Maria ELEKTOROWICZ[1], Khalid BANI MELHEM[1], Jan OLESZKIEWICZ[2]

[1]*Department of Building, Civil and Environmental Engineering*
Concordia University
[2]*Department of Civil Engineering*
University of Manitoba

NOVEL SUBMERGED MEMBRANE ELECTRO-BIOREACTOR (*SMEBR*) FOR ADVANCED QUALITY EFFLUENT

NOWATORSKI ZANURZENIOWY ELEKTRO-BIOREAKTOR MEMBRANOWY (*SMEBR*) DLA POPRAWY JAKOŚCI OCZYSZCZANIA ŚCIEKÓW

A new technology called Submerged Membrane Electro-Bioreactor (SMEBR) was developed for wastewater treatment by combining membrane filtration, electrokinetic phenomena, and biological processes in one reactor. It can generate an excellent quality effluent and control the problem of membrane fouling which has been considered one of the major challenges to widespread application of membrane bioreactor technology. This paper describes principles of SMEBR and provides some outcomes generated during laboratory studies. The results showed that the application of the SMEBR system enhanced the membrane filterability and produced excellent nutrients and COD removal without any backwashing of the membrane module.

1. Introduction

An increase of effluent quality is a challenging technological problem leading to search for new treatment methods. SMEBR (Submerged Membrane Electro-Bioreactor) is a novel approach to sustainable wastewater treatment minimizing total energy and footprint while simultaneously improving the effluent quality leading to protection of water resources (Elektorowicz et al., 2009). Then the objectives of designing new system were not only reducing the membrane fouling by changing operation conditions and characteristics of wastewater but also improving the effluent quality due to developing a hybrid operation unit – the SMEBR system.

2. Description of the SMEBR system

The original design of the SMEBR system lies at the inter-relationships of three fundamental processes (Bani-Melhem and Elektorowicz, 2010): biodegradation, electrokinetics (including electro-coagulation and electroosmosis) and membrane filtration (Fig. 1). Therefore, the distinguishing point between the proposed design and other methods is the integration of three above processes into one hybrid unit for an advance and sustainable wastewater treatment technology.

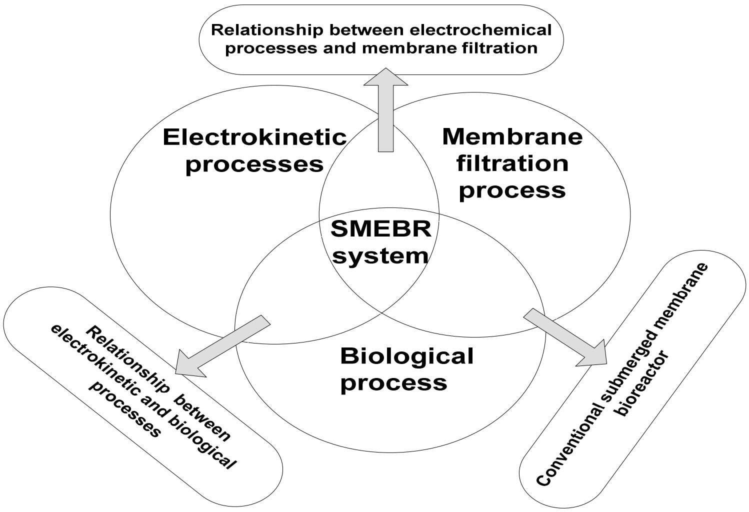

Fig. 1 Conceptual framework of the submerged membrane electro-bioreactor (SMEBR) system

As it was described in Bani Melhem and Elektorowicz (2010), the shear-induced diffusion increases with the increase in particle size and in general, particles penetration into the membrane pores can be reduced by increasing the particle size, and this will enhance particle back transport from the membrane surface to the bulk solution (Lee et al., 2001). The increasing the floc size of the MLSS solution can be achieved by a chemical coagulation (e.g. aluminum salts, iron salts, zeolite and organic polymers) prior to the membrane filtration processes (Wu and Huang, 2008; Kurt et al., 2008). In this study, an electrocoagulation was applied in the SMEBR system due to generation of DC field between electrodes immersed in the MLSS solution.

