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Prolonged reuse of domestic wastewater after membrane bioreactor treatment

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ABSTRACT

In this study, experience in a nine-year operation of a full-scale 2000 PE vacuum rotating membrane bioreactor having a submerged flat-type membrane module having pore size of 0.038 μm and a total surface area of 540 m^2 is discussed. The plant was designed to treat and reuse raw wastewater collected from dormitories and the academic village at METU campus. Throughout the study, 99.99% BOD_5 and above 95% COD removals were achieved most of the time. Moreover, turbidity was consistently measured below 1 NTU and around 6–7 log coliform removals were achieved with less than 1 coliform/100 mL in the effluents most of the time, except for the leakage from the bearings. During the study, energy consumption by the plant was also analyzed by routinely measuring energy consumption in different parts of the plant. Consumption was analyzed in two parts. Energy consumed by the blower supplying aeration to the biological treatment tank was monitored separately from the rest of the plant. Except for the periods when problems have occurred during operation, the total energy consumption of the system was variable between 1.1 and 2.53 kWh/m^3, averaging around 2 kWh/m^3. The main problems encountered during operation were poor floc formation and dispersed growth, and sludge deposition between the membrane plates and mechanical malfunction of the bearing seals. The treated wastewaters were stored and used for the irrigation of METU Technopolis lawns.

Keywords: Wastewater treatment; Membrane bioreactor; Prolonged; Reuse

1. Introduction

The world population is estimated to grow dramatically from 2004 to 2020 with accompanying scarcity of clean waters [1]. Due to this increase, clean water resources are becoming increasingly scarce in many areas of the world [2,3]. In order to obtain new fresh water resources, newer technologies have been investigated. One of the innovative activated sludge processes for wastewater reuse is membrane bioreactor (MBR), which employs membrane filtration instead of secondary clarifiers to achieve biomass separation [4–7]. Although filters have been use since early 1960s as filtration devices, their usage as a means of water and wastewater treatment goes back only few decades [8]. MBR technology is considered superior over the conventional biological systems in that it produces far better-quality effluents. In MBRs, hydraulic retention

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time (HRT) is independent of the sludge retention time, SRT [9], and truly infinite SRT is achievable in these systems [10]. In addition to producing sparkling clear effluents, MBRs are efficient in concentrating mixed liquor suspended solids (MLSS) to remarkably high levels, thereby reducing plant footprint [11]. Apart from the many advantages of MBRs, the high investment cost was the main drawback of this technology by the end of 1990s. Due to the advancement of the polymer industry, membrane costs declined rapidly after the turn of the twentieth century [6,12] and MBR plants became widespread. Moreover, in early 1990s, MBR plants were mostly being constructed in external configuration, where membrane modules were located outside the bioreactor and biomass was recirculated between the filtration unit and the reactor. Although the external membrane allowed a better access for the cleaning and reducing the membrane fouling, the operation cost was very high and not applicable for the treatment and reuse of municipal wastewater. External type of membrane is mostly used for industrial wastewater treatment. Owing to their high electricity consumption, submerged MBRs became the method of choice in municipal wastewater treatment after the mid-1990s [13]. This development has led to wider application of MBR plants in the world, as of the year 2000. Therefore, after 1990s, submerged MBR systems were developed for the treatment and reuse of municipal wastewaters. In this configuration, membrane modules were directly immersed in the activated sludge tank to decrease the electricity utilization of the system. In addition, there are many advantages of submerged systems, including simple design and higher hydraulic efficiencies, than external design. The transmembrane pressure (TMP) in submerged system is very low, around 0.3 bar, compared with external configuration, from 1 to 4 bar [14].

Wastewater reuse is done mainly for irrigation, toilet flushing, and some cleaning actions. In order to reuse wastewaters after treatment in irrigation, some regulations were set up to minimize the health risks of human exposure to the pathogens. In Turkish Water Pollution Control Regulation, "Technical Aspects Bulletin," was published on 4 September 1988 and considered during the study [15].

In this study, a nine-year operation performance of a full-scale vacuum rotating membrane (VRM) reactor, operating in METU campus, Ankara, Turkey, is analyzed.

