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Membrane Bioreactor with External Side-Stream Membranes and High Cross Flow Velocity to Treat Municipal Wastewater

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K E Y W O R D S

Membrane bioreactor, Side-stream membranes, Tubular ultra-filters, Water reuse.

A B S T R A C T

In this work, a pilot unit using side-stream MBR configuration was operated in BioFlow mode (i.e. no back pulse) and BioPulse mode (with intermittent back pulses) to treat municipal wastewater with relatively low MLSS. The results showed that the trans-membrane pressure (TMP) was less in the case of BioPulse over the whole period of system operation compared to that of BioFlow mode. However, the energy consumption per unit volume of permeated water is slightly higher in the case of BioFlow mode (3.4 kW.hr/m^3) than that in the case of BioPulse mode (3.2 kW.hr/m^3). Therefore, operation in BioPulse is preferable due to stable TMP caused by nearly fully recoverable fouling type, which results in lower chemical cleaning frequency. The MBR unit showed steady performance at a flux of 60 L/m^2.hr. The system could achieve good water quality that satisfies Iraqi standards requirements for wastewater reuse or discharge to water resources

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1. Introduction

Water reuse is becoming more important as water scarcity increases especially in the arid and semi-arid regions like Iraq. Water resources in Iraq are suffering from a severe shortage in terms of quantity and quality [1]. Therefore, the purpose of wastewater treatment is not only to remove pollutants that can harm the aquatic environment but also to provide another water resource to be used for different purposes. Membrane bioreactors (MBR) technology is an attractive option for treatment and reuse of municipal [2] and industrial wastewaters [3].

MBR is commonly understood as the combination of membrane filtration and biological treatment using activated sludge (AS) where the membrane primarily serves to replace the clarifier in the wastewater treatment system [4]. Compared to conventional AS systems, several advantages of the MBR have been identified which have promoted the development of commercial MBR options. These include better effluent water quality suitable for reuse, compact units with small footprints, complete solids removal, effluent disinfection, operation at higher suspended biomass concentrations resulting in long sludge retention times, low sludge production, and no problems with sludge bulking [5].

One of the major drawbacks of MBR is fouling, which is common for all membrane systems, where the efficacy of the process is constrained by the accumulation of materials on the surface or within the membrane resulting in a reduction in the membrane permeability [6,7].

In general, there are two main MBR configurations that developed in wastewater treatment namely side-stream and submerged configuration. The first one is based on a side stream membrane module position. It is generally developed for the industrial as well as municipal wastewater treatment because of its compactness even if it requires more energy due to the necessity of using high suspension flow rate recycled throughout the membrane module to minimize fouling rates. With this configuration, the membrane maintenance is easy because of the side stream position of the membrane module relative to the bioreactor. The second configuration, submerged MBR, is based on the immersion of the membrane module directly inside the bioreactor. This configuration is more extensive because of functioning under low trans membrane pressure (TMP) and requires low energy requirement because of using air fluid as turbulence supply [8,9]. Though, when some drastic membrane fouling or module clogging occurs, the cleaning protocol obliges to more difficult maintenance [10,11].

However, the main advantages of the side-stream configuration are high permeate flux (75–120 l/m2/hr) in comparison with (20–30 L/m2.hr) for submerged configuration [12] and ability to treat wastewater with extremely high fouling potential in addition to possibility of adding to existed conventional AS wastewater treatment plants to enhance effluent water quality or increase capacity, but the disadvantages are a complex control system with high energy required to generate sufficient sludge velocities across the membrane surface.

MBR system using side-stream configuration can be designed and operated in two distinct modes depending on shear velocity inside the membranes [13]. The first one is BioFlow mode with high velocity inside membranes (3.5–4.5 m/s) to treat extremely high fouling potential wastewater like oily wastewater with a relatively high permeate flux of (75-150 L/m2.hr). The second one is BioPulse mode with low velocity inside membranes (1–2 m/s) with intermittent water back pulse from permeate side to mixed liquor side to treat moderate fouling potential wastewater like industrial or municipal wastewater with a permeate flux of (40-70 L/m2.hr). Recently, Berghof Company has developed another mode (i.e. BioAir Ds), that is equipped with an air distributor fitted at the top of the module to allow air to be injected simultaneously into each individual membrane tube at a fixed and precise rate, for the treatment of low fouling streams [13].

The objective of this work is to operate a pilot unit using a side-stream MBR configuration in the two modes (i.e. BioFlow and BioPulse) to investigate the applicability of this configuration to treat real municipal wastewater.

