Desalination and Water Treatment
www.deswater.com

34 (2011) 336–343
October

doi: 10/5004/dwt.2011.2890

Various operating conditions affecting the performance of aerobic digestion coupled with membrane filtration

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Received 3 September 2010; Accepted 3 January 2011

ABSTRACT

An aerobic digestion coupled with membrane filtration (ADMF) system was investigated to determine the influence of various operating conditions to the efficiency of sludge thickening. Three different parameters were studied: the effect of hydraulic retention time (HRT), aeration and addition of coagulant. The effect of varying HRT was noticeable with the decrease in viscosity with increasing HRT. Transmembrane pressure, which indicates the extent of membrane fouling, increased with the decrease in HRT. Effect of aeration on the rate of increase in mixed liquor suspended solid concentration was observed to be insignificant, indicating that the aeration rate affected the filtration performance rather than the sludge reduction efficiency. Study on the effect of coagulant was evaluated by comparing two kinds of coagulants, organic and inorganic, at different concentrations. Dead-end filtration experiment and determination of critical flux were conducted to investigate the permeate performance according to coagulant addition. Higher value of critical flux was obtained with the addition of inorganic coagulant, while the total resistance was decreased with increasing coagulant concentration. Results show that while the addition of inorganic coagulant enhanced the ADMF system by improving membrane permeability, it is recommended that the system be operated at high HRT and aeration rate.

Keywords: Aeration; Aerobic digestion; Coagulation; Hydraulic retention time; Membrane filtration; Sludge thickening

1. Introduction

Several reports already proved that waste activated sludge is difficult and expensive to handle and dispose [1,2]. The cost of sludge treatment and disposal can account up to 60% of the total operating cost in wastewater treatment plants. Due to the stringent effluent criteria and restrictions to landfill, processing and disposal is becoming a more difficult and complex problem. For volume reduction, thickening and dewatering is usually practiced. Sludge thickening is particularly important because it influences the reliability and performance of the entire sludge treatment system [3]. Sludge thickening is generally accomplished by physical means, including gravity thickening, dissolved air flotation (DAF) thickening, and centrifugal thickening.

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Presented at the AMS6/IMSTEC10, The 6th conference of the Aseanian Membrane Society in conjunction with the 7th International Membrane Science and Technology Conference, Sydney Australia, November 22–26, 2010

Several problems and disadvantages still exist among the typical sludge thickening technologies such as the large footprint and low thickening efficiency and the release of phosphorus under long sludge retention time with gravity thickening process, lower quantity of sludge storage and higher energy cost with DAF thickening compared with gravity thickening, and much higher energy cost and advanced maintenance requirements with centrifugal thickening technology. If sludge thickening could not perform reliably, it would lead to an increase in volume load on the sludge dewatering process, a decrease in dewatering performance and an increase in pollution load [2,3].

Recently, researchers observed that the membrane can be used for solid-liquid separation at high mixed liquor suspended solids (MLSS) concentrations [4–7]. Studies have been undertaken on the application of flat-sheet membranes to sludge thickening [2,8]. Sludge thickening by the use of a submerged flat-sheet membrane has many advantages including small footprint, increased efficiency of pollutant removal, and reduced cost for the treatment of thickened supernatant due to high solid withdrawal ratio [9]. Wang et al. [1] studied the characteristics of using flat-sheet membrane for sludge thickening and digestion. He found out that sludge could be successfully concentrated using membranes. The membrane fouling of the thickening process was mainly due to the fact that the increase of sludge concentration in the reactor resulted in the increase of apparent viscosity and the decrease of critical fluid velocity along membrane surface. In another study conducted by Wu et al. [2], which investigated the influence of mixed liquor properties on critical flux, he observed that the critical flux significantly decreased with the increase of operation time. In addition, COD were found to have significant influences on critical flux while the extrapolymeric substances had mild impact on the critical flux. MLSS was then chosen as one of the most effective and convenient variables of sludge to predict the critical flux in the sludge thickening process.

Digestion can be performed under either aerobic or anaerobic condition. The stabilization mechanism of aerobic digestion is that the aerobic micro-organisms consume the degradable organic components in sludge, while the anaerobic microorganisms degrade the organic components and produce biogas [10]. Membrane filtration has been considered as a promising solution to treat anaerobic effluent to meet the increasingly strict discharge standards because membranes could remove physical, chemical and microbiological contaminants [11].