2. Materials and methods

2.1. The VRM MBR system at METU

A full-scale MBR, referred to as VRM, located in METU Campus, Ankara, was used in this study. As seen in Fig. 1, the plant consists of two tanks and the peripheral equipment. A partitioning wall between the tanks separates the two. However, the two tanks are connected by five orifices, each controlled manually, located at the bottom of the partitioning wall. The working volume of the first tank is 85 m^3, and is used for the aeration of the biological sludge. The second tank is about 23 m^3 in volume and is used to house the VRM unit. Wastewater from dormitories and academic village is first collected in a 10 m^3 holding tank and then pumped to the treatment plant located 50 m away from the storage tank at 15m elevation. A 4 cm coarse screen is located at the inlet to the storage tank. Wastewater is screened through a screw type fine screen having 3 mm openings, Rotomat Ro9, produced by Huber A.G. at the entry to the aeration tank.

Membrane diffusers for aeration are placed at the bottom of the aeration tank. On the VRM unit, whose picture is given in Fig. 2, flat plates are seated on a drum-like filter holder produced by Huber A.G. The filter holder is in continuous rotation driven by a motor. The rotation speed is 2.5 rpm. Suction is applied to the plate modules from inside via six radial hoses connecting the suction pump to the suction

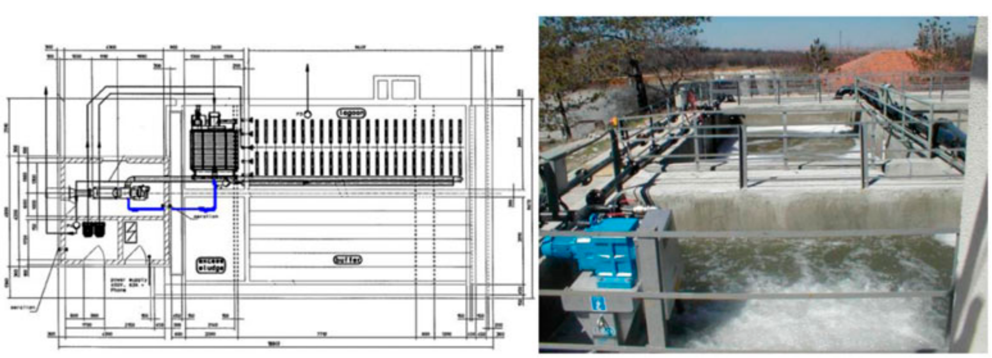

Fig. 1. VRM plant in METU.

Fig. 2. The VRM membrane holder and a membrane module cassette.

tubing on the membrane modules. A cross flow is applied over the plates by coarse aeration through two diffusers located under the plates at the center of the rotating drum. Membrane plates are separated 15–20 mm apart. Solids retention time (SRT) employed during this study were between 10 and 150 d, and HRT, was between 15 and 24 h. The typical flux rates employed were 8.3–13 $L/h\,m^2$ and the maximum attainable was 15 $L/h\,m^2$. A picture of the VRM unit at the factory shop floor and a membrane unit is given in Fig. 2. A portion of the mixed liquor was continuously being recirculated from the VRM tank to the aeration tank. Its ratio to the inflow was 3. System was initially operated in 10 min cycles with 8 min vacuum and 2 min relaxation. This was later changed to 4 min vacuum and 1 min relaxation, which also worked equally well. During relexation period, although vacuum pump was stopped, aeration of membran module and rotation were continued.

2.2. In situ, *on-line measurements*

These measurements included TMP, temperature (T), dissolved oxygen (DO), and pumping flows. Temperature and DO were measured online by a Jumo dTrans O_2-01 DO and temperature meter. The DO concentration in the aeration tank was controlled by means of a DO probe and a process control console linked to the blower, whereas temperature was only recorded. The probe was submerged in the aeration tank, and data obtained were transmitted to the PLC module located inside the process control console. Pumped flow was measured by a Siemens ultrasonic flow meter and TMP was measured by a transducer placed at the inlet of the vacuum pump. The online measurements were collected continuously during operation and stored in a Micromec data logger and downloaded at constant intervals.

