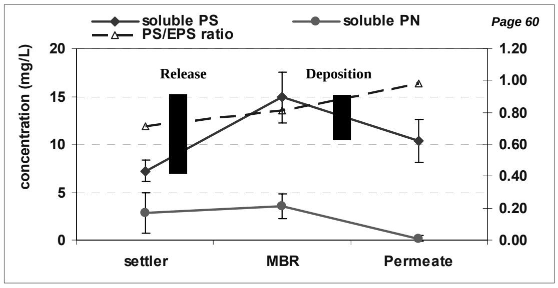
Membrane Fouling Behavior: Phase Ia

Fouling propensity of sludge fractions: Suspended Solids (SS), Colloids (CL) & Solutes (SL)



Fouling potential of SS, CL & SL were 12%, 39% & 49%;
Resistance percentage of SS, CL & SL were 2, 12 & 86 %;
➔ Soluble matters is the major fouling contributor

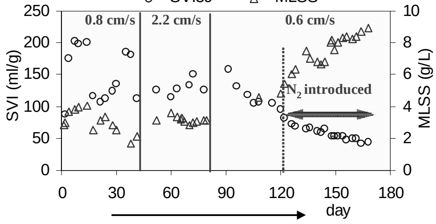
Membrane Fouling – Soluble Fractions

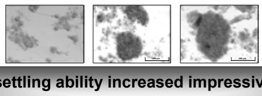


- Soluble PS increased in MBR (cell lysis, deflocculation)
- PS/EPS > 0.8;
- Soluble PS & PN deposited on membrane (11 mgPS/L.m² & 8 mgPN/L.m²);
- Soluble EPS extracted from membrane fibres: 20 μg/cm² (after 78 days)

Effect of Aeration Rates & Anoxic growth on SBAR Effluent– Phase I b

Sludge characteristics

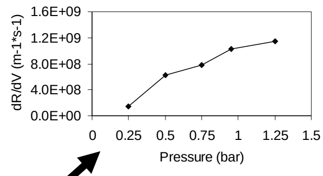


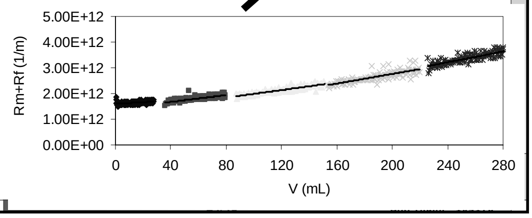


- Biomass conc. & settling ability increased impressively (SVI = 44 mL/g);
- Anoxic growth improves aggregate density & promote aggregation;
- Average effluent SS from SBAR reduced at Run III (200 to 50 mg/L).

Resistance Rate Calculation– Phase I b

$R_t = \Delta P/(J^*\mu)$





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Resistance Rate in SBAR Effluent: Phase I b

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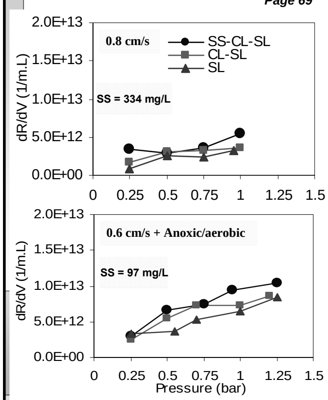

- At low aeration rate (0.8-0.6 cm/s): Resistance rates (SS, CL, SL) same order of magnitude;
- At high aeration rate (2.2 cm/s): resistance rates increases & resistance of SS plays a significant role ➔ release of small particles & SMPs.
- With anoxic: resistance slightly increases.