According to the principles of electrokinetic phenomena, due to application of a direct current (DC) field, the electrolysis of the anode material (M) into its cation (M^{n+}) and the formation of O_2 takes place under oxidation condition; simultaneously, water is reduced to hydrogen gas. Simultaneously, a formation of hydroxyls (OH^-) take place, and measurable increase of pH is observed at the cathode. If aluminum anode is applied, the metal ions (Al^{3+}) appear in the MLSS solution forming aluminum hydroxide which functions as sweep flocs; alternatively, the aluminum ions react with the hydroxyl ions to form $Al(OH)_3$ flocs. Subsequently, formed flocs accelerate the settling and the removal of solids bonded organic and inorganic components. In order to create an excellent electrocoagulation, a circular anode and cathode are designed in the SMEBR system. The electrodes are placed around the membrane module with an appreciable distance from the membrane. The perforation of the electrodes assembly enhances the wastewater feeding and flow toward the membrane module. An accurate distance between the electrodes is also kept in order to minimize the potential effect of an oxidation zone on microbial community. Furthermore, this distance permits on free movement of air and minimizing the sludge shear. This configuration permits for a uniform distribution of the DC field strength within the mixed liquor (MLSS) leading to homogeneous floc formation. It does not affect longevity of membrane material and the membrane module et it does not influence the efficiency of DC field. Electrode materials are crucial for electrochemical processes, but in the case of SEMBR, they are also important for microbial community and membrane fouling. Aluminum and iron are cheap, readily available materials and proven to be effective for electrocoagulation process.

3. Operation of the SMEBR system

The SMEBR design and configuration takes into consideration the requirements of the different simultaneous processes such as biodegradation, electrocoagulation and membrane filtration. Appropriate DC field conditions are adequate for electrolysis; however, they are applied in a discontinuous mode into the MLSS due to their potential impact on the microbial culture. The supplied air considers an adequate amount of oxygen for the microorganisms' metabolism and MLSS mixing without breaking down the flocs.

The following five major parameters controls the SMEBR operation: i) applied direct current (DC); ii) exposure time of MLSS to DC; iii) air supply; iv) hydraulic retention time (HRT); v) sludge retention time (SRT).

The SMEBR system is functioning in the following way: i) supply of wastewater taking place from the outside (primary clarifier or screening) across the perforated anode in order to undergo biological and electrochemical treatment between the electrodes (called Zone I); ii) air flow upward from diffusers for supplying sufficient amount of oxygen for microorganisms to achieve the biological processes and providing a good mixing of the MLSS (additional air is used across the membranes following membrane producer indications); iii) electro-formation of flocs and electro-settling due to the principles of electrokinetic phenomena; iv) treated water flow across the perforated cathode toward the membrane module (called Zone II); v) treated water flow into the membrane due to the vacuum pump connected to the membrane module; vi) separation of liquids (permeate and particles) taking place at the membranes; vii) effluent (permeate) discharge to a disinfection unit.

4. Performance of the SMEBR system

4.1. Experimental SMEBR configuration

After selecting the best electrical parameters for the SMEBR system, the performance of the up-scaled SMEBR was investigated. Figure 2 represents a schematic SMEBR system for the laboratory experiment, which consisted of the following major units: electro-bioreactor, membrane module, wastewater supply system, collecting effluent tank, aeration system, and DC supply system.