2.3. Laboratory analysis

The COD, BOD_5, total suspended solid (TSS), turbidity, and conductivity were routinely analyzed in the laboratory in duplicates. COD was measured using Hach Dr 2000 Model Spectrophotometer. Hach COD reagent (Cat No. 21259-51) for COD was used. The BOD_5 of the influent and effluent was measured according to Standard Method (5210B) [16]. TSS was analyzed according to Standard Methods (2540B) [16]. Standard Methods 9222B and 9222D were used for the analyses of total and fecal coliform. A Hach 2100 N model turbidimeter was used to determine the influent and effluent turbidities. A YSI 33 model conductivity and salinity meter was used for the measurement of conductivity. The electricity consumption was measured directly from the control panel of VRM plant.

3. Result and discussion

Full-scale VRM plant was successfully operated for more than nine years, and is still in operation in the METU Campus, Ankara. The operation was commenced in May 2004 with the transfer of activated sludge from Ankara Wastewater Treatment Plant, having 3 g/L MLSS. Initially, the plant was operated at 7.5 m^3/h and 13.8 $L/m^2\,h$ flux rates. The HRT of the system was arranged to 14–22 h and the plant operation regime was initially set as 8 min suction followed by 2 min relaxation without suction. This was later changed to 4 min suction and 1 min relaxation, which worked equally well. At the end of 5th year of operation, about 50 m^2 of membrane area was damaged and flux was increased to about 16 L/m^2 h to achieve the same flowrate.

During the entire nine years of the study period, the SRT was arranged from 10 to 150 d. At the beginning of the study, MLSS concentration was set 150 d without disposal of sludge. During this period, MLSS concentration in the membrane chamber has increased from 8 to 21 g/L. After this period, sludge was disposed not only to decrease the sludge concentration in the aeration tank but also to increase the active biomass population in the reactor. The highest sludge concentration reached during this period was 23 g/L, whereupon sludge was disposed to decrease MLSS concentration. The MLVSS/MLSS was between 0.50 and 0.78 during the study.

During the study, measurements of COD in influent and effluent were carried out routinely to understand assess efficiency of the system. The plant was so robust that daily fluctuations in influent COD had no effect over the treatment efficiency, even at SRTs as low as 10 d, as shown in Fig. 3.

As seen in Fig. 3, the peak COD was observed at noon and the lowest in the early morning. The average influent COD concentration was 426 mg/L and effluent COD concentration was steady at 19 mg/L. This indicated an average of 96% COD removal during the day. Throughout the study, the influent COD was measured between 240 and 1,200 mg/L. DO concentration in the aeration tank was variable between 0.1 and 4 mg/L. The plant still produced clear effluent when DO was so low. The highest influent COD was measured in summer of 2008 during a drought. Effluent COD concentration was still consistently below 60 mg/L, when the highest influent concentration was met and DO concentration was around 0.1 mg/L. This lowest oxygen concentration could be explained by the oxygen consumption during the organics removal. In addition, higher concentration of MLSS during that period was over 12 g/L in aeration tank. In other times, during normal operation, the effluent COD was mostly around 20 mg/L. A check on the effluent COD indicated that it is not biodegradable, probably originating from the inert influent COD and/or the soluble inert microbial products. The recorded influent and effluent COD concentrations in the course of operation between January 2004 and August 2012 are presented in Fig. 4, along with the corresponding COD removals.

The most important parameters for the assessment of reuse of wastewaters for irrigation are turbidity and coliform counts. Fecal and total coliform organisms are taken as good indicators of water quality. Particularly, fecal coliforms are true indicators of human origin, whereas total coliforms may sometimes be misleading as these may also be free living in nature. Turkish reuse standard, just like the US and Israel standards, calls for less than 2 NTU and 2/100 fecal coliform count for unrestricted reuse. Typical fecal coli bacilli counts attained at the METU VRM treatment plant are depicted in Fig. 5. From this figure, it is seen that less than 2 coli bacilli/100 ml could be achieved in the effluents. Since the pore size of the membrane is about 0.038 μm and the size of bacteria is about 1 μm, which is about 25 times bigger than pore size, it was not possible to pass bacteria from the membrane filter. Most of the times, over 90% of the samples, the number of fecal coliform in the effluent was zero. However, in some situations, due to contamination when taking samples, it could be possible to measure

