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Data envelopment analysis for assessing optimal operation of an immersed membrane bioreactor equipped with a draft tube for domestic wastewater reclamation

Amos Bick[a,b], Fei Yang[b], Semion Shandalov[b], Gideon Oron*[,b,c,d]

[a]*Department of Industrial Engineering and Management, Jerusalem College of Technology, Jerusalem, 91160, Israel*
email: amosbick@walla.com
[b]*J. Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Kiryat Sde Boker, 84990, Israel*
email: feiyang@bgu.ac.il; shandalo@bgu.ac.il; gidi@bgu.ac.il
[c]*Department of Industrial Engineering and Management, and the program for Environmental Engineering, Ben-Gurion University of the Negev, Beer Sheva, 84105, Israel*
[d]*The Grand Water Research Institute, Technion, Haifa, 32000, Israel*

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Abstract

Membrane fouling can be minimized by air lifting that plays a key role in cake removal from membrane surface. This study presents the results of tests that were carried out at Kiryat Sde-Boker, Israel, and focuses on the influence of hydrodynamic conditions on membrane fouling in a pilot-scale Immersed Membrane Bio-Reactor (IMBR) using a hollow fiber membrane module of ZW-10 (Zenon Environmental, Canada) under ambient conditions. In this system, the cross-flow velocities across the membrane surface were induced by a cylindrical draft-tube. The relationship between cross-flow velocity and aeration strength and the influence of the cross-flow on fouling rate (under various hydrodynamic conditions) were investigated using Data Envelopment Analysis (DEA).

According to DEA, Technical Efficiency (TE) is defined as the ratio between outputs and inputs of the system [in this case the inputs are: feed temperature and trans-membrane pressure and the outputs are: normalized flux and fouling rate (change of membrane pressure drop with time)].

The developed DEA model for 2# draft tube, Ø = 235 mm allows further modification by changing the input-output variables and analyzing a broad pattern of possibilities. Data normalization of the field results and implementing the DEA approach with reference to the technical efficiency is for that reason useful to characterize performance changes for data classification and detecting deviations from expected behavior of the system.

*Corresponding author.

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1. Introduction

The scarcity of water resources in arid and semi-arid areas of the world, especially in the Middle East region, has changed public attitude towards wastewater management. Adequate management of wastewater is now a necessity, not an option.

Membrane BioReactor (MBR) in which membrane separation process is combined with biological processes is an efficient alternative for wastewater treatment and reuse [1]. The MBR presents many advantages over conventional processes due to its' high organic loading rate, improved effluent quality, small footprint and low surplus sludge production [2]. However, the major process problem with MBRs remains the membrane fouling due to the physicochemical interactions between the membrane material and the components in the mixed liquor. Fouling results in a permeate flux decrease or Trans-Membrane Pressure (TMP) increase over time when the process is operated under constant-TMP or constant-flux conditions, respectively. Along with the fouling, membrane permeability decreases and energy demand increases.

In immersed MBR (IMBR), hydrodynamic characteristics, which vary with various operating conditions, play an important role concerning membrane fouling and system performance. A crossflow, induced by air bubbles rising from a diffuser below the membrane modules, creates shear stress and generates a mass back-transport of the deposited particles along the membrane surface. The crossflow has proved its' efficiency for minimizing membrane fouling [3].

The purpose of this study is threefold: (1) to investigate the membrane fouling rate under different operating conditions, (2) to optimize the performance of an IMBR system which was equipped with a hollow fiber membrane module and a draft tube, and; (3) to estimate the application of operational research tool of Data Envelopment Analysis (DEA) for performance analysis. Results from the first stage of operation of the IMBR are presented.

2. Management modeling

2.1. General

Management modeling provides effective means of rapidly testing and evaluating different scenarios for a given system operated under diverse conditions. Well-defined models allow examination diverse hypothetical situations, which yield perceptive insight into the analyzed phenomena. The various aspects of IMBR can be viewed at the following levels: (1) the local level of the isolated process: economic, chemical, microbial and membrane performance criteria [4], and; (2) at the regional level of water sources utilization, including membrane technology issues [5]. At this level, IMBR performance is only one link in a multi-component system. Other phases to be considered in management modeling include environmental considerations, disposal of concentrates, regulatory and risk issues [6].