Irreversible/Reversible Resistance in SBAR Effluent: Phase I b

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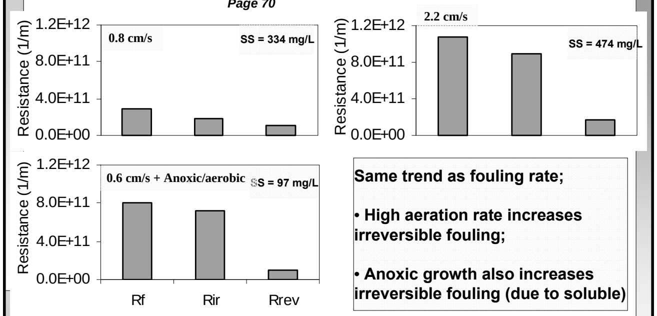

Same trend as fouling rate;

- **High aeration rate increases irreversible fouling;**
- **Anoxic growth also increases irreversible fouling (due to soluble)**

Reduction of aeration and improvement of denitrification leads to lower irreversible fouling

Comparison of Specific cake resistance of Effluent & Sludge: Phase I b

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Source	SBAR Effluent			SBAR Sludge	
Aeration rate	0.8 cm/s	2.2 cm/s	0.6 cm/s + ano/aero	2.2 cm/s	0.6 cm/s
C (kgSS/m³)	0.334	0.474	0.097	3.160	4.750
Specific cake resistance - α (10^{12} m/kg)	27.2	20.1	214.0	7.5	1.6

An inverse trend for "Sludge" & "Effluent" behavior during filtration:

- Anoxic growth seems to have a negative impact on effluent (SMP) but a positive role on sludge filtration (aggregate densification).

- Specific cake resistance (α) is always lower for Sludge than Effluent (due to particles properties and role of soluble)

Soluble Matters Characteristics: Phase I b

Characterization of soluble compounds by Chromatography

Size exclusion chromatography (SEC) shows :

- **Macromolecules (40-600 kDa) are increasingly produced at high aeration rate (2.2 cm/s),**
- **Compounds from 5.7- 6.2 kDa were especially released during denitrification intensification (anoxic growth) and granular sludge formation**

Hydrophobic Interaction Chromatography (HIC) shows :

- **At high aeration rate, Supernatant in effluent contained larger (60%) hydrophobic fraction with low hydrophobic intensity;**
- **At low aeration rate with anoxic growth, supernatant in effluent contained less hydrophobic fraction (20%) with high hydrophobic intensity.**

Continuous Granulation MBR (CG-MBR): Phase II

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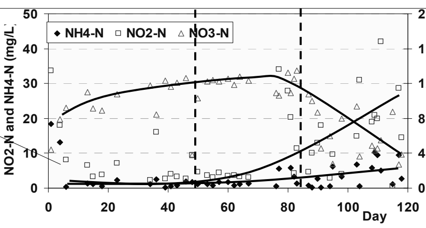
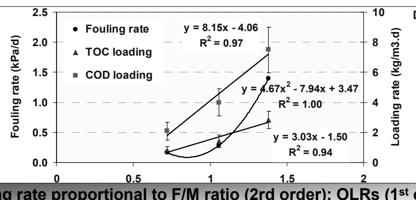


+ NO_3 reduced, NO_2, NH_3 increased at OLR 8;

+ Nitrifying activity ↓ at high OLR ➔ not compete with heterotrophs

Fouling Propensity of CG-MBR: Phase II



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+ Fouling rate proportional to F/M ratio (2rd order); OLRs (1st order);
+ Membrane contacts with high amount of organic matters ➔ fouling.

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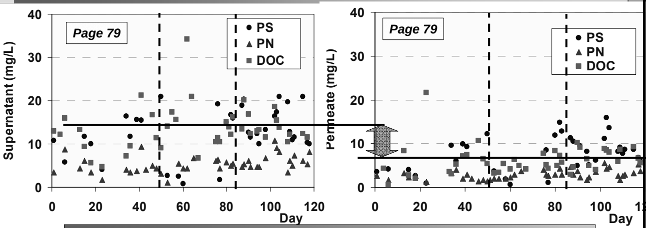
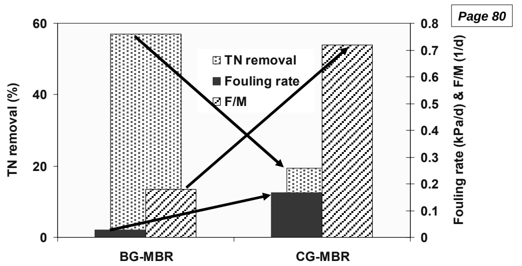
Behavior of Soluble Matters in CG-MBR



