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Influence of sludge rheological properties on the membrane fouling in submerged membrane bioreactor

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ABSTRACT

Rheological characterization is of crucial importance in sludge management both in terms of biomass dewatering and stabilization properties and in terms of design parameters for sludge handling operations. The mixed liquor suspended solid (MLSS) and coagulant concentration have a significant influence on biomass properties in biological wastewater treatment systems and in particular in membrane bioreactors (MBRs). In this work the rheological behavior of the biomass in a MBR operated under different MLSS was studied. The range of MLSS in the bench scale MBR was 3800 mg/l to 15200 mg/l. The rheological properties were measured over time and the apparent viscosity was correlated with the concentration of suspended solids under steady-state conditions. Furthermore, a correlation was obtained between sludge viscosity and permeate flux. Results showed that viscosity of activated sludge affects the membrane fouling tendency in an exponential relation between viscosity and fouling in the investigated range in membrane bioreactor. Also coagulants cause reduction of activated sludge viscosity and hence membrane fouling.

Keywords: Membrane bioreactor; Fouling; Viscosity; MLSS; Rheology; Activated sludge

1. Introduction

Membrane fouling is a major obstacle for wider application of membrane bioreactors (MBRs). Membrane fouling results in severe flux decline, high-energy consumption, and frequent membrane cleaning or replacement [1]. In submerged MBRs, membrane modules are immersed in the aeration basin. Therefore, the membrane fouling mechanisms are very complicated due to the complex rheological and physiological characteristics of mixed liquors and hence investigate the mechanism of membrane fouling to control membrane fouling is indispensable. It was reported that the sludge apparent viscosity in a submerged membrane bioreactor increased exponentially with an increase in the solid content of sludge. Rosenberger et al. [2] observed that mixed liquor suspended solids (MLSS) was a major parameter influencing apparent viscosity in membrane bioreactors; however, there is still a lack of information on the role of sludge rheology in membrane performance and membrane fouling. Many previous investigators also studied the sludge physiological properties, such as extracellular polymeric substances (EPS) [3–5], soluble microbial products (SMPs) [6], carbohydrates and proteins [7] in MBRs. Despite these intensive mentioned efforts, the accumulation of knowledge to establish a general understanding of the relationship between sludge rheological and physiological characteristics and membrane performance in full-scale MBRs is insufficient.

In this study, a lab-scale MBR was operated to investigate the rheological and physiological characteristics of sludge and their correlations with membrane filtration performance and membrane fouling.

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Furthermore the effect of coagulant on the rheological and physiological characteristics of sludge and membrane fouling has been studied.

2. Materials and methods

2.1. Experimental setup

The sludge filtration test was conducted in a 1.5 l stirred cell using a 0.45 μm flat-sheet cellulose acetate membrane filter (Albet-AC-045-47, Spain). The liquid samples were stirred at 700 rpm (Heidolph, MR3001K, Germany). The membrane surface was rinsed with air at a flow rate of 1 l/min. In each run the stirred cell was filled with 1 l of one of the samples described in following section and a constant vacuum of 0.6 bar was applied for filtration by a vacuum pump. The total permeate volume after 5 h of filtration at ambient temperature under pressure was measured.

2.2. Experimental procedure

The activated sludge mixed culture in this research was taken from Arak petrochemical complex wastewater plant. In order to study the effect of solid concentration on membrane fouling the different samples with various MLSS were prepared. These sludge mixtures were made by dilution with activated sludge supernatant or thickening and were adjusted to 3800, 7600, 11400, and 15200 mg/l. In second stage, at fixed solid concentration effect of coagulant concentration on membrane fouling has been investigated. The coagulants which used in this study are $FeCl_3$ and Al_2O_3 in four concentrations (0, 50, 100 and 200 ppm). The samples were then transferred to stirred cell for fouling examination.

3. Analytical methods

3.1. Sludge filterability

The dewatering ability of the sludge suspension was determined using the filterability test as described by Wisniewski and Grasmick [8]. To minimize the deposition of particles during experiments, the cell is equipped with a magnetic stirring rod which induces tangential stresses near the membrane. Furthermore, air scouring on the surface of the membrane prevents the cake formation. The permeate flow rate was measured as an indicator of sludge filterability.