2.2. Data envelopment analysis

Data Envelopment Analysis (DEA) was first introduced as a general method for classifying a population of observations and was designed as a decision support tool for complex systems, where a large number of mutual interacting variables are involved [7].

According to the DEA theorem, the efficiency of a system is defined as the ratio between outputs of the system and inputs where it is imperative to consider multiple inputs and outputs [8]. The DEA method differs from other decision supporting methods that it does not focus on the complete data set, but rather on individual Decision-Making Units (DMU). These DMU use a variety of identical inputs to produce a variety of identical outputs. It can be assumed that there is data available for n DMUs' (IMBR test records: $j = 1,2, \ldots, n$). In order to find the efficiency of a specific k test record, the following optimization problem has to be solved [9]:

$$\text{Max}\left(\sum_{r=1}^{R} \alpha_r \cdot y_{rk} / \sum_{i=1}^{m} \beta_i \cdot x_{ik}\right) \quad k = 1,2,\ldots,K \tag{1}$$

subject to a series of constraints given by:

$$\left(\sum_{r=1}^{R} \alpha_r \cdot y_{rj} / \sum_{i=1}^{m} \beta_i \cdot x_{ij}\right) \le 1 \quad j = 1,2,\ldots,n \tag{2}$$

$$\alpha_r \ge 0,\ \beta_i \ge 0 \quad r = 1,2,\ldots,R \ i = 1,2,\ldots,m \tag{3}$$

where y_{rj} is the output of the IMBR quality parameter of the j monitored entity (sampling time of one system), x_{ij} is the input of the bioreactor quality parameter of the i monitored entity (by common $i \neq j$), R is the number of output types (IMBR quality parameters), m is the number of input types (bioreactor quality parameters), α_r is a decision variable related to a weight factor of quality parameter r for the k record, and similarly β_i is a decision variable related to the weight factor of the effluent quality parameter i for the k tested record.

The purpose of the objective function is to maximize the ratio of the weighted outputs *vs.* the weighted inputs for the DMU under consideration. The optimum is found subject to the condition that the ratio for all DMUs' will be less than or equal to one [Eq. 2]. It is rather complicate to solve the above model and in order to avoid infinite number of solutions the constraints [Eq. 4] are applied in a Linear Programming (LP) formulation.

$$\sum_{i=1}^{m} \beta_i \cdot x_{ik} = 1 \tag{4}$$

The k test record and the objective function F are given by [9]:

$$\text{Max } F = \sum_{r=1}^{R} \alpha_r \cdot y_{rk} \qquad k = 1,2,\ldots,K \tag{5}$$

subject to

$$\sum_{r=1}^{R} \alpha_r \cdot y_{rj} - \sum_{i=1}^{m} \beta_i \cdot x_{ij} \le 0 \quad j = 1,2,\ldots,n \tag{6}$$

$$\sum_{i=1}^{m} \beta_i \cdot x_{ik} = 1 \qquad k = 1,2,\ldots,K \tag{7}$$

$$\alpha_r \ge 0,\ \beta_i \ge 0 \quad r = 1,2,\ldots,R \ i = 1,2,\ldots,m \tag{8}$$

Alternatively, the DEA model can be described by using the dual LP formulation [9]:

$$\text{Min } Z_k \qquad k = 1,2,\ldots,K \tag{9}$$

subject to

$$\sum_{j=1}^{n} y_{rj} \cdot \lambda_j - y_{rk} \ge 0 \quad k = 1,2,\ldots,K \ r = 1,2,\ldots R \tag{10}$$

$$z_k \cdot x_{ik} - \sum_{j=1}^{n} x_{ij} \cdot \lambda_j \geq 0 \qquad (11)$$
$$k = 1, 2, \ldots, K \; i = 1, 2, \ldots, m$$

$$\lambda_j \geq 0 \qquad j = 1, 2, \ldots, n \qquad (12)$$

where Z_k expresses the Technical Efficiency (TE) of the k test record ranging from zero to one (scalar) and the vector λ_j is an $n \times 1$ matrix of weights (constants). When Z_k is equal to one, the DMU is on the frontier and is technically efficient. If $Z_k < 1$, then the DMU lies below the frontier and is technically less inefficient.