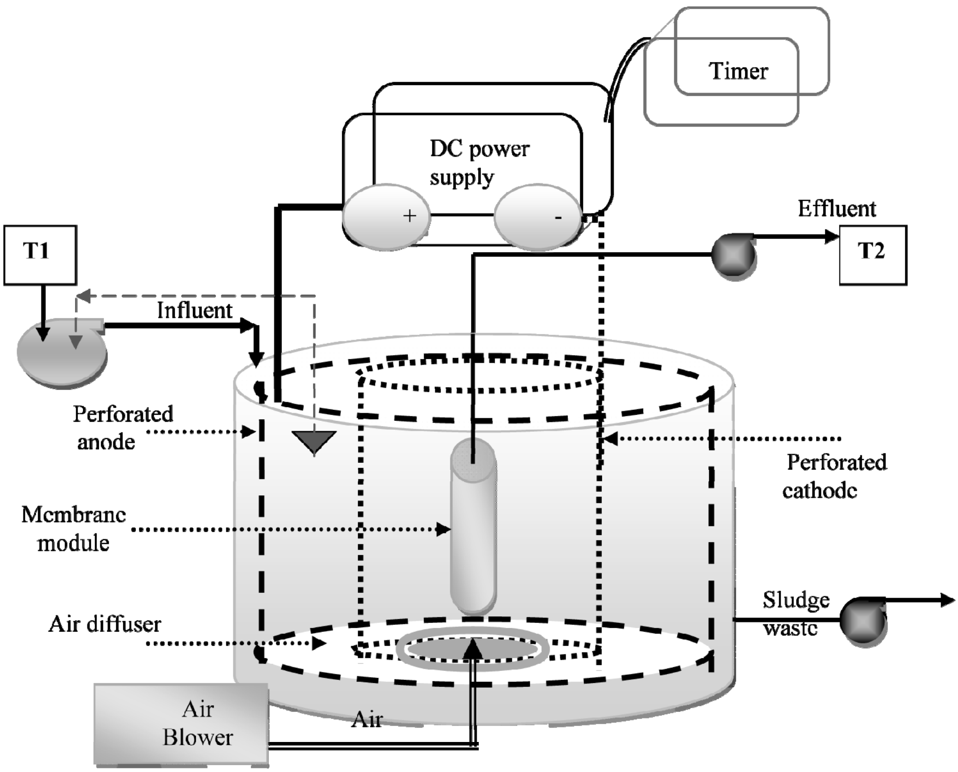

Fig. 2. Simplified configuration of the SMEBR system

The tank of electro-bioreactor had a working volume of 13 L. Centered cylindrical iron mesh cathode and aluminum anode were designed (Zone I). Electrodes were connected to a digital external DC power supply (TES 6230) with possibility of controlling the operating mode (duration of DC supply). The hollow fiber membrane module ZeeWeed-1 (Zenon Environmental Inc., Canada) was fixed vertically in the centre of the electro-bioreactor. Porous air diffusers supplied air continuously to maintain the required dissolved oxygen level above 5 mg/L and agitate the sludge. A feed tank (T1) and the tank (T2) collecting the effluent resulting from membrane filtration process, peristaltic pumps, level sensor completed the design of the SMEBR system.

The SMEBR system was fed with synthetic wastewater to maintain the consistency of the influent composition during the experimental period. The sludge for inoculation was taken from the secondary clarifier of the municipal wastewater treatment plant in the City of Saint-Hyacinthe (QC, Canada). The synthetic wastewater was acclimatized for two months in order to achieve stable conditions prior to the membrane filtration experiments. Initial MLSS were around 3300 mg/L and COD between 300 and 360 mg/L.

Based on preliminary studies (Bani-Melhem 2008), a voltage of 1 V/cm was applied since it was able to maintaining the pH in the mixed liquor solution within the range 5≤ pH≤ 9 during the 6 h of electro-bioreactor operation – pH range acceptable for microbial growth.

In order to study the fouling degree accurately, the process was operated at constant transmembrane pressure mode. The fouling rate was evaluated by measuring the decline of the flux through the membrane. No back washing of the membrane module was performed during the operation. However, in order to enhance the recovery of the membrane permeability during the operating period, the membrane module was periodically taken out of the electro-bioreactor when the permeate flux significantly declined and externally washed with distillate water for few minutes to remove the attached sludge cake particles over the membrane surface.

Other parameters (zeta potential and specific filtration resistance), which have indirect indication about the fouling behavior were also measured. Analyses of COD, phosphorous and ammonia-nitrogen were done on samples from feed tank, each zone and effluent. The response of microorganisms to the SMEBR processes was assessed by the specific oxygen uptake rate (SOUR). During the entire operating period, a volume of about 350 mL per week of sludge was removed for sampling, corresponding to average sludge retention time (SRT) of 200 days.

The operational period (66 days) was divided into four sequential stages, where the Stage I without an input of DC was considered as a reference stage simulating common Submerged Membrane Bioreactor (MBR) conditions. Subsequent Stages (II-IV) simulated the SMEBR systems with a different time of MLSS exposure to DC field in each Stage (Table 1).

Tab. 1 Experimental conditions

Items	Stage I	Stage II	Stage III	Stage IV
Operation time (days)	33	7	17	9
SRT (days)	≈200	≈200	≈200	≈200
Continuous supply of air (DO (mg/L)	5-8	5-8	5-8	5-8
DC voltage gradient (V/cm)	0	1	1	1
DC exposure time (minutes)	0	15 ON / 45 OFF	15 ON / 45 OFF	15 ON / 105 OFF
Strategy of applying DC field	No DC	Simultaneously with operating the membrane module	Before and subsequent simultaneous operation with membrane module	Before and subsequent simultaneous operation with membrane module
Influent temperature (°C)	19-21	19-21	19-21	19-21

4.2 Results and discussion

The output results showed that operating the SMEBR system enhanced the membrane permeability up to 52.5 % for the mode of operation 15 minutes ON / 105 minutes OFF (Stage IV). Furthermore, the SMEBR system did significantly improve the removal of COD and nutrients. Also, effluent had neither color nor odor.

Since the SMEBR system was operated under a mode of constant transmembrane pressure, the permeate flux decreased with time due to the fouling phenomenon. During Stage I, with no input of DC power, the permeate flux dramatically decreased (80% after 5 days of operation only). However, in Stage IV (the mode of 15 minutes ON / 105 minutes OFF), showed reduction of 38% only after 5 days of the continuous operation without any kind of backwashing of the membrane module.