2. Materials and Methods

I. Materials

Typical influent wastewater quality is presented in Table 1, which can be classified as medium strength wastewater. The activated sludge was hardly settled with sludge volume index (SVI) < 250 ml/gm.

II. Experimental setup and operating conditions

Figure 1 shows a schematic diagram of the 150 L/hr (max.) side-stream MBR system used in this study. The MBR system consists of a bioreactor aerated by fine air bubble distributors with hydraulic retention time (HRT) of about 8 hr; one of FRP (fiberglass reinforced plastic) casing side-stream membrane module of 3 inches in outer diameter and 1.5 m in length contains bundle of in/out PVDF (polyvinylidene fluoride) tubular ultrafilter membranes type is 66.03.18LE manufactured by Berghof Membrane Technology Co., 8 mm in nominal diameter with pore size 0.03 μ and membranes total area in the module of 2 m2; variable speed mixed liquor circulation pump (25 m3/hr at 1 bar.g) to circulate the mixed liquor between the bioreactor and the membrane module sufficient to achieve maximum cross-flow velocity inside the tubular membranes of 2.5 m/sec; variable speed permeate suction pump (1 m3/hr at 1 bar.g) capable to withdraw water and creating a negative pressure in the membrane module casing; backwash/back pulse system and cleaning-in-place system. During back pulse phase, the cross-flow velocity inside the tubular membranes is attained at 0.5 m/s to reduce the pressure inside these tubular membranes. The back pulse flux is 150 L/hr.m^2. During the experiments with BioPulse mode in this work, the back pulse duration is adjusted to 4 min and the normal operation period between each two successive back pulses is adjusted to 30 min. The operation of the MBR system is controlled automatically by a PLC (programmable logic control). The whole system excluding the bioreactor, backwash tank and CIP (cleaning in place) tank (shown in Figure 1) is supplied by Berghof Membrane Technology Co.

Table 1: Typical influent wastewater quality

No.	Parameter	Concentration (mg/L)
1	COD	300 - 350
2	BOD	180
3	TN	30
4	NH_3-N	20
5	TSS	100
6	TP	5

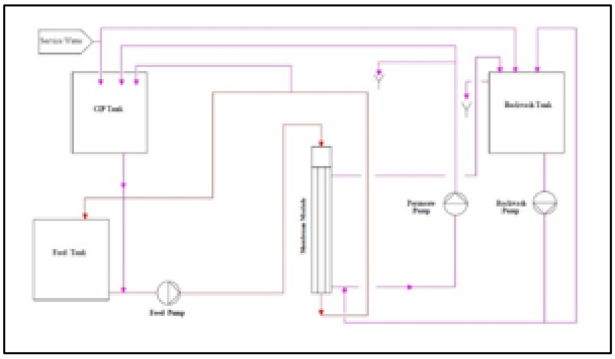

Figure 1: Schematic diagram of the pilot-plant side-stream MBR system

The influent to the side-stream MBR system was real municipal wastewater that was collected daily on the same time from an on-campus sewer line at the Ministry of Science and Technology. The ambient temperature throughout the operation period was in the range 20-25 ºC. The mixed liquor suspended solids (MLSS) concentration was about 3,000 mg/L. The dissolved oxygen concentration in the bioreactor was in the range of 7.0-8.0 mg/L. The sludge discharge is adjusted so that an approximately constant MLSS was maintained in the bioreactor throughout the operation period. Different runs were done by changing the cross-flow velocity of mixed liquor inside the tubular membranes in the range 1-1.5 m/s. Permeate flow value was held approximately constant at 100 L/hr (equivalent to permeate flux of 50 L/m^2.hr). Chemical cleaning to the membrane module was done after each run to remove fouling and recover its hydraulic characteristics. The performance of the system is regularly monitored in terms of mixed liquor circulation flow rate, permeate flow rate, permeate side suction pressure and pressure drop between membrane module inlet and outlet. The circulation flow rate and permeate flow rate were controlled and measured by magnetic type flow transmitters. Pressures at the inlet, outlet and permeate side of the membrane module were measured by three pressure transmitters. The trans-membrane pressure (TMP) was determined as:

$$TMP = \frac{P_1 + P_2}{2} - P_3 \qquad (1)$$

The flux of permeated water is determined approximately as:

$$Permeate\ Flux = \frac{Q_p}{A} \qquad (2)$$

Note that average values of P_1, P_2, and P_3 during the normal operation intervals of the module are used to evaluate Eq.'s (1&2).

