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Impacts of sludge retention time on membrane fouling in thermophilic MBR

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Abstract. The aim of this study is to investigate the membrane fouling in a thermophilic membrane bioreactor (TMBR) operated different sludge retention times (SRTs). For this purpose, TMBR was operated at four different SRTs (10, 30, 60 and 100 days). Specific cake resistance (α), cake resistance, gel resistance, total resistance, MFI (modified fouling index) and FDR (flux decrease ratio) were calculated for all SRTs. It was observed that flux in the membrane increases with rising SRT although the sludge concentrations in the TMBR increased. The steady state flux was found to be 31.78; 34.70; 39.60 and 43.70 LMH (Liter/m^2/h) for the SRTs of 10, 30, 60 and 100 days respectively. The concentrations of extracellular polymeric substance (EPS) and soluble microbial product (SMP) decreased with increasing SRT. The membrane fouling rate was higher at shorter SRT and the highest fouling rate appeared at an SRT of 10 d. Both the sludge cake layer and gel layer had contribution to the fouling resistance, but the gel layer resistance value was dominant in all SRTs.

Keywords: EPS; flux; fouling; MBR; resistance; SMP; SRT; thermophilic

1. Introduction

Temperature is one of the most important parameters that effects microbial growth and hence is critical in biological treatment systems. Bacterial growth is quite low at low temperatures, but as temperature increases, growth rates also increase. Microorganisms that can survive at high temperatures are thought to have proteins not degrading at such high temperatures. However, at temperatures above 60°C, such proteins degrade and the growth of microorganisms halts. Microorganisms living at high temperatures (> 45°C) are thermophilic and the metabolic rates of these microorganisms are very high. For this reason, they are preferable over mesophilic microorganisms for the rapid degradation of organic wastes. Thermophilic aerobic wastewater treatment systems can be operated with higher biodegradation rates and lower sludge output (LaPara and Alleman 1999, Suvilampi and Rintala 2003). Despite higher removal efficiency compared to mesophilic systems, thermophilic treatment demands more oxygen.

Ultimate performances of biological treatment systems depend on the degree biomass produced is separated from the aqueus phase. In activated sludge systems, the environmental conditions in the reactor define the decoupling characteristics of the biomass. The precipitation characteristics of sludge differ by many factors such as reduced amounts of dissolved oxygen, lack of organic matter with high biodegradability and excessive release of organic loads (Nagwekar 2014, Ji *et al*. 2016). For these reasons, today there is a trend towards membrane technology both for promoting the solid-liquid separating process and increasing reactor performance (Chinnaraj *et al*. 2014, Yu *et al*. 2016).

The main goal of pressure-driven membranes (microfiltration, ultrafiltration, nanofiltration and reverse osmosis) is to obtain the highest flux with the lowest possible energy. However, microorganism flocs, particles and colloids in the activated sludge system foul the membrane during membrane filtration, resulting in reduced flux. Factors that cause and accelerate membrane fouling are quite diverse. Primarily, these are adhesion of colloidal materials, macromolecules, growth of microorganisms, biofilm adhesion on the membrane surface and dissolved matters (Visvanathan *et al*. 2007, Iorhemen *et al*. 2016). Membrane fouling cannot fully be explained due to varied cross-interaction of these factors and the complex effects they produce. As a natural consequence of membrane fouling, filtrate flux is reduced. This is evident in two ways, reduced filtrate in system operation at constant transmembrane pressure (TMP) or increased TMP pressure at constant filtrate flow rate.

Several studies in the literature report that membrane fouling in thermophilic systems is faster compared to mesophilic systems (Visvanathan *et al*. 2007, Abeynayaka and Visvanathan 2011a, Dereli *et al*. 2012). This is because the extracellular polymeric material (EPS) produced in activated sludge systems operated at thermophilic conditions is abundant. Visvanathan *et al*. (2007) reported that the amount of EPS produced in the TMBR system is 2.5 times higher than that of mesophilic MBR. It is also reported in the literature that, compared to the mesophilic sludge, thermophilic slurry contains a higher content of small-diameter flocs (Vogelaar *et al*. 2002a, b).