3.2. Membrane filtration resistances and cake porosity

Membrane resistance was evaluated by the resistance-in series model on the base of Darcy's law as follows:

$$R_t = R_m + R_p + R_c = \frac{\Delta P}{\mu J} \quad (1)$$

where ΔP is the trans-membrane pressure gradient (Nm^{-2}), μ the viscosity of the permeate (Pa.s), and J the permeation flux ($m.s^{-1}$). In this equation the total membrane resistance (R_t), consists of inherent membrane resistance (R_m), pore fouling resistance (R_p), and resistances due to sludge films (R_c). The experimental procedure to get each resistance value is presented in Meng et al. [9].

In order to compare the cake porosity, weight of dry cake versus wet cake was measured. The weight of wet cake was measured (B), and then dried to constant weight (A) in an oven at 103 to 105°C and cooled in desiccators. The porosity index calculated as:

$$Porosity\ \ Index\ \ (\%) = \left(1 - \frac{A}{B}\right) * 100 \quad (2)$$

3.3. Rheological behavior

Sludge rheological characterization was performed on pre-sieved biomass samples [10]. The shear stress was measured with a rotational rheometer (DV-II + PRO Digital, Brookfield) equipped with concentric cylinders and operated under constant temperature (20°C). The average shear stress for each shear rate was experimentally determined in order to evaluate a main parameter of activated sludge in membrane biofouling.

The parameters of the correlation and hydraulic resistance were obtained by linear regression analysis.

3.4. Compressibility and settleability

The compressibility and the settleability of the activated sludge were evaluated by the sludge volume index (SVI), and the zone settling velocity (ZSV), respectively. SVI is the volume of 1 g of the total suspended solids after 30 min of settling. A higher SVI corresponds to a poorer compressibility. The ZSV is a key parameter for evaluating the sludge settling properties, since it determines how much the secondary clarifier can be loaded. ZSV and SVI were measured in a 1 l settling cylinder according to the Standard Methods [11]. The zone settling velocity is defined as the maximum gradient of the curve of the interface displacement with time.

4. Results and discussion

4.1. Effect of MLSS on fouling

Although, MLSS concentration often considered at first sight as the main fouling parameter, MLSS concentration has indeed a complex interaction with MBR fouling. Results show that membrane fouling increase with MLSS concentration (Fig. 1a). Fig. 1a shows the influence of MLSS on membrane fouling. Further, results show cake resistance is the main portion of hydraulic resistance and constitute over 95% of total resistance. Chang and Kim [12] indicated fouling in MBR increases with MLSS. Two correlations were proposed for the relation of MLSS and total resistance. Correlations indicate that membrane fouling increases exponentially with MLSS concentration. As shown in Fig. 1b, cake resistance is proportional with MLSS but pore blocking resistance has no significant change. It seems that settled materials on membrane surface increase with solid concentration. But cake layer formation prevents development of pore blocking and consequently pore blocking has no change significantly with MLSS.

To understand better the effect of MLSS on fouling, porosity index of cake layer was examined. Porosity index of cake layer increases from 2.2% to 4.3% with change of MLSS from 3800 to 15200 mg/l respectively (Table 1). Whereof suspended flocs are the main constituent of cake layer, larger flocs cause higher porosity of cake layer. It seems that flocs size increase with increment of MLSS. Previous studies showed, the cake resistance (R_c) increase and the specific cake resistance (α_c) decrease as MLSS increased so that, although they have similar meaning conceptually R_c and α_c seemed to behave inversely [12]. Eq. (3) shows the relation between R_c and α_c:

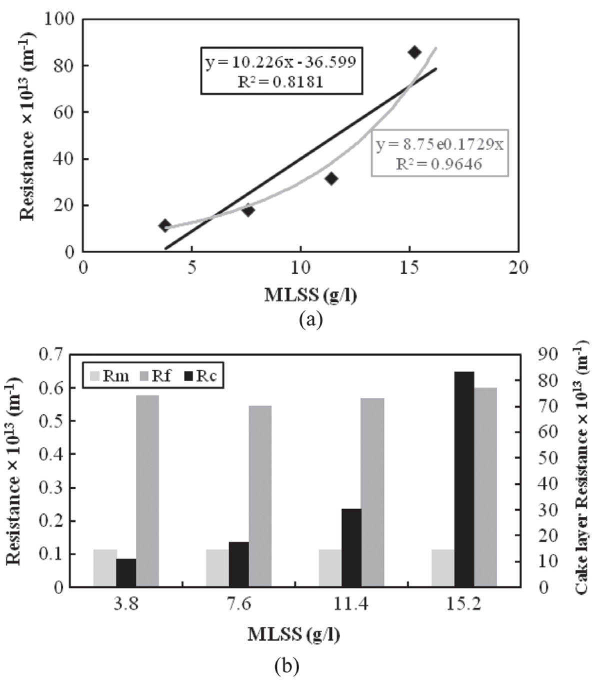

Fig. 1. Total resistance versus MLSS (a), resistance distribution (b).

Table 1
Porosity of cake layer in different suspended material concentration

MLSS (mg/l)	3800	7600	11400	15200
Porosity index (%)	2.2	3.2	3.5	4.3

$$R_c = \alpha_c \times m_c \quad (3)$$

where α_c is the specific cake resistance, m_c is the cake load/area of membrane. The cake load m_c would tend to rise with MLSS concentration.

It seems increase in MLSS induces cake formation and cake layer thickening is the main cause of increscent in membrane fouling with MLSS and also, Table 1 indicates cake layer porosity raises in high MLSS concentration. Previous studies showed larger flocs as the main constituent of cake layer causes fouling mitigation [13].

4.2. Rheological properties of activated sludge

Rheological properties of activated sludge are important in dewatering and especially in membrane fouling in MBRs. Viscosity is a main parameter in hydrodynamic design of activated sludge and MBR processes. Studies show activated sludge viscosity increases with suspended materials concentration (MLSS). Furthermore, oxygen transfer rate (OTR) and hence dissolved oxygen reduce in high viscose activated sludge. Fig. 2 shows the apparent viscosity of activated sludge in various MLSS. It indicates apparent viscosity rises exponentially with suspended materials concentration. Previous studies showed viscosity have the linear and then exponentially relation with MLSS [14]. Results indicate although rising in biomass concentration increases removal efficiency and reduces excess sludge production, it leads

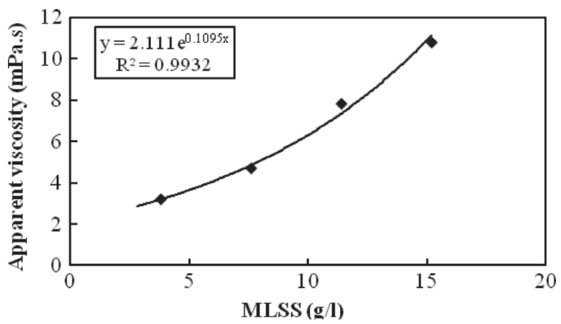

Fig. 2. Apparent viscosity of activated sludge in various MLSS.

to increment of viscosity that induces membrane fouling. Turbulency and hence back mixing phenomenon on membrane surface decline with viscosity so that settlement of suspended material on membrane surface induces. Furthermore, increase in viscosity deteriorate oxygen transfer rate (OTR) in activated sludge culture. (Therefore,) it indicates when MBRs operate in high biomass concentration, the oxygen supply and fouling mitigator are the crucial operating parameters in MBRs.

However viscosity of activated sludge is a crucial property in hydrodynamic design, its rheological behavior is (the main parameter in pumping) (an important parameter too). According to Fig. 3, activated sludge has the non-Newtonian behavior especially in higher MLSS. Fig. 3 shows the change of apparent viscosity of activated sludge with shear rate. Rosenberger et al. [2] showed activated sludge has the shear thinning behavior, but some other researchers reported activated sludge has yield stress and behaves such as Bingham Fluids [15]. Fig. 3 indicates activated sludge has the pseudoplastic fluid behavior in low concentration of suspended solid but its properties change to Bingham fluids with MLSS. It seems in low MLSS due to low concentration of suspended solids, yield stress is near to zero, but yield stress increases with MLSS.