Where،

P_1 is inlet pressure of the membrane module (bar.g).

P_2 is outlet pressure of the membrane module (bar.g).
P_3 is permeate side pressure of the membrane module (bar.g).
Permeate Flux is permeate flow rate per unit area of membrane surface (L/m^2.hr).
Q_p is permeate flow rate (L/hr).
A is the membrane surface area (m^2).

II. Analytical methods

Chemical oxygen demand (COD), total nitrogen (TN), ammonia (NH_3-N) and total phosphate (TP) were measured using spectrophotometer (DR-5000 Hach). Biological oxygen demand (BOD_5) was measured with OxiTop®, WTW system. TSS and MLSS are done as per standard methods (APHA, 2012).

3. Results and Discussion

I. Effluent water quality

Table 2 presents the effluent water quality from the side-stream MBR system throughout the experiments. It is clear that the system could achieve good COD and BOD_5 removal. Both values are below maximum permissible limits according to Iraqi standards for wastewater reuse or discharge to water resources. NH_3-N is below 2 mg/L which indicates high nitrification efficiency in the bioreactor. This can be attributed to the high sludge age providing an opportunity for nitrifying bacteria growth. The effluent water that permeated through the membrane module is very clear and the concentration of total suspended solids is negligible throughout the operation time. That means that the membrane module works well without any defect (leak or crack) throughout the operation period.

II. TMP & energy consumption

Figure 2 shows the variation of TMP with the time of operation for both modes (i.e. BioFlow and BioPulse) at a cross-flow velocity of 2 m/sec. The figure reveals a steady increase in TMP when the permeate flux was 50 LMH (l/m2.hr) in case of BioFlow mode. After about fifteen days from the beginning of system operation, the TMP reached about 0.6 bar.g. This can be attributed to insufficient shear stress and self-scouring done by mixed liquor flow inside the tubular membranes to prevent fouling, so an increase in cross-flow velocity or intermittent back pulses is needed to restore its initial permeate flux. The TMP was approximately constant during fifteen days of system operation when the system was operated in BioPulse mode.
Figure 3 compares the energy consumption per unit volume of permeated water when the system was operated in BioFlow and in BioPulse modes. It is clear that the consumed energy was approximately constant during fifteen days of operation for both modes. They were about 3.4 and 3.2 kW.hr/m3 for BioFlow and BioPulse modes, respectively. Since the contribution of energy consumption due to cross flow velocity (high circulation rate) is much more than that due to permeation rate throughout the tubular membranes, the approximately constant value of the consumed energy per unit volume of permeated water could be attributed to that an increase in TMP did not result from increase in cake layer thickness on the membrane internal surface, which in turn might reduce the effective internal diameter of the tubular membranes and higher pressure drop between inlet and outlet of the membrane module, rather the TMP is resulted from internal pores blockage inside the membranes. The pore blockage was recoverable that membrane's flux could be restored using back pulses cleaning in BioPulse mode.
Figure 4 shows the change of TMP with time when cross-flow velocity was reduced to 1.5 m/sec. The figure shows a steady increase in TMP when the permeate flux was 50 L/m^2.hr in case of BioFlow mode at a higher rate than that when the cross-flow velocity was 2 m/sec. After about ten days from the beginning of system operation, the TMP reached about 0.6 bar.g. The TMP was approximately constant during fifteen days of system operation when the system was operated in BioPulse mode. In this mode, the energy consumption per unit volume of permeated water is much less when the cross-flow velocity was 1.5 m/sec (1.3 kW.hr/m^3, Figure 5) than that of 2 m/sec (3.2 kW.hr/m^3, Figure 3).

Table 2: Effluent Wastewater quality

Parameter	Concentration (mg/L)	Environmental Regulations limits
COD	< 40	100
BOD_5	< 10	20
NH_3-N	< 2	5
TSS	Nil.	30

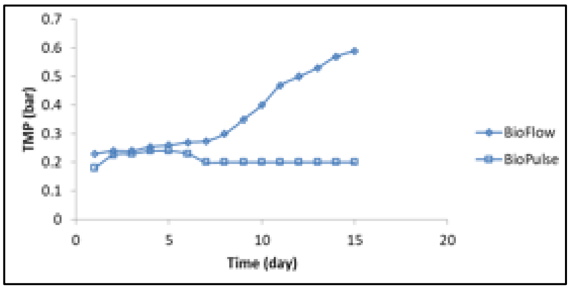

Figure 2: Variation of trans-membrane pressure with time (cross-flow velocity=2 m/sec, Permeate Flux =50 L/hr.m^2, MLSS = 3,000 mg/L)