Generally, low membrane fouling rates are observed in increasing SRT (Van den Broeck *et al*. 2012). Furthermore, in a review study, it was reported that the most important

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factor in membrane fouling in MBR systems is SRT (Drews 2010). Although SRT does not have a direct effect on membrane fouling, it has an indirect influence as it affects many biological properties. Some researchers reported that at higher SRT, bound EPS content (Massé *et al*. 2006) and colloid and dissolved carbohydrate concentrations are low (Grelier *et al*. 2006). In addition, the microbial structure is also affected by the SRT (Ahmed *et al*. 2007, Wu and Fane 2012). Still, Drews (2010) noted that also temperature (Miyoshi *et al*. 2009) and dissolved microbial product fractions such as carbohydrates (Rossenberger *et al*. 2006) have major effects in fouling. At higher SRTs, activated sludge is tougher, more stable and has less fouling rate (Van den Broeck *et al*. 2012).

EPS is formed especially during the proliferation of microorganisms and is derived from existing molecules in the wastewater or from cell lysis. It contains many organic substances such as carbohydrates, proteins and nucleic acids. Earlier studies report that humic acid is also an EPS family and accounts for 8.4% to 30.6% of total EPS (Eriksson and Alm 1991, Frølund *et al*. 1995, Xiu-Fen *et al*. 2008). EPS plays an important role in flocculation, biogranulation or in the formation of granular sludge (Xiu-Fen *et al*. 2008, Gao *et al*. 2011, Zhu *et al*. 2015). The major component of bioaggregates to keep flocs together and bridge multivalent cations is EPS (Guibaud *et al*. 2005, Xiu-Fen *et al*. 2008, Salama *et al*. 2016). When EPS concentration is low, microbial adhesion on solid surface is inhibited due to the electrostatic interaction between the cells, whereas adhesion is promoted as the EPS concentration increases due to the polymeric interaction (Tsuneda *et al*. 2003, Sheng *et al*. 2010, Merlin *et al*. 2015).

Contrary to the availability of studies on mesophilic MBRs exploring cake resistance, fouling resistance and membrane resistance as the major parameters involved in membrane fouling, no study on thermophilic systems could be found in the literature. In this study, the effect of thermophilic aerobic activated sludge on membrane fouling was investigated at four different SRTs and the permeate volume variation over time was employed, keeping TMP constant in a thermophilic operated jet loop membrane bioreactor (JLMBR) containing side stream membrane. The effect of EPS and dissolved microbial products (SMP) on membrane fouling was shown.

2. Experimental design

2.1 Wastewater

Wastewater used in this study was obtained from a factory producing potatoes, corn chips and corn nuts. The potato process wastewater was supplied from the wastewater channel without mixing wastewater from peeling, washing and slicing operations with other process (corn processing) water. The properties of the wastewater supplied from the plant are provided in Table 1.

Table 1 Wastewater characterization

Parameter	Unit	Range	Method (APHA, 2005)
COD	mg/L	5400-5750	STM 5220 C
BOD_5	mg/L	4500-4800	STM 5210 B
pH	-	6.7-7.0	-
TP	mg/L	75-85	STM 4500-P D
TKN	mg/L	200-240	STM 4500-Norg B Macro-Kjeldahl
Ammonia	mg/L	88-95	STM 4500-NH_3 C
Sulphate	mg/L	45-55	STM 4500-SO_4^{2-}
TSS	mg/L	850-1100	STM 2540 D

COD: Chemical Oxygen Demand; BOD_5: Biochemical Oxygen Demand; TKN: Total Kjeldahl Nitrogen; TP: Total Phosphorus; TSS: Total Suspended Solids

2.2 Thermophilic membrane bioreactor

Despite higher removal efficiency compared to mesophilic systems, thermophilic treatment demands more oxygen. The Jet-Loop reactor can satisfy this demand thanks to its high mass transfer characteristics.