Measuring the pH value in the mixed liquor after introducing DC field in the activated sludge is an important parameter for the study of the impact of applying DC on bacterial growth. In all stages, MLSS had an acceptable pH values between 5.7 (Stage I) and 7.8 (Stage III). In the best performing conditions (Stage IV), pH fluctuated between 6.8 and 7.2. The temperature of the influent and the effluent were close to each other and fluctuated according to the room temperature ($21 \pm 2\ ^oC$).

Starting from Stage II, the results demonstrated that by using the electokinetic phenomena in the SMEBR system, the floc size of the MLSS solution was significantly improved. The measured filtration resistances were compared to the specific resistance to filtration of the MLSS solution at the beginning of the operation of the SMEBR system. According to the Carman-Kozeny the specific resistance to filtration (SRF) of the particles is inversely proportional to the square of particle diameter. The significant decrease in the SRF was observed throughout Stage IV. On day 60, the SRF had decreased by 46 % and 44 % in Zones I and Zone II respectively. The above results are in agreement with those reported in the literature about the significant role of the smaller size particles of the activated sludge on the membrane fouling phenomenon (Lim and Bai, 2003; Chang and Kim 2005).

The improvement in membrane permeability within the SMEBR system can also be confirmed by measuring the zeta potential of the sludge flocs. The application of SMEBR system decreased the zeta potential values from -37 mV to -4 mV in both zones (Stage IV), which means that the colloidal particles of the mixed liquor solution were closed to their isoelectric point – an ideal condition for floc formation.

The total COD removal efficiency of the system was maintained at a high level (93% in Stage I and 98% in Stage IV). It was observed that the COD removal in Stage I was mostly due to membrane filtration; however, the COD removal in Stage IV was in 91% (for a total of 98%) due to other processes (biological and electrochemical) taking place in the SMEBR system. Consequently, applying a DC field to the mixed liquor influences its colloidal fraction and it can reduce the load contributed by the organic matter on the membrane fouling.

The ammonia removal rate fluctuated in the SMEBR system between 98% and 70%. During the operational period, no significant difference in NH_3–N concentration in the sample supernatant between the two zones and the membrane effluent were observed, which implies that the NH_3–N removal was mainly achieved by the electr-bioreactor.

The influent phosphorus as orthophosphate (PO_4-P) varied from 19 to 31 mg/L. During the first period of Stage I, the membrane module has played as an adsorbent support for phosphorous removal; only 82% was removed by coagulation in two zones. Starting from Stage II (after applying the SMEBR system), a dramatic increase in the PO_4-P removal (97%) was observed in the two zones. The improvement in phosphorus uptake continuing during Stages III and IV was associated with Al^{3+} ions from the electrolysis of the aluminum anode and floc formation. Due to simultaneous and subsequent processes, the phosphorous molecules got a better chance to be adsorbed onto these flocs and precipitated. The SMEBR permitted to decrease the membrane load - the total removal in Stage IV reached 98%.

The specific oxygen uptake rate (SOUR) of the activated sludge was also determined in each zone in order to analyze the effect of applying a DC field on microbial activity. In Stage II (reference stage), a reduction in the microbial activity was observed. This was attributed to the acidic conditions in the SMEBR system during this period of operation. After the pH adjustment to neutrality, an increase in the microbial activity was observed. Furthermore, the decrease in microbial activity was less pronounces in Stage IV in comparison with Stages II and III. This might be due to the fact that the exposure time to a DC field in Stage IV was shorter.

The results demonstrated that the energy consumption per cubic meter of the treated wastewater per operating day was lower (0.517 kWh/ m^3.day) in Stage IV in comparison to Stages III and II and its unitary electrode consumption reached 32 g/ m^3.day.

5. Conclusions

The SMEBR system is only hybrid method for sustainable wastewater treatment. The conclusions of lab tests using SMEBR system configuration with aluminum anode can be summarized by the following points: i) SMEBR system can generate excellent quality effluent – superior in reference to “common” submerged membrane bioreactor; ii) permeate has neither color nor odor; iii) the pH value of treated suspensions is close to neutral for the best treatment conditions; iv) large floc size formation and liquid/solids separation is observed due to electrocoagulation; v) membrane fouling can be improved by 58%; vi) the best quality of effluent showed for an operation mode of 15 min ON/105 min OFF, where the removal for COD, ammonia nitrogen, phosphorous reached 97 %, 80% and 98 % respectively.

The SMEBR system can be applied to either large wastewater treatment facilities and mobile units or facilities in remote locations.

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