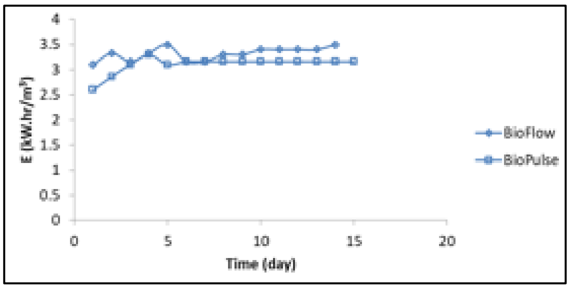

Figure 3: Variation of energy consumption per unit volume of permeated water with time (cross-flow velocity=2 m/sec, Permeate Flux =50 L/hr.m^2, MLSS = 3,000 mg/L)

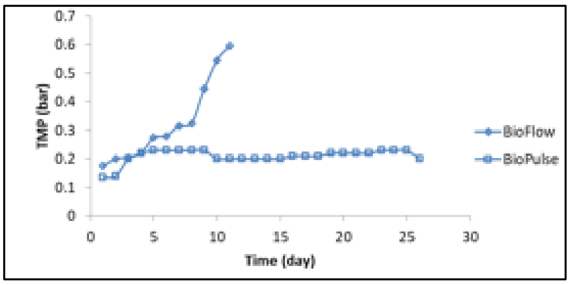

Figure 4: Variation of trans-membrane pressure with time (cross-flow velocity=1.5 m/sec, Permeate Flux =50 L/hr.m^2, MLSS = 3,000 mg/L)

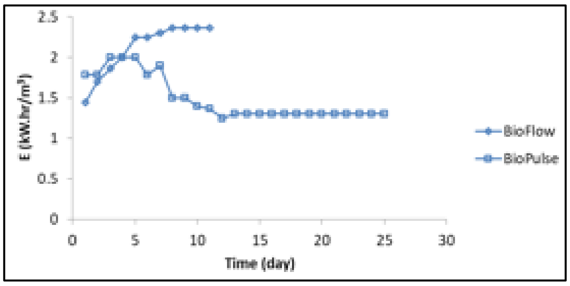

Figure 5: Variation of energy consumption per unit volume of permeated water with time (cross-flow velocity=1.5 m/sec, Permeate Flux =50 L/hr.m^2, MLSS = 3,000 mg/L)

Figure 6 shows the variation of TMP with time when cross-flow velocity was adjusted to 1 m/sec. The figure reveals a sudden increase in TMP in BioFlow mode while a steady increase in TMP in BioPulse mode was recorded. After about three days from the beginning of system operation in BioFlow mode, the TMP reaches about 0.6 bar while it took 12 days to reach this value in case of BioPulse mode. That is why we only see three points in Figure 6 and Figure 7 for the BioFlow mode experiment. It is clear that in this case, the performance of system in BioFlow mode is unacceptable while it was more attractive in BioPulse mode. In addition, the consumed energy per unit volume of permeate in BioPulse mode was relatively low compared to that of the BioPulse mode as shown in Figure 7. Higher frequency of back pulses may give better results in case of BioPulse.

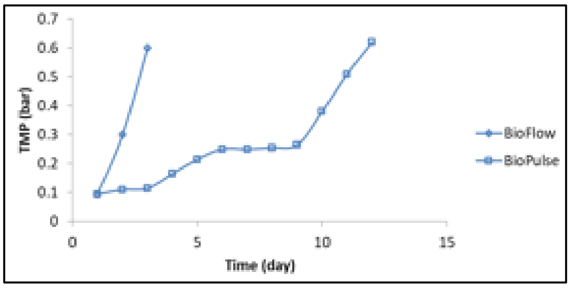

Figure 6: Variation of trans-membrane pressure with time (cross-flow velocity=1 m/sec, Permeate Flux =50 L/hr.m^2, MLSS = 3,000 mg/L)