The reactor consists of a cylindrical reactor (outer) and a draft channel (inner) both made from stainless steel with a conical bottom. There were sight glasses in the reactor to observe the loop process. In this reactor, circulation was achieved by a liquid jet drive. The schematic representation and dimensions of the thermophilic reactor are presented in Fig 1. Wastewater was fed to the reactor by means of an automated peristaltic pump (Heidolph 5201). Other important operating parameters such as dissolved oxygen, temperature and pH were continuously measured with a multi-parameter meter (WTW). The reactor was operated at 45±2°C, organic loading rate of 2.0 kg COD/m^3·day and neutral pH for 18 months. In addition, dissolved oxygen concentration within the reactor was between 2-3 mg O_2/L. In order to ensure filtration in JLMBR, a Microdyn-Nadir (MD 063 TP 2N) tubular PP (polypropylene) microfiltration membrane with a porosity of 0.2 µm was fit externally to the circulation line of the reactor. The membrane surface area and cross-flow velocity were 0.036 m^2 and 4.5 m/s, respectively. Also, transmembrane pressure (TMP) was fixed 190 kpa for all SRT. The membranes were cleaned with physical and chemical washing. The physical washing was performed with backflushing during 3 min per 3 hours. As for as the chemical washing was applied on average every month according to the manufacturer's recommendation. The chemical washing procedure includes these steps; (i) washing with 10% NaOH for half an hour, (ii) washing with distillation water for 10 minutes, (iii) washing with 3% HCl for half an hour, (iv), washing with distillation water until reaching neutral pH. In addition, the data obtained from the precision scale were monitored for 24 hours via a card automation system.

2.3 EPS and SMP analysis

In order to identify the effect of EPS released by activated sludge on membrane fouling, the system was operated at different SRTs. Furthermore, protein and carbohydrate content of EPS causing fouling was also measured.

EPS was identified by the formaldehyde extraction method (Tinggang *et al*. 2008). More specifically, also SMP was measured by this protocol. In particular, the sum of carbohydrate (C) and protein (P) was considered as total EPS (Total EPS = $EPS_P + EPS_C + SMP_P + SMP_C$). The modified version of the phenol-sulfuric acid method was used to determine the carbohydrate content in total EPS. 80% phenol solution and concentrated 95-97% H_2SO_4 were used in the assay. 25 μL of 80% phenol and 2.5 mL of H_2SO_4 was added to 1 mL of sample and then held in a water bath for 15 minutes at 30°C. The folin method relying upon the use of bovine serum albumin was applied to determine the protein.

2.4 Assessing membrane fouling

Based on Darcy's law, the degree of membrane fouling was calculated using the following equation (Ouyang and Liu 2009, Siddiqui and Field 2016).

$$R = \frac{\Delta P}{\eta J} \tag{1}$$

$$R_t = R_m + R_f \tag{2}$$

$$R_f = R_c + R_g \tag{3}$$

where;
R: Filtration resistance (1/m),
ΔP: Transmembrane pressure difference (N/m^2),
η: Filtrate viscosity ($N \cdot s/m^2$),
J: Membrane filtrate flux ($m^3/m^2 \cdot s$),
R_t: Total filtration resistance (1/m),
R_m: Membrane resistance (1/m),
R_f: Fouling resistance (1/m),
R_c: Cake resistance; filtration resistance of the cake layer formed on the membrane surface (1/m),
R_g: Gel resistance; filtration resistance due to the adsorption of dissolved materials and colloids in the supernatant as well as contaminants on the membrane surface leading to the fouling of pores (1/m).

R_m was measured by distilled water filtration using Eq. 1. R_t was calculated with Eq. 1 using the data obtained from stable membrane filtration without any further process in the system. Thus, in Eq. 2, values R_t and R_m were put in place to calculate R_f. In order to find R_g, the activated sludge from JLMBR was left to precipitate for 2 hours, then the supernatant was subjected to filtration. Using the results obtained and considering the experimental conditions, R_g was calculated by Eq. 1 and R_c was calculated by Eq. 3.

Besides resistance values, the flux decrease ratios (FDR) were also calculated according to the following equation in order to assess membrane performance in activated sludge filtration at different SRTs;

$$FDR\ (\%) = \left(\frac{J_i - J_{ss}}{J_i} \right) \times 100 \tag{4}$$

FDR: Flux decrease ratio (%)
J_i: Initial flux in filtration (LMH)
J_{ss}: Steady state flux in filtration (LMH)