3. Materials and methods

3.1. Experimental setup

The schematic diagram of the experimental setup is showed in Fig. 1. The pilot MBR was equipped with a hollow fiber ultrafiltration (UF) membrane module of ZW-10 (Zenon Environmental Inc., Canada). The cylindrical module was submerged in a 190 L (working volume) drum-tank and operated under constant-flux mode. The membranes had a nominal pore size of 0.04 μm and a total filtering surface area of 0.93 m^2. A 2# draft tube, Ø = 235 mm was used to induce the crossflow velocity. The draft-tube was located in the centre of the bioreactor and divided the bioreactor into a riser zone, where the membrane module was submerged in the centre, and a downcomer zone, which was connected by a bottom flow channel and an upper flow channel. Air supply was maintained by coarse air bubble sparkling from 4 small holes (Ø = 2 mm) which were located at the bottom of the membrane bundle.

3.2. Operating conditions

The experiments were conducted under ambient conditions in the Sde Boker campus, Ben Gurion University of the Negev, Israel. Domestic wastewater was taken from the mobile houses (Caravans) residential area in Kiryat Sde-Boker, and fed into the bioreactor through a 0.8 mm screen. Initially, the bioreactor was inoculated with the activated sludge collected from the Beer Sheva Municipal Wastewater Treatment Plant.

During the operating period, excess sludge was discharged daily to maintain the concentration of Mixed Liquor Suspended Solids (MLSS) around 6.5 g/L. The average SRT

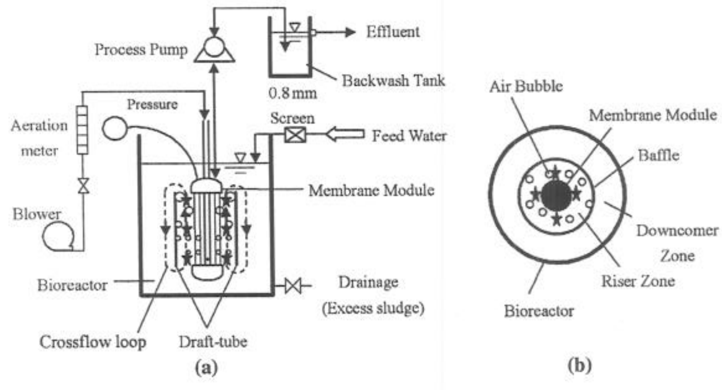

Fig. 1. Schematic diagram of the MBR. (a) Sectional figure ; (b) Above view. ★ indicates velocity measuring points.

was 30 days. The permeate was intermittently extracted with a suction mode of 5 min extracting/15 seconds backwashing. The experiments were manipulated under combined hydraulic conditions with different aeration rates and different permeate rates, according to the scheme of the integrated experimental design. The temperature range in the reactor during the operating period was 6.1 to 31.1°C with the mean of 19.5°C.

During each experimental stage, at the end of each test, stopping suction, aeration at 3.4 m^3/hr without filtration was continued for 24 h to remove sludge deposited on the membrane surface. Then the next test was conducted. Chemical cleaning with a 750 mg/L sodium hypochlorite solution was carried out after each experimental stage for the membrane permeability recovery.

Filtration performance was evaluated by fouling tendency. Under constant-flux mode, TMP increase over time *(dP/dt)* indicates membrane fouling rate. In order to determine the fouling rate for the conditions tested, a flux-step method was employed (Germain *et al.*, 2005): without backwashing, increased permeate flux step by step with a step duration of 1.5 h. Between each step, the membrane was backwashed with permeate for 30 min in order to eliminate the reversible fouling built up during one step to be transferred to the next step.