Membrane fouling is a major obstacle for the application of membrane in wastewater treatment, which can be attributed to both membrane pore clogging and sludge cake deposition on membranes which is usually the predominant fouling component [12]. Membrane fouling results in a reduction of permeate flux or an increase of transmembrane pressure (TMP) depending on the operation mode. Many studies were conducted to prevent or reduce membrane fouling. Air-sparging or air-scouring, which causes a shearing stress through uplifting air bubbles, is one such measure removing the cake layer deposited on membrane surfaces before the cake layer becomes compacted [13]. Studies on chemical additives, such as chelating agents, surfactants, biocides and polymeric coagulants, to prevent fouling from occurring gain additional attention. An example of which is the study conducted by Song et al. [14] which proved that injection of coagulant minimizes membrane fouling.

This study investigated the effect of various operating parameters, such as hydraulic retention time (HRT), aeration and coagulation, to the efficiency of sludge thickening using an aerobic digestion coupled with membrane filtration (ADMF) system. In addition, effectiveness of organic and inorganic coagulant addition in the performance of the ADMF system was also evaluated. The research aimed to increase the performance efficiency of the ADMF system by optimizing the operating condition through appropriate selection of aeration intensity, HRT and type of coagulant to be applied.

2. Materials and methods

2.1. Experimental set-up

The schematic diagram of the ADMF system used in this study is shown in Fig. 1. The reactor has a total working volume of 2l with a dimension of $16l \times 19w \times 45h$ (cm). A flat-sheet PVDF (polyvinylidene fluoride) membrane with a mean pore size of 0.08 µm was used. The membrane has an effective membrane area

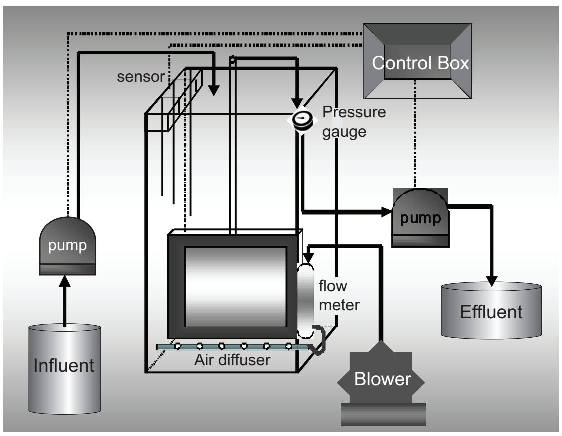

Fig. 1. Schematic diagram of the ADMF system.

of 0.03 m^2 with a dimension of 130*l* × 130*w* × 7*h* (mm). The ADMF system is composed of three portions: the influent sludge, the reactor and the effluent. The sludge was aerated in the container and then fed to the reactor using a peristaltic pump. Sensors were installed inside the reactor to monitor the level of the sludge. Sensors are designed to detect the upper limit which prevents sludge overflow, and the lower limit which signals the influent pump to supply sludge. To ensure sufficient oxygen uptake for microorganisms, air was provided by an air pump, which also scoured the membrane surface to help minimize membrane fouling.The sludge was aerated in the container and then fed to the reactor using a peristaltic pump. Water suction was done using a flat-sheet membrane submerged inside the reactor. The water that passed through the membrane was collected in an effluent container with another peristaltic pump. The pump was operated intermittently for 5 min suction and 5 min rest, and the trans-membrane pressure (TMP) was monitored by a pressure gauge.

2.2. Operating conditions

In this study, a batch test for dead-end filtration experiment and determination of critical flux was carried out. Five different coagulant concentrations were evaluated: 250 and 500 ppm organic coagulant, 250 and 500 ppm inorganic coagulant, and without coagulant that serves as the control. Poly aluminum chloride and MPE 50 were used as inorganic and organic coagulant, respectively. In addition, a batch test to determine the rate of decrease in total solid (TS) concentration without sludge withdrawal was also conducted. Then, series of continuous experiments was performed at various operating conditions.

Table 1 shows the various operating conditions for the continuous experiment, which was divided into three different modes, where the first two modes were operated for three weeks while the last mode was run for a week. Intermittent suction was done for 5 min filtration and 5 min relaxation. Effect of HRT, aeration and coagulant addition in sludge reduction was evaluated in Modes 1, 2 and 3, respectively. The characteristics of the influent sludge are listed in Table 2. The condition of the sludge differs from each mode due to the changes occurred in the pilot plant where the sludge samples were obtained. However, it was assured that same condition of influent sludge was fed in each mode to be able to compare and evaluate the effect of varying operating condition at a specific mode.