Statistical analysis of results show that apparent viscosity of activated sludge increase exponentially with MLSS and have the non-linear relation with shear rate. Eq. (4) shows their relation.

$$\vartheta = a \times e^{(b \times MLSS)} \times \left(\frac{dv}{dy}\right) c \tag{4}$$

Where:

a = 2.46
b = 0.147
c = –0.646
R^2 = 0.958

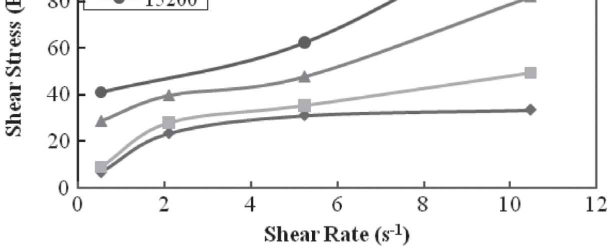

Fig. 3. Activated sludge's rheological behavior in different MLSS.

Where ϑ is the apparent viscosity (Pa), a, b, and c are constant parameters.

As mention above activated sludge follows Ostwald model so that increase in turbulency in activated sludge causes reduction of viscosity. Therefore, howbeit turbulent flow near the membrane surface increase back mixing flow, it causes decline in viscosity on membrane surface. On the other hand in turbulent flow OTR increases due to drop off viscosity. One of the ways that increase turbulency near the membrane surface is aeration so that aeration on membrane surface induces membrane souring in MBRs.

Effect of activated sludge viscosity is also considerable on membrane fouling. The results show fouling increase exponentially with activated sludge viscosity (Fig. 4). Fig. 4 shows the relation of membrane fouling based on hydraulic resistance to sludge viscosity.

Also, Meng et al. [16] claimed that membrane fouling was induced with increase in viscosity. Increment of viscosity reduces back mixing and induces biomass settling on membrane surface so the cake layer thickness rises with viscosity. As mentioned before, although membrane fouling increases with MLSS, its porosity decreases. It seems that cake layer grows with MLSS due to increment of viscosity.

4.2. Coagulant in relation to MBR performance

The most advantage of MBR is its operation at high cell density such as 15000 mg/l. But as mention above, increase in MLSS concentration induces the membrane fouling. One of the ways that mitigate the membrane fouling is utilization of coagulants. In this research Al_2O_3 and $FeCl_3$ were used as coagulant. Fig. 5 shows the effect of coagulant on membrane resistance. Fig. 5 indicates membrane fouling decreases with coagulant concentration. Results show coagulants have more effect on membrane fouling in low concentration and the effectiveness of coagulant reduce with concentration of coagulant.

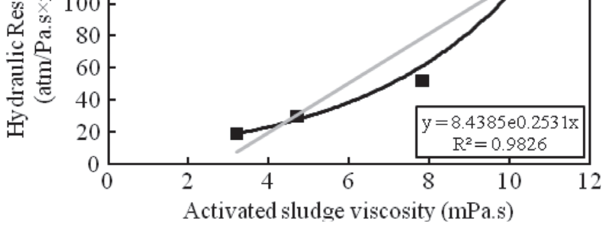

Fig. 4. Membrane fouling based on hydraulic in relation to activated sludge viscosity.