Flux-step method was used to determine membrane fouling rate under the combinations between permeate flux and aeration rate (1.7, 2.55, 3.4, 4.25, 5.1 m^3/hr) in 2# draft tubes. The permeate fluxes at different temperature were normalized to 20°C according to Eq. (13) (Bersillon and Thompson, 1998):

$$J_{20} = J_t \times \frac{\mu_t}{\mu_{20}} = J_t \cdot e^{-0.0239(T-20)} \qquad (13)$$

where J_t is the permeate flux at t time, L/(m^2.hr); J_{20} is the normalized permeate flux (at 20°C), L/(m^2.hr); μ_t and μ_{20} is the viscosity of permeate at t time and 20°C, mPa.s, respectively; T is the temperature at t time,°C.

The airflow rate was controlled by a rotameter. The filtration flux was monitored using a volumetric method. The TMP was monitored by a digital pressure indicator. The mixed liquor temperature was monitored by a temperature indicator located on the reactor wall. The effluent temperature was detected using a thermometer.

The crossflow velocities were measured by an electromagnetic flow velocity meter (Model 2000, Marsh-McBirney, USA) at 12 measuring sites (Fig. 1), respectively. For each site, the observed flow velocity was an average of 6 measured values. The final adopted crossflow velocities were the mean values of the observed data.

4. Results and discussion

According to test results, fouling rate was reduced significantly with the increase of aeration rate (Fig. 2). However, the effect tended to be very close when aeration rate was beyond 3.4 m^3/h.

According to DEA, Technical Efficiency (TE) is defined as the ratio between outputs and inputs of the system and Fig. 3 presents the Technical Efficiency [in this case the inputs are: feed temperature and trans-membrane pressure and the outputs are: normalized flux and fouling rate prevention (minimum change of membrane pressure drop with time) Table 1].

According to the experimental data the TE measure is preferable on the flux decline illustration: (1) it takes into account the temperature and the TMP, and; (2) the new variable clearly shows the effect of aeration (data is not close when aeration rate was beyond 3.4 m^3/h).

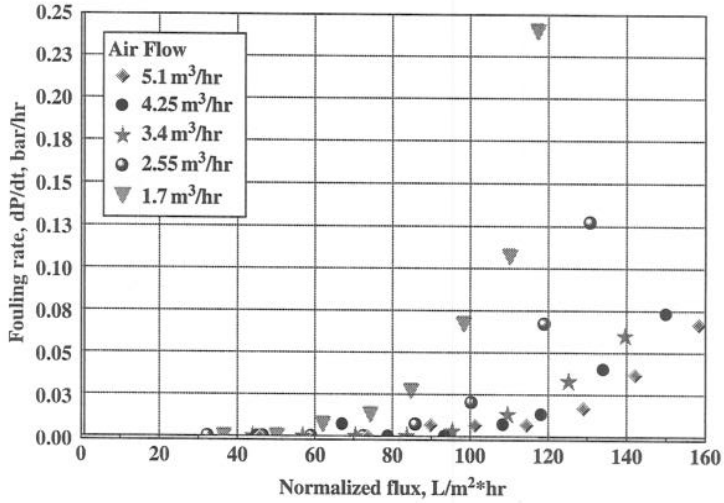

Fig. 2. Fouling rate dP/dt vs. permeate flux J_{20} at different aeration rate in the 2# tube.

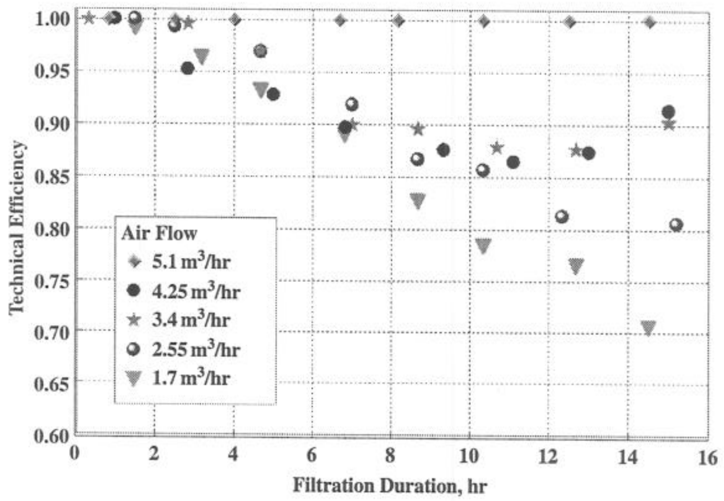

Fig. 3. Technical Efficiency vs. filtration hours at different aeration rate (2# draft tube, Ø = 235 mm).