There are several models developed to elucidate membrane fouling. Of them, the simplest one is based on the cake filtration model. A theoretical model correlating pressure, cross flow rate, velocity and fouling layer thickness to permeate flux was derived from the Darcy equation. In order to identify the fouling condition of the membranes, it is first necessary to define the volumetric limit flux according to the traditional filtration theory. Rearranging and afterwards abbreviating Eq. 1 and assuming V_f as the amount of liquid (filtrate) passing through the unit membrane area,

$$\frac{t}{V_f} = \frac{\eta . R_m}{\Delta P} + \frac{\eta . \alpha . C_B . V_f}{2\Delta P} \tag{5}$$

where; t: time (s), V_f: the amount of filtrate passing through the unit membrane area (V_f = V/A, V is filtrate volume (L) and A is membrane area (m^2)), α: specific cake resistance (m/kg) and C_B: the particle and colloid concentration (mg/L)

MFI is used to measure the particulate fouling potential of the feed solution and is based on the cake filtration mechanism. MFI was obtained from the slope of the linear portion of the t/V_f-V_f graph which is composed three portion such as pore blocking, cake filtration/linear portion and cake filtration with clogging and/or cake compression plotted by the help of fluxes from the membrane used in the study. α value representing the specific cake resistance was also calculated using the MFIs obtained.

$$MFI = \frac{\eta . \alpha . C_B}{2\Delta P} \tag{6}$$

3. Results and discussion

3.1 Membrane flux variation

In this study, for all of the SRTs, a decrease was observed in flux by time (Fig. 1). For all flux data, the concentration polarization and cake formation rose in the initial period of 100 minutes, therefore flux rapidly decreased. From minute 100, flux gradually became stable. After this point, the drag force of the filtrate flux that adheres the particles and/or colloids to the membrane surface was equal to the total of shear force of the cross flow and back diffusion originating from concentration gradient, which decoupled the particles and colloids from the membrane surface. In flux trials on the thermophilic JLMBR, steady state fluxes obtained from the membrane were found to be 31.78, 34.70, 39.60 and 43.70 LMH for 10, 30, 60 and 100 days SRT, respectively.

Membrane flux is impacted by wastewater characteristics, type of membrane (ceramic, metal, polymer) used and operation conditions of the TMBRs. The reported membrane flux in thermophilic aerobic MBR, varied in a large range from 7 to 72 LMH. However, in a TMBR giving flux value, implemented using polymer membrane with pore size of 0.2 μm, flux determined as 20 LMH. This flux is less than ones obtained from all SRTs in this study.

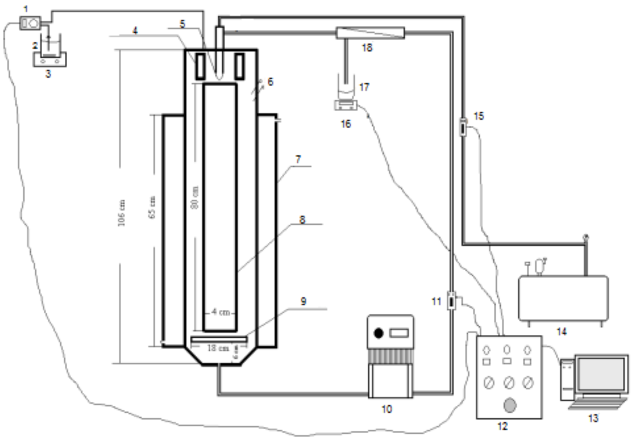

Fig. 1 Schematic depiction of the JLMBR system and its dimensions (1: peristaltic pump, 2: wastewater, 3: stirrer, 4: viewing window, 5: nozzle, 6: pH and DO probes, 7: jacket, 8: draft tube, 9: impact plate, 10: pump, 11: liquid flowmeter, 12: control panel, 13: computer, 14: compressor, 15: gas flowmeter, 16: analytical balance, 17: treated wastewater, 18: membrane)

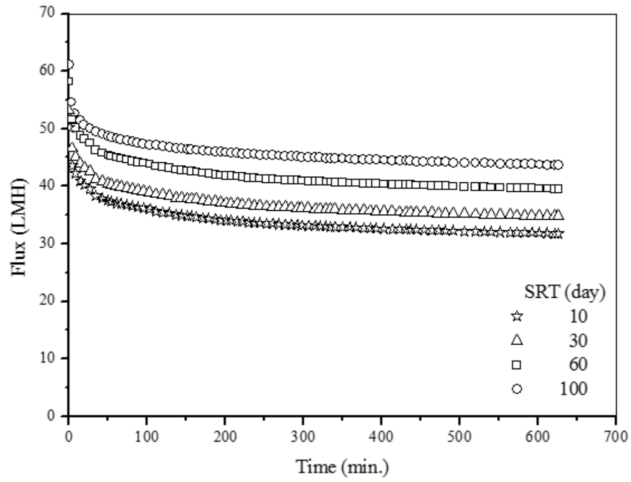

Fig. 2 Fluxes obtained at different SRTs (TMP = 190 kpa, cross-flow rate = 4.5 m/s)