2.3. Analytical methods

The critical flux was determined by increasing the flux in a step-wise method while the corresponding TMP was monitored [15]. Flux-step tests were conducted using the lab-scale submerged flat-sheet membrane for measuring the critical flux and evaluating the fouling reversibility. Each step of the measurement lasted for 15 min and the incremental flux step was chosen at 6 l/m^2h. For each flux-step, two TMP values were obtained, the initial TMP and the final TMP. The rate of TMP increase was calculated by dividing the change in TMP with the operating time in each step. The sludge concentration, aeration rate, and temperature were set to 20,000 mg/l, 5 l/min, and 20°C, respectively.

Table 1
Operating conditions for the continuous experiment

Parameter	Mode 1 HRT			Mode 2 Aeration rate			Mode 3 Coagulation		
Aeration rate (l/min)	2	2	2	2	4	6	2	2	2
HRT (d)	1	3	6	3	3	3	3	3	3
Concentration (ppm)	–	–	–	–	–	–	250 (organic)	250 (inorganic)	500 (inorganic)
Filtration flux (LMH)	6.25								
SRT (d)	60								

Table 2
Characteristics of influent sludge at different modes

	Temp. (°C)	Viscosity (cP)	pH	DO*	MLSS*	MLVSS*	COD*	T-N*	T-P*
Mode 1	20.4	4.0	4.9	4.9	4,667	3,986	43.7	33.4	14.7
Mode 2	23.8	4.0	6.0	4.8	5,748	4,095	55.3	52.6	21.1
Mode 3	21.5	3.5	7.3	5.8	5,040	3,610	75.1	61.7	32.1

*in mg/l.

Dead-end filtration was conducted using a filtration cell (Amicon cell 8200, Amicon, USA) to determine the specific fouling resistances of the fouled membrane. The membrane flux was measured by capturing the total permeate after filtration with the flat-sheet membrane and then calculating the average flux using a membrane area of 28.3 cm^2. The pressure, sludge volume, sludge concentration, and membrane diameter were 10 kPa, 200 ml, 20,000 mg/l, and 60 mm, respectively. Filtration was continued for 30 min, which allowed the permeation flow rate to be stable. The fouling resistances were estimated using Darcy's equation as described in Eq. (1):

$$R_t = R_m + R_f + R_c = \frac{TMP}{\mu \cdot J} \tag{1}$$

where R_t is the total hydraulic resistance, R_m is the membrane resistance, R_f is the fouling resistance, R_c is the cake layer resistance, μ is the dynamic viscosity, and J is the permeate flux. Each resistance value was determined by the experimental procedure reported by Lee et al. [12].

Following the standard method, sludge concentration was determined by measuring the amount of suspended solids and volatile components of the mixed liquor [16]. Brookfield DV-2 Viscometer was used to obtain the viscosity of the sludge. Total nitrogen (TN), total phosphorous (TP) and chemical oxygen demand (COD_{Cr}) were analyzed using reagent kits (HACH).

3. Results and discussion

3.1. Batch test

3.1.1. The rate of sludge reduction in ADMF system

In order to determine the net sludge reduction rate in the reactor, a batch test was carried out without the withdrawal of excess sludge. Fig. 2 shows the change in total solids (TS) concentration at different temperatures. TS concentration decreased from 31,200 mg/l to 17,850 mg/l at 25°C. This result indicates that sludge reduction by aerobic digestion and auto-oxidation occurs inside the reactor during the experimental period. Moreover, sludge reduction efficiency increased as temperature increased. Bernard and Gray [17] reported sludge reductions of 42–53% for MLSS and 53–64% for MLVSS under the following conditions: an initial MLSS of 3,000–5,000 mg/l and an HRT of 35 d with an aerobic digestion process, which was also observed in this experiment.

