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Comparative performance evaluation of microfiltration submerged and pressurized membrane treatment of wastewater

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ABSTRACT

Continuous microfiltration (CMF) submerged or pressurized membranes, has been widely used recently as a treatment process for the removal of particles and pathogens from water and wastewater. The CMF technology has great potential for wide ranging applications including treatment of surface seawater, municipal and industrial wastewater treatment, groundwater and drinking water. The technical feasibility of this process has been demonstrated through a number of pilot and bench scale research studies in the Kuwait Institute for Scientific Research, Kuwait. Full scale systems are operational in various parts of the world. The CMF process is already considered as a viable alternative for many waste treatments. The emergence of submerged membranes that utilize fairly economical polymer-based membranes and require less energy than external membranes has revolutionized municipal wastewater treatment and has tremendous potential in larger scale, high volume throughput facilities across the globe. This paper discusses the technical and analytical performance of two types of microfiltration system, one with submerged membranes and the other with pressurized membranes. The paper covers performance data and discusses the technical parameters of water productivity and filtrate quality. It also covers the evaluation of membrane performance, system availability and techno-economic study for both systems.

Keywords: Secondary treatment; Backwash; Chemical cleaning; Turbidity

1. Introduction

In Kuwait, continuous urbanization, population growth and the expensive process of producing potable water lead to the necessity of finding other water resources that can be utilized to handle this expansion. Treated wastewater effluent is the only increasing resource that is being generated, due to the high consumption of potable water desalinated by multistage flash technology [1]. Therefore, treated wastewater is regarded as an important water resource in Kuwait, which is an economic source available for extensive and appropriate use. However, this extremely important source of water is met with alarming beliefs that have delayed its proper utilization. Its usage is also hindered by the incomplete elimination of contaminants, and the lack of a distribution network. Therefore, the characteristics of its danger have constrained decision makers in renovating the standard wastewater treatment with new technologies, such as membrane processes, for further reclamation that can meet a variety of human needs.

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Microfiltration (MF) is one of a number of membrane processes which can be used to treat water and wastewater. Membrane configuration in MF can vary between manufacturers, but the "hollow fiber" type is the most commonly used [2]. There are two main configurations associated with hollow fiber, low-pressure membrane systems pressurized and submerged (Fig. 1). Typically, pressurized external membranes (Continuous microfiltration [CMF]) systems run up to 20–30 psi, while the submerged (CMF-S) systems operate between 10 and 12 psi. Some applications, such as groundwater and pretreatment to reverse osmosis (RO) systems, are typically better suited for pressurized configurations. Conventional plant retrofits, for example, are better suited for submerged configurations because they easily fit into existing filter bays. Submerged membranes had successfully replaced the settling clarifier and, thereby, it was possible to operate the system without any concern of biomass settling leading to a significant improvement in the treatment efficiency in terms of the removal of organics and colloidal particles [3]. Membrane separation is carried out either with cross-flow filtration in side-stream membrane bioreactor or with submerged membranes, which operate in dead-end mode. Although the latter have smaller fluxes, they are generally more favored because of the lower energy consumption required for filtration [4].

Treatment of municipal wastewater with MF mostly utilizes the submerged configuration. Although studies on drinking water and groundwater treatment involve mostly external CMF as pesticide removal and denitrification, there is no apparent reason why CMF-S could not be employed in this area [5]. The energy and space saving characteristics of submerged membranes have prompted many to view them as the most efficient and cost effective wastewater treatment technology [6]. The complete retention of sludge allows operation at much higher biomass concentrations. Moreover, in this technique the refreshing of feed along with the membrane is achieved by pneumatics (aeration) rather than by hydraulics; a significant reduction in cost can be obtained if the membranes are cleaned by means of air scouring, rather than by cross-flowing of the feed solution [7].

Several relatively large immersed membrane installations demonstrate the capability of the industry to implement successfully large and small submerged-membrane installations. Moreover, for a continuous bioprocess, sterile operation is a crucial issue, and is greatly affected by the sterility of the integrated units. CMF-S offers a unique advantage in this respect as they are wholly integrated within the system. Thus, no extra care needs to be taken, and the whole system is sterilized at the same time.