In the literature, many researchers have studied to explain effect of SRT induces on membrane fouling. Some researchers reported that high SRT was appropriate for MBR systems. While Adham and Gagliardo (1998) recommended SRTs longer than 30 days, Cicek *et al*. (2001) reported that MBRs could also be operated with sludge younger than 10 days. Other researchers found that fouling was less when SRT increases from 2 to 10 days (Trussell *et al*. 2006) and from 20 to 60 days (Ahmed *et al*. 2007).

Grelier *et al*. (2006) reported that biodegradation of organic matters and nutrients was better in SRT above 40 days. Ke and Junxin (2009) achieved a better yield of organic matter removal with higher MLSS (mixed liquor suspended solids) concentration in long SRT. Furthermore, they reported that maximum fouling rate occurred with 10-day old sludge. Additionally, they reported that the least fouling was with no sludge withdrawal SRT.

In the literature, no study on thermophilic side-stream MBRs that could be used to compare the fluxes is found. However, in their study, Farizoglu and Keskinler (2006) investigated mesophilic whey treatment in JLMBR employing membranes with a pore diameter of 0.45µm. As expected, the steady state fluxes they obtained are higher than those obtained in this study. This is probably due to using membrane with higher pore diameter and higher EPS concentration in the TMBR.

3.2 EPS and SMP

Visvanathan *et al*. (2007) compared the mesophilic MBR system with the TMBR system and reported that EPS concentration was 2.5 times greater than the mesophilic one in the thermophilic MBR. SMP production was also higher in thermophilic aerobic treatment due to increased microbial activity (Abeynayaka and Visvanathan 2011a, b).

The effect of EPS and SMP on membrane fouling in membrane bioreactors is crucial. Therefore, in this study, an EPS and SMP analysis was carried out in the system once thermophilic JLMBR got up to steady state for different SRTs (Fig. 3). A decrease was observed in total EPS and type concentration in the reactor due to the increase in SRT. To detail the root cause, an increase in SRT brings about an increase in MLSS concentration resulting in declined food/microorganisms (F/M) ratio and this causes the microorganisms to deplete these substances as substrates, ultimately leading to a decrease in EPS and SMP concentrations (Massé *et al*. 2006).

As can be seen in Fig. 2, lower SRTs yielded lower fluxes. The figure further shows that membrane fouling is high at low SRTs under such thermophilic conditions. EPS produced lead to the formation of a denser and less porous cake layer on the membrane surface of the thermophilic activated sludge. High EPS concentration negatively affects membrane permeability (Pollice *et al*. 2008).

Ke and Junxin (2009) reported that in MBRs operated with SRTs 3, 5, 10 and 20 days, total organic carbon, protein and carbohydrate concentrations in the supernatant declined with increasing SRT. Similar results were also obtained by Li and Wu 2014, in MBRs operated with SRTs 5, 10, 20 and 40 days, protein and carbohydrate concentrations decreased with increasing SRT. However, Lee *et al*. (2003) reported that for SRTs of 20, 40 and 60 days, a switch to 60 days from 20 created an insignificant change in EPS. In addition, a study showed that the structure and surface properties of biological flocs were linked to EPS and that operating conditions had a significant effect (Wilén and Balmer 1999, Wilén *et al*. 2003).

The underlying reason of the decrease in EPS due to the increase in SRT can be interpreted as slower production or faster degradation rate of the microbial products. As is known, increase in shear stress and turbulence, which are high in the jet loop reactor, accelerates the microbial product release (Liu *et al*. 2005). This was another reason of high EPS concentration in thermophilic JLMBR.