3.1.2. Critical flux

Membrane fouling can be managed by operating the system below the critical flux [18]. The critical flux is generally regarded as the flux above which cake or gel formation by particles or colloids occur [19]. In order to examine the effects of the coagulant on the critical flux during the experiment, the flux-step method was conducted. Fig. 3 shows the Flux-TMP profile at various coagulant concentrations. It was observed that after addition of coagulant, the system could be operated at higher critical flux. Addition of 500 ppm inorganic coagulant obtained the highest possible operating flux, however, the difference in the critical flux of other coagulant concentrations as compared to the system without coagulant was almost incomparable. This is due to the high MLSS concentration in the ADMF system causing an immediate fouling in the membrane surface after a step increase in the critical flux test. It was observed that the increase of MLSS concentration had a mostly negative effect on the flux [20]. However, some researchers observed that MLSS concentration alone is not sufficient to predict filterability and determine the critical flux [21,22]. In this

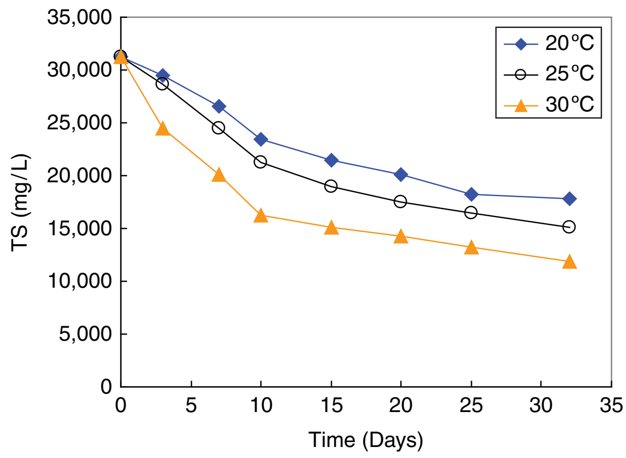

Fig. 2. Changes of TS concentration with temperature.

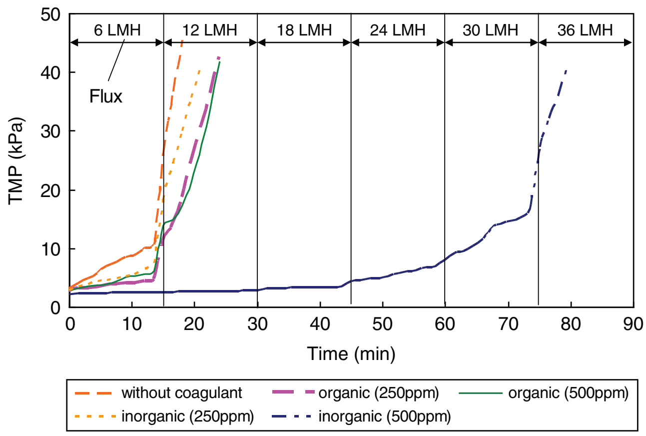

Fig. 3. Flux-TMP profile with the coagulant concentration.

study, it was found that the selection of the coagulant also had a great influence in the determination of critical flux. In ADFM system, addition of inorganic coagulant was more effective than organic coagulant.

3.1.3. Filtration resistance analysis

Comparison of the specific resistances was the main objective of the dead-end filtration experiment. It was found that after 30 min of filtration with Amicon cell, the membrane used in the sludge sample without coagulant (control) was almost blocked with foulants. At this point, the operating flux approached to zero while maintaining the pressure at 10 kPa. Thus, for the succeeding sludge samples with coagulant addition, the dead-end filtration was conducted for 30 min then the fouled membrane was recovered and subjected for the determination of the fouling resistance (R_f). Thirty-minute filtration was set as the standard for the comparison of the effect of coagulant addition on the specific resistances between the sludge samples with coagulant and the control.

Dead-end filtration experiment was conducted to determine the specific resistances that could predict the fouling mechanism in the membrane surface. It was evident that addition of coagulant decreases the total resistance providing higher flux for the system operation. The resistances are shown in Fig. 4. The total resistance (R_t) without the addition of coagulant was 3.83×10^{12} m^{-1} and it decreased according to increasing coagulant concentration. When 500 ppm of the organic coagulant and the inorganic coagulant were injected, the R_t values were 3.06×10^{12} m^{-1} and 1.89×10^{12} m^{-1}, respectively. It was found that R_t was reduced about 40% after addition of inorganic coagulant as compared to organic coagulant. Therefore, in the ADMF system, inorganic coagulant was more favorable. It was also observed that pore blocking was very minimal than the fouling caused by the formation of cake layer. These results were almost parallel to the results obtained in critical flux.