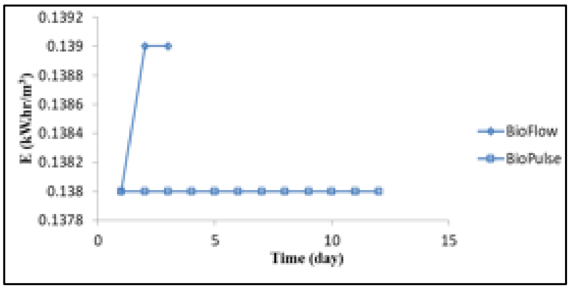

Figure 7: Variation of energy consumption per unit volume of permeated water with time (cross-flow velocity=1 m/sec, Permeate Flux =50 L/hr.m^2, MLSS = 3,000 mg/L)

III. *Feed flow rate*

Figure 8 shows the variation of TMP with time for different permeate flux when cross-flow velocity was adjusted to 2.5 m/sec in BioFlow mode. The figure reveals a steady increase in TMP when the permeate flux was 75 L/m2.hr. After about eight days from the beginning of system operation, the TMP reached about 0.6 bar.g. This can be explained by that higher flux resulted in higher fouling rate that caused the increase in TMP. An increase in cross-flow velocity or intermittent back pulses is recommended to recover the performance of the system. The TMP was approximately constant during eight days of system operation when the permeate flux was 60 and 50 L/m3.hr.

Energy consumption per unit volume of permeated water for the different permeate flux is presented in Figure 9. After one day of system operation, the consumed energy was 1.45, 1.15 and 1.11 kW.hr/m3 for permeate flux of 50, 60 and 75 L/m2.hr respectively. It was clear that lower flux resulted in higher consumed energy per unit volume of permeate since the mixed liquor circulation rate was the same for the three cases.

IV. *Backwash*

The side-stream MBR system is designed to control the permeate flux using variable speed permeate suction pump (1 m^3/hr at 1 bar.g) capable to withdraw water and creating a negative pressure in the membrane module casing so that the permeate flowrate between successive back pulses in case of BioPulse mode is constant as shown in Figure 10.

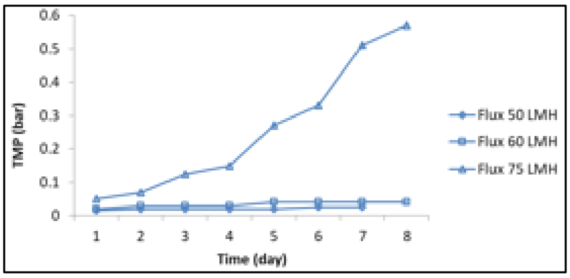

Figure 8: Variation of trans-membrane pressure with time (cross-flow velocity=2.5 m/sec, MLSS = 3,000 mg/L)

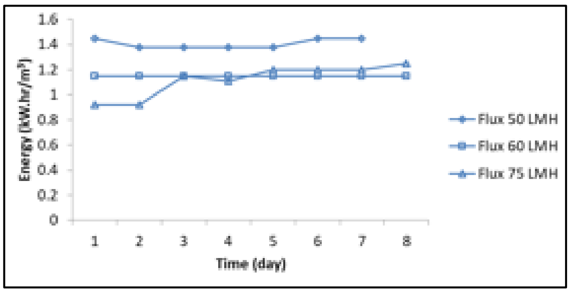

Figure 9 Variation of energy consumption per unit volume of permeated water with time at different permeate (cross-flow velocity=2.5 m/sec, MLSS = 3,000 mg/L)

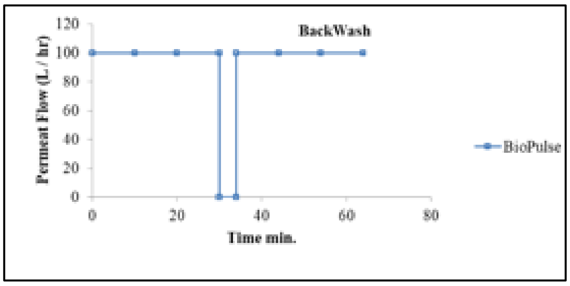

Figure 10: Change of permeate flowrate during a typical cycle when the system is operated in BioPulse mode

4. Conclusions

The performance of pilot plant side-stream MBR in two modes (i.e. BioFlow and BioPulse) for the treatment of real municipal wastewater was tested in this paper. Increasing the cross-flow velocity resulted in better performance even the energy consumption was relatively higher. The pilot plant system showed steady performance at permeate flux below 60 LMH. The results also showed that BioPulse mode is more suitable in treatment of municipal wastewater at the tested conditions. Further research on the BioAirDs mode is recommended to compare it with the BioFlow and BioPulse modes.

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