As shown in Fig. 2, with increasing SRT, membrane fouling was reduced. Studies in the literature also reported that fouling rate was higher in lower SRTs. As dissolved

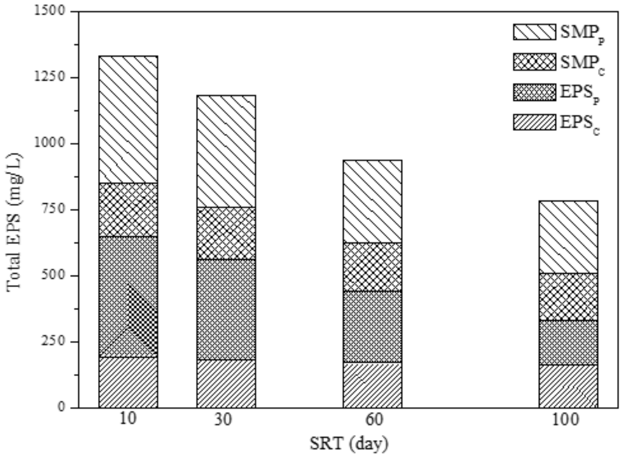

Fig. 3 EPS and SMP concentrations for different SRTs

Table 2 MLSS concentration, P/C ratios in EPS and SMP and particle size at different SRTs

SRT (day)	MLSS (g/L)	P/C EPS	P/C SMP Reactor	P/C SMP Effluent	Partical size (µm)
10	3.20	2.35	2.38	6.09	9.18
30	5.10	2.07	2.21	5.99	8.77
60	7.40	1.58	1.72	3.47	7.92
100	12.50	1.03	1.56	1.99	6.98

EPS decreases with longer sludge, flux increases. Because membrane fouling in MBR systems is closely associated with EPS, activated sludge and colloids (Defrance *et al*. 2000, Lee *et al*. 2003, Cho *et al*. 2005a, Li *et al*. 2005, Rojas *et al*. 2005, Rosenberger *et al*. 2006, Iorhemen *et al*. 2016).

Dissolved P/C (Protein/Carbohydrate) ratio is an indication of microbial activity. As temperature increases, this ratio also increases. Although protein concentration decreases under thermophilic conditions, this decrease was reported to be very small compared to carbohydrate concentration (Abeynayaka and Visvanathan 2011a).

Comparing the protein content to the carbohydrates in the reactor and effluent, protein reveals a predominant. In their MBR study, Ouyang and Liu (2009) reported, based on the results of the analysis in the output filtrate and samples (the supernatant fraction) from the reactor, that EPS concentration was higher in the supernatant. This indicates an EPS accumulation on the membrane. On the other hand, carbohydrate concentration was found to be lower in the effluent like in EPS. As can be seen in Table 2, P/C ratio decreased with higher SRT. Liao *et al*. (2003) also reported a decline in P/C ratio when they switched SRT from 12 to 20 days. For suspended solids, filtration resistance is positively linked to the P/C ratio (Lee *et al*. 2003). Therefore, this parameter serves as the indicator for the fouling tendency of suspended solids. Moreover, the decrease in bound protein with higher SRT was more evident than the decrease in carbohydrate.

In both the supernatant and the effluent, the

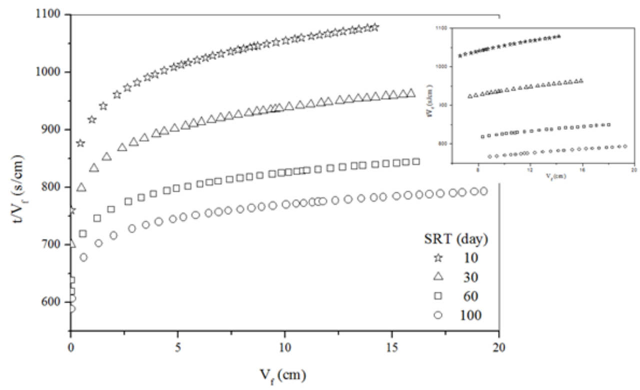

Fig. 4 t/Vf-Vf Graph (TMP=190 kpa, cross-flow rate=4.5 m/s)

Table 3 Parameter values of membrane fouling at different SRTs

SRT (day)	MFI (s/cm^6)	α (*10^{11} m/kg)	FDR (%)
10	10.849	29.431	36.64
30	8.477	13.800	34.71
60	5.565	5.662	31.90
100	2.295	1.868	28.54

carbohydrate and protein concentration decreased with higher SRT. The concentration of carbohydrate and protein in activated sludge was higher compared to the effluent for all SRTs. This proved that carbohydrates and proteins accumulate in JLMBR. The amount of protein at reactor output was higher than the carbohydrate concentration. This showed that the proteins pass more through the membrane with a pore diameter of 0.2 µm compared to carbohydrates.