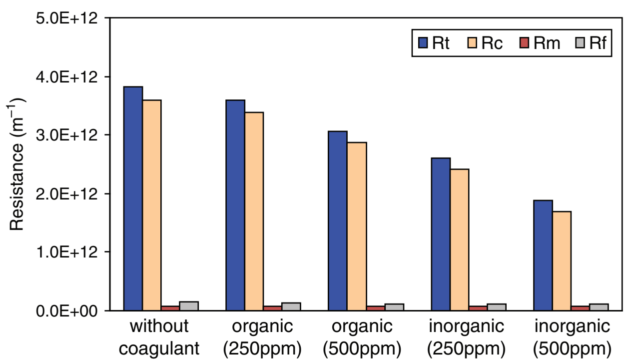

Fig. 4. Variation of resistances at different coagulant concentrations.

3.2. Continuous experiment

The system was operated for three weeks with different operating HRTs of 1,3 and 6 d. Changes in HRT indicate variation of hydraulic loading rates for the organics, and other nutrients, affecting membrane fouling. For a given HRT, higher MLSS concentrations allow operation at increased MCRTs resulting in reduced sludge production [23,24]. The viscosity decreased with increasing HRT from 1 d to 6 d as shown in Fig. 5. On the contrary, trans-membrane pressure (TMP), which indicates the extent of membrane fouling, increased with the increase in HRT. For the system operated at HRT of 1 d, TMP increased from 2.4 kPa to 31.3 kPa. While for 3 and 6 d, TMP increased from 2.4 to 25.7 kPa and 2.4 to 22.5 kPa, respectively.

Many researches have been conducted to study the mechanisms of membrane fouling through studying the influence of sludge characteristics on membrane permeability. Membrane fouling can be mainly attributed to the complex properties of sludge mixed liquors, especially at high and increasing MLSS concentrations [25]. Fig. 6 shows the change in MLSS concentration at

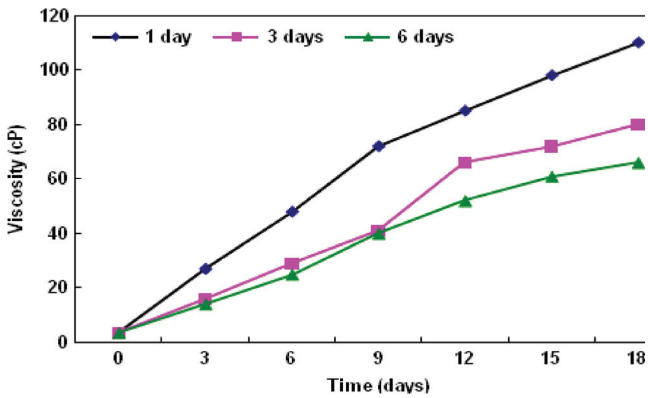

Fig. 5. Change in viscosity at different HRTs.

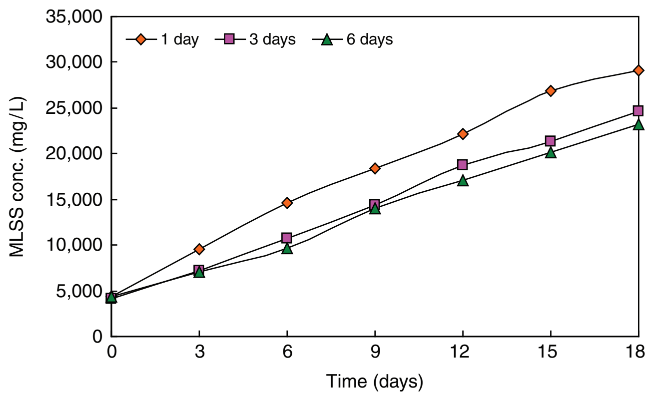

Fig. 6. Change in MLSS concentration at different HRTs.

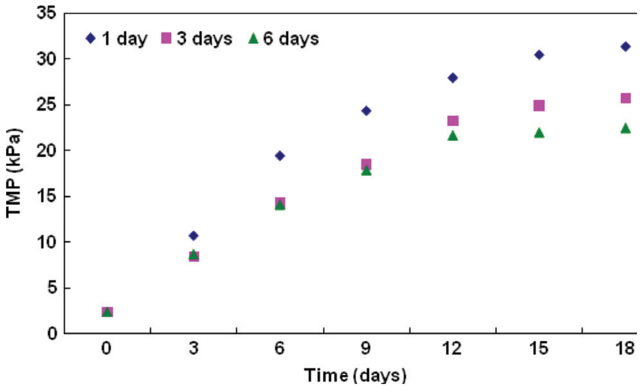

Fig. 7. Increase TMP at different HRTs.