+ Soluble matters (DOC, Polysaccharides, Protein):
(Supernatant > Permeate!) ➔ deposited on membrane ;

Deposition rates (mg/L.m²membrane)	OLR (kgCOD/m³.d)		
	2	4	8
DOC	16.3	18.2	17.2
sPS	13.1	11.3	13.7
sPN	5.6	5.0	6.7
sEPS	18.7	16.3	20.5

Comparison: BG-MBR vs CG-MBR



+ Granule was instable in CG-MBR
➔ higher F/M, higher fouling and lower N removal.

+ Granule stuck on the membrane fibres (lack shear stress)
➔ Flatsheet module is suitable for granulation MBR!

Comparison: Treatment Systems

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Items	Anaerobic reactor	Submerged MBR	BG-MBR
Operating temp. (°C)	30-55	25-35	8-55
Energy requirement (kWh/m³)	0.1	0.9	1.6
Sludge failure	Possible	-	Possible
Shock load resistance	Possible	-	Yes
Start-up time (days)	100	10	30
MLSS (g/L)	2-60 (depends)	8-15	Up to 18 g/L (2-4 g/L: MBR)
SRT (day)	10-300	15-30	10-100*
SVI (mL/g)	10-280	120-250 mL/g	10-40 mL/g
Settling velocity (m/h)	< 10	< 10	20-100 (higher for granule)
Particle size (µm)	0.5-8.0 mm (granule) 0.3-200 (flocs)	1-250 (flocs)	0.5-9.0 mm (granules) 0.3-301.7 (flocs in MBR)
OLR (kg COD/m³.d)	Up to 40	< 8	2-30
SND	No	Possible	Good (1.76 mgTN/gVSS.h)
Fouling potential	-	High (0.168 kPa/d)	Less (0.027 kPa/d)

BG-MBR shows the potential application for high strength C, N wastewater

Conclusions

+ BG-MBR system:

+ Ability for C & N removal. The SND at OLR of 2 kgCOD/m³.d was 47% or 22 mgTN/L.h (1.76 mgTN/gVSS.h).

+ Aerobic granules disintegrated under anaerobic condition and long SRT.

+ Release of soluble matters in MBR depends on the HRT which influences the fouling propensity & supernatant quality. SMPs are the main cause for fouling where polysaccharides were dominant (11 mg/L.m² & 8 mg/L.m² for sPS & sPN).

+ The disintegration of granules resulted in the release of SMPs that increased the fouling propensity of the BG-MBR system

CG-MBR system:

+ Granule is disintegrated in continuous operation mode (CG-MBR);

+ Fouling rate showed 2rd order increment with F/M ratio & 1st order with OLR.

+ SMPs deposited on membrane.

Conclusions (cont'd)

Effect of aeration rates:

+ The anoxic/aerobic conditions enhanced the biomass retention, settling ability, denitrification & filterability.

+ Resistance rate & specific cake resistance of SBAR effluent were higher than that of sludge in anoxic/aerobic operation despite higher SS.

+ Resistance & irreversible resistance of SBAR effluent were increased at high aeration rate (2.2 cm/s) due to release of macromolecules (30-50 kDa) & small particles while SMPs were released at lower aeration rate (0.8 cm/s).

+ At high aeration rate (2.2 cm/s), 60% of the hydrophobic fraction was found in the soluble fraction of SBAR effluent with low hydrophobic intensity. While at the low aeration rate (0.6 cm/s + anoxic growth), 20% of the hydrophobic fraction was found with high hydrophobic intensity.