The fouled membrane surface forms additional resistance for dissolved EPS. Proteins and carbohydrates may pass through the membrane at different rates (Ng *et al*. 2006). EPS, particularly carbohydrates play an important role in the formation of bioaggregation. Carbohydrate fibers serve as support for various compounds and cells (Meng *et al*. 2006, Walker and Bob 2001, Ke and Junxin 2009). In this case, the amount (concentration) of carbohydrates affects the size of the microbial floc. Briefly, low carbohydrate concentration means small floc size. As the SRT increases, the carbohydrate and protein concentration decrease. Therefore, as can be seen Table 2 microbial floc size decreases as the SRT increases.

It may be concluded after assessing collectively the EPS and flux results obtained in the thermophilic JLMBR that there was a linear relationship between EPS and membrane fouling. With increasing SRT, whereas MLSS concentration increased the flux increased due to decreased EPS and SMP. Furthermore, decreasing of P/C ratio probably caused accumulate less floc on the membrane surface by decreasing hydrophobicity. Chang and Le Clech (1998) came to similar results and reported that such fouling results from intra-pore obstruction and the gel layer form. In another study conducted with lower SRTs, it was observed that EPS concentration decreased with increasing SRT (Ng and Hermanowicz 2005). Abeynayaka and Visvanathan (2011a) reported that the excessive membrane fouling observed in TMBRs.

3.3 Parameter values for membrane fouling

MFI, α and FDR values relating to membrane fouling were determined for different SRTs in thermophilic JLMBR. The graph depicting pore blocking and cake filtration in Fig. 4, plotted to calculate the MFI values from linear portions, which was also shown in the small figure, indicated that the slope increased with decreasing SRT. Therefore, as the SRT decreased, membrane was fouled faster and more.

During the filtration of activated sludge, a cake layer occurs on the surface of membrane called as the secondary membrane or dynamic membrane forming hydrolic resistance to the filtration. The degree of this resistance can be determined by calculating the specific cake resistance. For a given size of suspended solids, α value will be the only factor determining the permeate flux, if the rest of the filtration parameters (i.e., membrane type and surface area, cross-flow velocity etc.) are fixed. Therefore, it is significant to determine how α value is influenced with changing SRT.

As can be clearly seen from Table 3, α value decreased with increasing SRT. Specific cake resistance decreased with increasing SRT while MLSS concentration increased (Table 2). The main reason of this was why EPS and SMP decreased with increasing SRT. The flocs in this system were small, but compact and regular size (Liao *et al*. 2001) due to decrease in EPS and SMP. Therefore, porosity of cake layer increased and thus the flux increased. Also, MFI and FDR values decreased with increasing SRT, resulting from decreasing α value. However, in extended operation, the cake layer, formed on the surface of membrane, develops a dynamic biofilm layer. Its structure changes biologically due to underneath anoxic layer (Hosseinzadeh *et al*. 2013). Additionally, a new biofilm layer forms the existing deposited biofilm. Thus, the opening pores on the membrane surface area change through the filtration process, resulting in cake clogging and/or cake compression.

The dynamic layer contains the cake layer consisting of sludge particles adsorbed and/or retained by the membrane and the gel layer formed by dissolved organic and EPS. In general, the degree of membrane fouling is explained by resistance to the filtrate. Therefore, in order to assess membrane fouling, the resistances (R_g, R_c, R_f and R_t) also were calculated in this study. However, no comparison could be made due to lack of a TMBR study investigating these resistances.