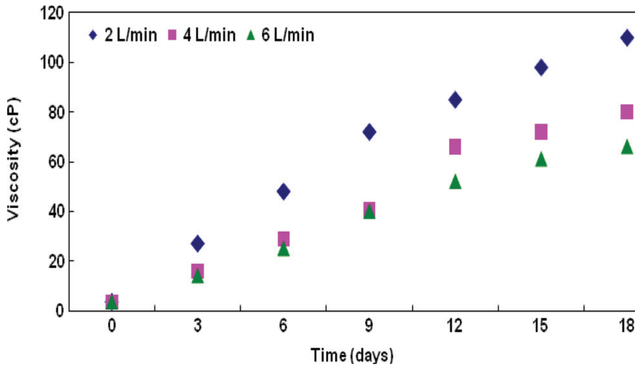

Fig. 8. Viscosity profile at various aeration rates.

different HRTs. The MLSS concentration decreased with increasing HRT. This is due to the low influent flowrate at high HRT which decreases the supply of nutrients needed by the microorganisms for growth and reproduction, thus decreasing the concentration of MLSS inside the reactor. During the operation, it was found that viscosity goes up with the increase of sludge concentration. The increase in viscosity of the mixed liquor inside the reactor could be associated to membrane fouling. Due to the low nutrient supply, the sludge tends to undergo degradation to provide food for itself and releases extrapolymeric substances which contributes in membrane fouling. These substances blocked the pores of the membranes which commonly cause an irreversible fouling that resulted in TMP increase.The results are well consistent with the study conducted by Wang et al. [1]. At the end of the operation, effluent samples were collected and it was found that the COD value was lowest at HRT of 1 d, however, it obtained the highest TN and TP concentrations of 89 and 44 mg/l as compared to the other two HRTs. Effluent quality is listed in Table 3. These values were significantly lower in comparison with the nutrient concentration using conventional thickening and dewatering processes.

It was observed that as the aeration rate increases, the viscosity also increases as illustrated in Fig. 8. During the 3-week operation, the increase in TMP values was almost similar for the three aeration rates until the 9th d of operation as depicted in Fig. 9, then, it increased in sequence of decreasing aeration rate. An increase in aeration rate offers the dual benefit to oxygen transfer which increases the amount of available oxygen and also decreases biomass viscosity by increasing shear stress. Aeration has three major roles: providing oxygen to the biomass, maintaining the activated sludge in suspension and mitigating fouling by constant scouring of the membrane surface [9]. Parts of the accumulated foulants could be removed by shear stress generated from the intensive aeration on the membrane surface [26].

In this study, the major contributor to membrane fouling was the cake layer formed during filtration, which is presented in the resistance analysis. Comparing the lowest and the highest aeration rates, the TMP values at 2 and 6 l/min reached 29.6 and 16.9 kPa, respectively. This observation proves that aeration could remove the foulants on the membrane surface by applying shear force. Le-Clech et al. [27] reported similar results. Increase in the concentration of MLSS and MLVSS at different aeration rates is presented in Table 4. It was observed that an increase in aeration rate increases MLSS concentration. Viscosity increases

Table 3
Effect of HRT on effluent quality

Effluent concentration (mg/l)	Hydraulic retention time (day)		
	1	3	6
COD	25	39	42
TN	89	73	72
TP	44	37	35

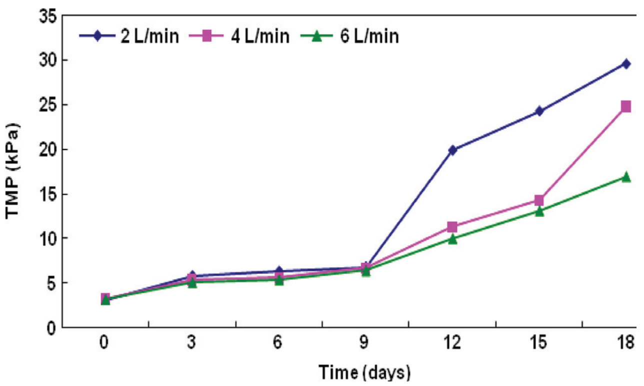

Fig. 9. TMP profile at various aeration rates.