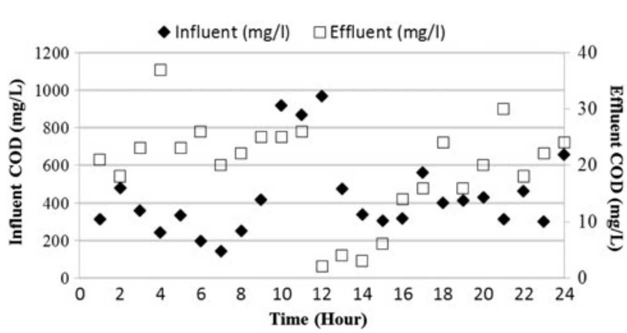

Fig. 3. Influent COD fluctuation during the day.

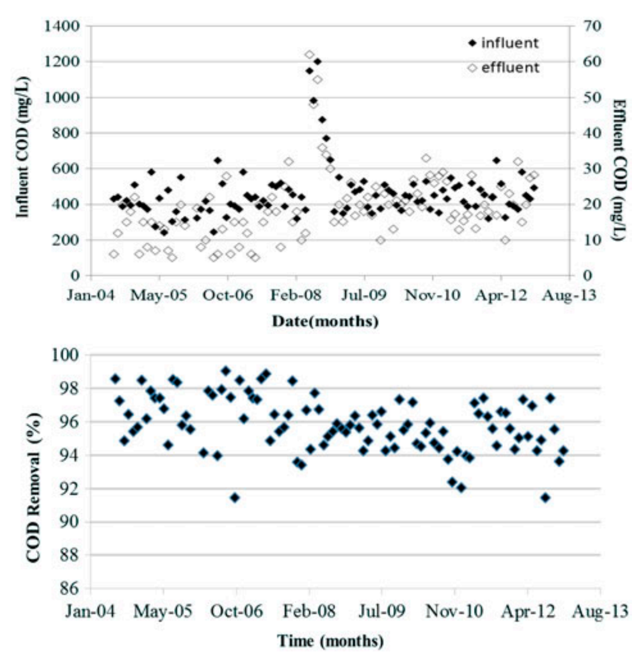

Fig. 4. Typical influent and effluent COD values with corresponding COD removal percentages.

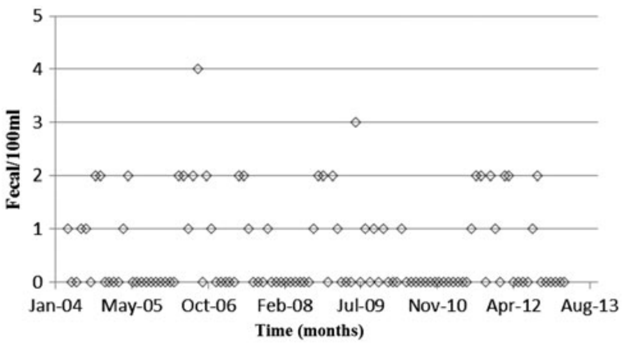

Fig. 5. Typical numbers of fecal coliforms recorded in the effluent.

FC in the effluent. It was also clearly seen from the turbidity measurements that it was not any damage in membrane modules. During this nine-year period of the operation, the number of fecal coliform in the effluent was less than 1 in 90% of effluent samples. Approximately, 7 log reductions in fecal coliform counts and 5–6 log reductions in total coliform counts have been constantly achieved.

Turbidity of the influent was between 115 and 210 NTU (Nephelometric Turbidity Units), while typically this ranged between 0.1 and 1.1 NTU, as shown in Fig. 6. Turbidity of the water was around 0.5 during this period.