In the literature, many studies reported that membrane fouling is fast at low SRTs and is slow with increasing SRT (Van den Broeck *et al*. 2012). R_c and R_g values represented an important part of the fouling resistance. Unlike mesophilic MBR studies (Khan *et al*. 2009, Ouyang and Liu 2009), R_g was higher than R_c in this study. As the SRT increased, cake and gel resistance decreased. However, decrease in gel resistance was higher compared to the cake resistance. The thermophilic process has smaller flocs than the mesophilic process due to poor floc formation at thermophilic conditions (Abeynayaka and Visvanathan 2011a). These could be lifted easily by cross flow with air scouring and removes the excess cake layer. Hence, accumulation of excess sludge on the membrane surface was limited in the TMBR. In additionally, observations on

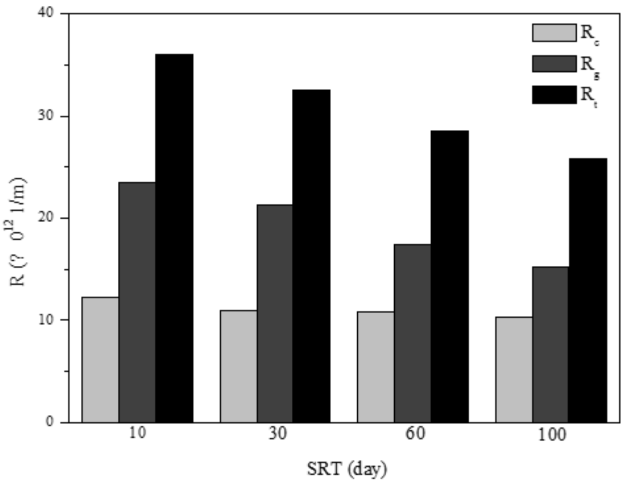

Fig. 5 Resistances of various fractions from the mixed liquor at different SRTs

EPS concentrations (Fig. 3) indicate the presence of higher EPS in TMBRs. EPS has a linear relationship with biological fouling which causes internal pore blocking and gel layer formation. Therefore, the gel resistance (R_g) formed the majority of the total resistance.

5. Conclusions

The thermophilic aerobic MBRs can be operated with higher biodegradadion rates and lower sludge output. However, membrane fouling in the TMBRs is faster due to be produced more EPS in thermophilic conditions. Therefore, it was investigated to effects of SRT, the most important operating parameter, on membrane fouling in TMBR, in this study. Thus, TMBR was operated at SRT of 10, 30, 60 and 100 days. It was observed that flux increased with rising SRT in spite of increasing MLSS concentration. The main reason was why increasing of porosity of cake layer on the membrane surface with increasing SRT, resulting in decreasing specific cake resistance. Furthermore, MFI and FDR values decreased depending on α value. Considering R_t, its majority was composed by R_g. However, R_c and R_g values decreased with the increase in SRT. Therefore, extended SRT can be used for decreasing membrane fouling in TMBRs.

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CC

Symbols

R : Filtration resistance (1/m)

ΔP : Transmembrane pressure difference (N/m^2)

η : Filtrate viscosity (N·s/m^2)

J : Membrane filtrate flux (m^3/m^2·h)

R_t : Total filtration resistance (1/m)

R_m : Membrane resistance (1/m)

R_f : Fouling resistance (1/m)

R_c : Cake resistance (1/m)

R_g : Gel resistance (1/m)

J_i : Initial flux in filtration (LMH)

J_{ss} : Steady state flux in filtration (LMH)

V_f : Filtrate volume passing through the unit area (m^3/m^2)

t : time (s)

α : Spesific cake resistance (m/kg)

C_B : The particle and colloid concentration (mg/L)

A: Membrane area (m^2)

V: Filtrate volume (L)

Abbreviations

BOD_5	5-day Biochemical Oxygen Demand
C	Carbonhydrate
COD	Chemical Oxygen Demand
EPS	Extracellular Polymeric Substance
FDR	Flux Decrease Ratio
F/M	Food/Microorganism
HRT	Hydraulic Retention Time
JLMBR	Jet Loop Membrane Bioreactor
LMH	Liter/m^2/h
MBR	Membrane Bioreactor
MFI	Modified Fouling Index
MLSS	Mixed Liquor Suspended Solids
P	Protein
PP	polypropylene
SMP	Soluble Microbial Products
SRT	Sludge Retention Time
TKN	Total Kjeldahl Nitrogen
TMBR	Thermophilic Membrane Bioreactor
TMP	Transmembrane pressure
TP	Total Phosphate