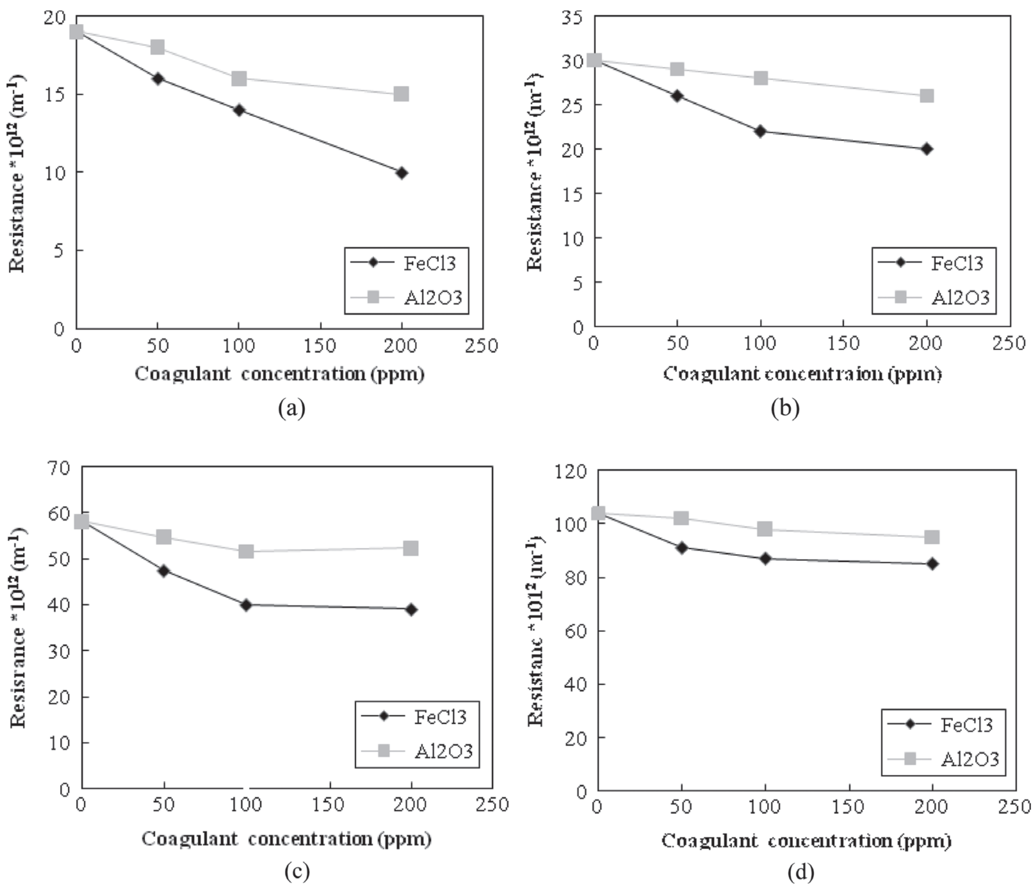

Fig. 5. Total resistance at different coagulant concentration (MLSS = 3800 mg/l (a), MLSS = 7600 mg/l (b), MLSS = 11400 mg/l (c), MLSS = 15200 mg/l (d)).

Furthermore, Fig. 5 show $FeCl_3$ is more effective on improvement the permeability of membrane.

Previous study on effect of alum and ferric chloride by Song et al. [17] showed the flux increased more than twice at coagulant dosage over 200 mg/l than that of without coagulant addition. Our previous study also showed that divalent cations such as calcium and magnesium ions decrease the membrane fouling [18].

Flocs are the main constituent of cake layer fouling in membrane bioreactors. Adding coagulant causes to aggregation of suspended flocs and growth of flocs in activated sludge culture. In general, bioflocs have been found to have a net negative charge, which is a result of functional groups present on the biopolymers. Multivalent cations bridge negatively charged functional groups within the biopolymers and this bridging helps to aggregate and stabilize the matrix of biopolymer and microbes and therefore promote bioflocculation.

5. Conclusions

Although, MLSS concentration often considered at first sight as the main fouling parameter, MLSS concentration has indeed a complex interaction with MBR fouling. Results show that membrane fouling increase with MLSS concentration. Statistical analysis indicates that membrane fouling increase exponentially with MLSS concentration. Furthermore, results indicate apparent viscosity rises exponentially with suspended materials concentration. This work shows activated sludge has the pseudoplastic fluid behavior in low concentration of suspended solid but its properties change to Bingham fluids with MLSS. Increase in turbulency near the membrane surface increases back mixing and further reduces activated sludge viscosity and consequently induces cake removal on membrane surface. One of the ways that increase turbulency near the membrane surface is aeration so that aeration on membrane surface induces membrane souring in MBRs.

The results showed, fouling increases exponentially with activated sludge viscosity. One of the ways that mitigate the membrane fouling is utilization of coagulants. Results show coagulants have more effect on membrane fouling in low MLSS and the effectiveness of coagulant reduce with concentration of coagulant. Additionally, $FeCl_3$ is more effective in fouling mitigation than Al_2O_3.

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