Table 4
Increase in MLSS concentration during the experimental period

Concentration (mg/l)	Aeration rate (l/min)	Operation time (day)						
		0	3	6	9	12	15	18
MLSS	2	6,033	11,500	17,067	22,650	27,100	32,650	37,300
	4	6,033	11,367	16,957	21,100	26,300	31,300	36,650
	6	6,033	11,133	16,533	20,650	25,950	30,650	34,950
MLVSS	2	4,433	9,233	15,600	19,150	22,300	26,350	29,633
	4	4,433	8,967	15,133	18,767	21,650	25,233	29,067
	6	4,433	8,633	14,300	17,950	21,700	25,033	28,700

roughly exponentially with increasing MLSS concentration [28–29]. However, a comparable increase in MLVSS concentration compensated the increase in MLSS. These results show that aeration rate affected the membrane filterability more than the sludge reduction efficiency.

Recently, various chemicals including synthetic or natural polymers, metal salts, resins, granular or power activated carbon have been tested for filterability and fouling reduction [30]. There are three functions of coagulant in reducing membrane fouling as suggested by Wu et al. [31] which include restraining the formation of a gel layer, decelerating the development of foulants and removing stable foulants from the membrane surface. It was proven that small particles became bigger after addition of coagulant which eventually helped in lessening the tendency of membrane fouling [14,32].

Three different coagulation conditions were investigated. Organic coagulant concentration of 250 ppm was used in the experiment, while 250 and 500 ppm inorganic coagulant concentrations were tested for comparison. Fig. 10 shows the change in TMP at different coagulant type and dosages. The system injected with 500 ppm inorganic coagulant obtained the lowest rate of increase in TMP as shown in Fig. 10. A slight difference in TMP values between 250 and 500 ppm inorganic coagulant was observed, while the system added with 250 ppm

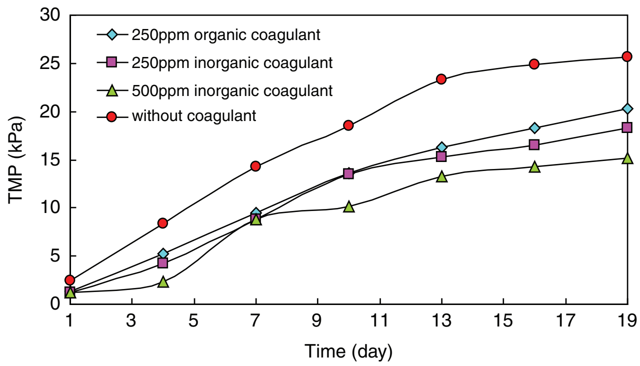

Fig. 10. TMP increase at different coagulation conditions.

organic coagulant reached the highest TMP, which sharply increased from 1.3 to 8.9 kPa. This indicates that inorganic coagulation was more effective in reducing membrane fouling, which was similar with the batch test results. In addition, the final viscosity recorded for the system with 250 ppm organic coagulant, 250 and 500 ppm inorganic coagulant were 34, 48 and 51, respectively. This shows that the tendency of viscosity due to different coagulation condition was opposite to that of the TMP, which was different from the results in Mode 1. At high viscosity, it was reported that more small particles were accumulated on the membrane surface [33], hence, the high viscosity of the raw sludge resulted to a more severe fouling compared to the system with coagulant.

4. Conclusions

This study evaluated the effectiveness of organic and inorganic coagulant addition in the performance of an aerobic digestion coupled with membrane filtration (ADMF) system. Three different modes were tested: effect of HRT, aeration and coagulant addition.

It was found that proper selection of coagulant greatly affect the effectiveness efficiency of the ADMF system, which could be determined through critical flux and dead-end filtration analyses. It was observed that addition of inorganic coagulant was more effective than organic coagulant, which resulted to a 40% reduction in the total membrane resistance, R_t. Therefore, it was concluded that inorganic coagulant was more favorable in the ADMF system. The viscosity decreased according to increasing HRT from 1 d to 6 d. On the contrary, the trans-membrane pressure, which indicates the extent of membrane fouling, increased with the increase in HRT. When the 500 ppm of inorganic coagulant was injected, the rate of increase in TMP was the lowest. For the effect of aeration rate, the rate of increase in MLSS and MLVSS concentration at increasing aeration rate was observed to be similar. This result shows that the aeration rate affected the membrane filterability more than the sludge reduction efficiency. Thus, the ADMF system should be operated at high HRT and aeration rate, and also with the addition of inorganic coagulant, which enhances membrane filterability.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean Government (MEST) – NRF-2010-0015685.

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