Influent conductivity was measured typically between 1,350 and 1,450 μmho/cm. There was very little decrease in the effluent conductivity through treatment, which ranged between 1,250 and 1,350 μmho/cm. Conductivity of the tap water was around 1,000 μmho/cm. A picture of the sprinkle irrigation employed at METU Technopolis lawns is shown in Fig. 7.

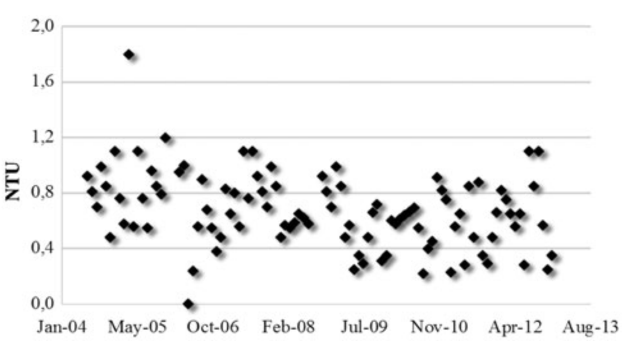

Fig. 6. Effluent water turbidities.

Fig. 7. Irrigation of lawns with reuse water at METU Technopolis.

3.1. Rheology of VRM sludge

Rheology of sludge is extremely important during the operation of the VRM plant since highly viscous sludge tends to block spaces between membrane plates. This became even more important when sludge concentration in the VRM tank has increased to over 20 g/L when the plant had to be operated in extended aeration mode without excess sludge wastage. The rheology of sludge increases dramatically as the MLSS concentration in the aeration tank increases. This becomes detrimental when viscosity goes beyond 20 cP. In fact, 10% of the filter media was lost when trying to remove a blockage of inter-membrane spaces. During blockage, effluent flux tends to decline and TMP increases, and steady TMP below −350 mbar is indicative of chemical cleanup. In conventional activated sludge systems, sludge mostly behaves non-Newtonian and pseudo plastic [17]. Similarly, MBR sludge is reported to behave non-Newtonian and pseudo plastic [18] in character, whereas in VRM plant, rheological characteristics of sludge in the filter chamber are plastic. A truly plastic sludge should be better and more strongly packed into interplate spaces causing strong blockages. The viscosity observations on this plant are already published by Komesli and Gokcay [19].

3.2. Energy consumption and cost calculations

Energy consumption is an important aspect in wastewater treatment plant, which, sometimes, could affect the feasibility of a treatment method. In order to optimize the energy utilization of VRM plant, the

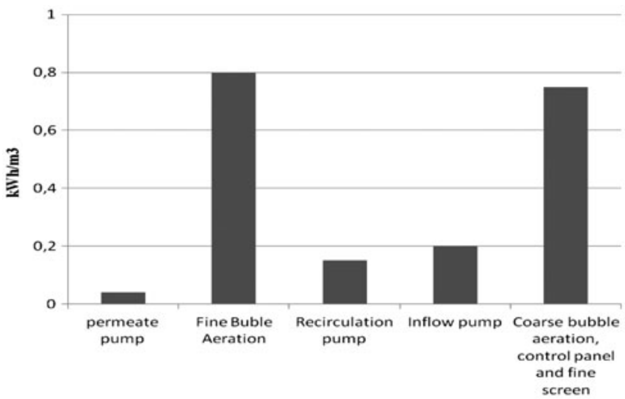

Fig. 8. Normalized energy consumption by each device making up the VRM plant.

electricity consumption during the study was investigated. In VRM plant, energy consumed was divided into two parts: fixed and variable energy consumption. Fixed electricity utilization includes power consumption by rotation, blower for coarse aeration, control panel, and fine screen. Variable energy utilization was due to inflow, permeate and recirculation pumps, and consumption by the blower for activated sludge. The energy utilization by each device per cubic meter of treated effluent, when treating 6 m^3/h, is given in Fig. 8.