5. Conclusions

This study evaluates the performance of an IMBR for domestic wastewater reclamation and reuse in an isolated site in an arid land. The technical efficiencies of the IMBR performance are assessed using a DEA model. The procedure allows determining the relative technical efficiency (as a function of temperature, trans-membrane pressure, normalized permeate flux and fouling prevention). The results indicate that aeration plays an important role in IMBR data analysis. Implementing the DEA approach with reference to the technical efficiency is consequently useful to characterize performance changes for data classification and detecting deviations from expected performance of the system.

Table 1
A sample of IMBR pilot plant DEA parameters (Air flow 5.1 m^3/h)

DMU (Decision Making Unit)	Accumulated Operating Hours	Input		Output	
		Temp.°C	TMP bar	Permeate Flux Liter/m^2-h	0.5-dP/dt bar
1	0.83	27.5	0.09	45.7	0.500
2	2.5	25.2	0.15	73.5	0.500
3	4	25.0	0.20	89.8	0.493
4	6.67	25.4	0.25	101.2	0.493
5	8.17	26.2	0.30	114.4	0.493
6	10.33	26.2	0.35	128.9	0.483
7	12.5	26.0	0.42	142.2	0.463
8	14.5	26.6	0.51	158.3	0.433

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References

[1] G. Oron, A. Bick, L. Gillerman, N. Buriakovsky, Y. Manor, E. Ben-Yitshak, L. Katz and J. Hagin, A two-stage membrane treatment of secondary effluent for unrestricted reuse and sustainable agricultural production, Desalination, 187 (2006) 335–345.

[2] A. Bick, J.P. Plazas and G. Oron, Immersed Membrane Bioreactor (IMBR) for treatment of combined domestic and dairy wastewater in an isolated farm, Water Sci. Technol., 51(10) (2005) 327–334.

[3] A. Sofia, W.J. Ng and S.L. Ong, Engineering design approaches for minimum fouling in submerged MBR, Desalination, 160 (2004) 67–74.

[4] N. Cicek, M.T. Suida, P. Ginestet and J.M. Audi, Impact of soluble organic compounds on permeate flux in an aerobic membrane bioreactor, Environmental Technology, 24 (2002) 249–256.

[5] G. Oron, Management modeling of integrative wastewater treatment and reuse systems, Water Sci. Technol., 33(10–11) (1996) 95–105.

[6] M. C. Mickley, Membrane concentrate disposal: practices and regulation, U.S. Department of The Interior, Bureau of Reclamation Technical Service Center Water Treatment Engineering and Research Group, Program Report No 69, 2001.

[7] A. Charnes, W.W. Cooper and H. Rhods. Measuring the efficiency of decision-making units, Eur. J. Oper. Res., 2 (1978) 429–444.

[8] N.S. Partangel, The relationships between process and manufacturing plant performance: a goal programming data envelopment analysis approach, Master thesis, Department of Industrial and Systems Engineering, Faculty of Virginia Polytechnic Institute, 1999.

[9] I. Fraser and D. Cordina, An application of data envelopment analysis to irrigated dairy farms in Northern Victoria, Australia, Agric. Systems, 59 (1999) 267–282.

[10] E. Germain, T. Stephenson and P. Pearce, Biomass characteristics and membrane aeration: toward a better understanding of membrane fouling in submerged membrane bioreactors (MBRs), Biotechnol. Bioeng., 90(3) (2005) 316–322.

[11] J. Bersillon and M.A. Thompson, In situ evaluation and operation in water treatment membrane processes, McGraw-Hill, Madrid, 1998.