+ BG-MBR showed better operational performance than CG-MBR (granule stability, N removal & fouling propensity).

+ Higher biomass retention in BG- MBR compared to CG-MBR
➔ lower F/M ➔ lower fouling.

Recommendations

+ Study on the granule stability at various SRT & sludge removal methods (mixed sludge, top sludge, & bottom sludge).

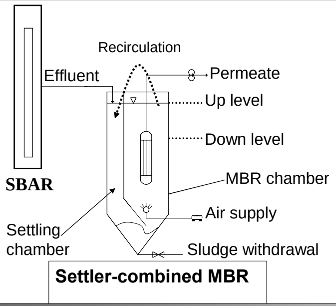
+ To accelerate and stabilize the granulation process, methods namely support media addition, bridging polymer addition, aeration rates, cycle length, etc should be investigated and optimized.

+ In BG-MBR, HRT of MBR affects the release of SMPs ➔ relates fouling
➔ Investigate fouling and sludge characteristics at various HRT.

+ SMPs played an important role in fouling of granulation MBR ➔ study on the quality and quantity of soluble fraction through SEC-EEM-DOC for understanding the nature of foulants at certain operating conditions

+ Study on the possibility of granulation and fouling characteristics in sequencing batch MBR in which membrane functions as an ideal decanter in a SBR. The light fraction of sludge is removed periodically (feast/famine).

Recommendations (Cont'd): Proposed Batch Granulation-MBR



+ Investigate compacted BG-MBR which membrane is integrated in an aerated zone of settler.

+ Recirculation ratio from aeration zone to settling zone can improve further N removal.

Recommendations (Cont'd): Proposed CG-MBR

+ Study on the application of flat-sheet membrane in CG-MBR. This semi-continuous system can maintain granule stability

(Sludge discharge interval 1-4 h, to control feast-famine condition).

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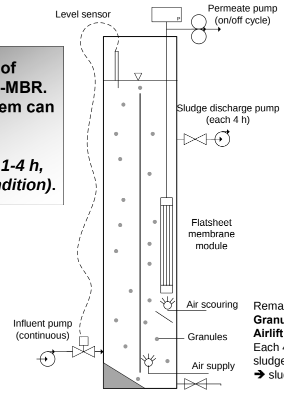

Remark:
Granulation Membrane Airlift Bioreactor
Each 4 h, system stops and sludge settling for 1-2 minute
➔ sludge discharge

Publications

Journal Publications:

Thanh, B.X., Visvanathan, C., Spérandio, M., Ben Aim, R. (2008). Fouling characterization in aerobic granulation coupled MBR, *Journal of Membrane Science*, 318 (1-2), 334-339.

Thanh, B.X., Visvanathan, C., Ben Aim, R. (2009). Characterization of aerobic granules at various organic loading rates, *Process Biochemistry*, 44, 242-245.

Thanh, B.X., Visvanathan, C., Ben Aim, R. (Submitted). Fouling behavior in external submerged MBR treating granulation effluent, Separation Purification and Technology.

Book chapter:

Jegatheesan, V., Shu, L., Visvanathan, C., Thanh, B.X. (2008). Aerobic Environmental Process: Chapter 23 in Advances in Fermentation Technology, Ed. Pandey et al., pp. 622-654, Asiatech Press, New Delhi. ISBN: 81-87680-18-0.

IWA International Conferences:

Thanh, B.X., Sperandio, M., Guigui, C., Ben Aim, R., Wan, J.F., Visvanathan, C. (2008). Coupling SBAR and membrane filtration: Influence of nitrate removal on sludge characteristics, effluent quality and filterability, *Conference on Membranes in Drinking Water Production and Wastewater Treatment*, Oct 20th-22nd, 2008, Toulouse, France.

Thank you for your attention!