It is clearly seen from Fig. 8 that almost half of the energy was consumed by fine aeration, whereas the highest energy consumption is attributed to the coarse aeration in the literature by about 2 kWh/m^3 [20]. This may be attributed to the fact that, in static plants, the cross flow is maintained by installing a series of diffusers to cover the entire bottom of the membrane plates, whereas in VRM, only two diffuser pipes are placed at the center of the membrane holder unit and coarse aeration is maintained from this point, although membranes revolve around the diffusers to expose them alternatively to the cross flow. Since energy utilization of a treatment plant depends on the capacity of the plant, it is not possible to completely compare the energy utilization of different capacities of the plants. However, due to Fenu et al., course bubble aeration was the largest energy consumption device in static MBR plant [14]. In another study conducted by Krzeminski et al., three different configurations of full-scale MBR plants were compared. However, the capacity of each configuration was different and 10–100 times bigger than our plant. In those plants, the energy utilization was from 0.6 to 1.8 kWh/m^3 [21]. In this study, the largest energy utilization device was also coarse bubble aeration from 36 to 64 of all the energy consumption. In another study by Ueda et al., MBR plant with 4 m^2 membrane surface area was used and the energy consumption was 70, which was very high and was not meant to be compared by this study [22].

The total energy consumption by the plant changed appreciably in time since the commissioning of the membrane plant, i.e. from 1.1 to 2.53 kWh/m^3 (permeate), due to wear on the blowers and the permeate pump. Our observation showed that under close control and optimum maintenance, the cost of operation may be reduced to 1.4 kWh/m^3. Taking the depreciation period of the membrane as 10 years, at the most, and assuming 140 m^3/d uninterrupted flow for 10 years, and the most recent quote for 540 m^2 membrane as € 80,000, the depreciation cost of membranes corresponding to 1 m^3 of treated wastewater works out as €0.156. Therefore, the realistic cost of 1 m^3 reuse of wastewater is 2.14 kWh/m^3 and €0.156 for the membrane depreciation. This figure may be reduced to 1.4 kWh/m^3 and €0.156/m^3, at the ideal case. Considering the selling price of electricity, it is

Fig. 9. Sludge layer on membrane plates and filled inter-plate spaces.

€cents 9.5 in Turkey in 2012, and the complete cost of 1 m^3 reuse water is calculated as €cents 35/m^3. This is around 1/10th of the selling price of water by the municipality in Ankara, which is currently €3/m^3.

3.3. Operational problems

During the initial years, several mechanical problems have occurred in the plant. Most serious was the leakage of the central bearing seal. The problem was realized when mixed liquor in the filter chamber penetrated into the vacuum area causing increase in effluent NTU. The problem was rectified by Huber A.G. technicians by adopting a new bearing design. Since then, VRM is operating flawless with its regularly maintained bearings. The other important problem to be aware of is sludge accumulation between the membrane plates as shown in Fig. 9. Occasional chemical cleaning of the membrane modules with 0.5% $NaOCl^-$ for 5–10 h, as per required, frees clogging in mild cases. Sludge accumulation was noticed when MLSS concentration approached 20 g/L, but situation could be rectified by lowering MLSS and by prolonged operation of the VRM without suction and washing plate interspaces by pressurized water. Dismantling or handling aged membrane plates is extremely risky as they get brittle in time and touching by hand causes punctures. Maintaining low MLSS concentrations, i.e. below 12 g/L or 20 cP, and 2–3 times chemical cleansing per year when TMP persisted to stay below −300 mbar prevented clogging of the METU plant.

4. Conclusion

During nine years of operation of a full-scale VRM plant, it has been demonstrated that treated effluents could successfully be used for the irrigation of sensitive lawns at a reasonable cost. The COD removal was consistently greater than 90–95%, and the COD in the effluent was below 20 mg/L for most of the samples. Turbidity and bacteria removals were excellent in this system, producing effluents with less than 1 NTU and close to zero fecal coliform count all the time. Blockage of inter-plate spaces, which is a form of fouling, might cause irreversible damage to the membranes. Hence, keeping an MLSS concentration below 12 g/L and a viscosity reading below 20 cP for the mixed liquor are recommended to avoid this to happen. Energy consumption of the system is lower than other MBR systems, which are stable. Rotation movement is not only for reducing the energy but also for increasing the cross flow in the tank. During nine years operation, membrane modules have not been changed and are continuing to filtration.

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