More recently, submerged membranes have been introduced. Initially developed to address large-scale installations, submerged membranes are not installed in a pressure vessel, but are placed into a basin. Raw water is introduced into the tank, and filtered water is drawn through the membrane using an extraction pump on the downstream side of the membrane. These systems offer some unique advantages including the flexibility of installing large process cells, thus reducing the number of valves, pumps and piping, and therefore, the system's complexity. Smaller installations can also benefit from the flexible design [8]. Moreover, the decrease in both membrane and process operating costs since the introduction of the submerged technology in 1990 had led to increased economic viability at even larger scales, such that currently the plant sizes range from 10 to 50,000 m^3/d^{-1} [9].

2. Process description of CMF (pressure driven membranes) unit

The MEMCOR 20M 10 CMF units is a MF machine designed to remove impurities larger than 0.2 mm from feedwater.

The machine design is compact and consists of filtration modules, circulation pump, associated valves, pipe work, instrumentation and control system, all mounted in a stainless frame. Installation of required unit electricity, feed supply, compressed air, drains, and filtrate pipe work to the termination points on the machine.

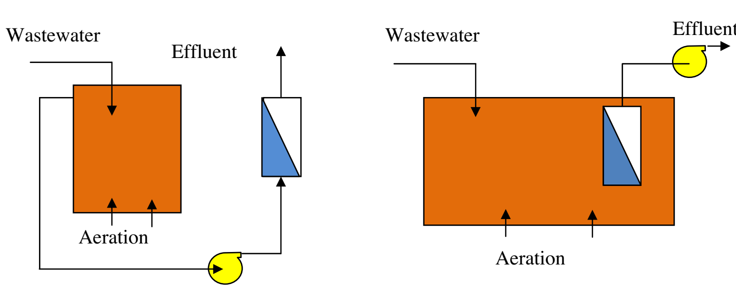

Fig. 1. MF system; external cross-flow (left), submerged (right).

A CMF unit has two MF modules made from polypropylene, and each has a nominal membrane filtration area of 10 m^2. A feed pump drives the raw seawater into the filtration modules from a buffer tank. The process valves are fitted with pneumatic actuators. A programmable logic controller (PLC) mounted in the control cabinet controls the pilot solenoid valves and pump operation. The PLC also monitors various control switches and other inputs, and illuminates the appropriate indicator lamps during machine operation.

After passing through a coarse strainer, wastewater is fed into a break tank, and then fed into the shell side of the two MF modules, where filtration takes place.

The CMF system uses an air backwash stream to clean the hollow fiber membranes. Backwash is automatically controlled by a PLC. Air at high pressure is injected into the center of the hollow fibers and bursts through the membranes, removing the foulants that have accumulated on the membrane.

There are two CMF flow pattern types. Cross-flow filtration is the method of introducing the feed across the surface of the membrane to minimize fouling. Only a percentage of the feed liquid passes through the membrane. The other is direct flow filtration, a method in which the feed stream is fed directly into the membrane surface. All of the feed liquid passes through the membranes. The main advantage of using dead-end (direct flow) CMF in treating the wastewater is that, most of the harmful particles (suspended solids, bacteria and viruses) are rejected, but most of the salts and organic matter (calcium, magnesium, nitrate, etc.) are left that can be of benefit in agriculture use.

3. Process description of CMF-S (submerged membranes) unit

MF is a fine filtration process using a polypropylene membrane filter to remove particles greater than 0.2 μm from a feed stream. The MEMCOR® CMF-S process utilizes hollow fiber membranes to provide a self-cleaning system which can maintain high flow rates by use of combined air scour and liquid backwash cycle. The membranes are assembled to form a "submodule." The CMF-S unit is fitted with four sub modules suspended within a "Membrane Tank." During filtration, the Membrane Tank is filled with feedwater after passing a fine strainer (400 μm) which is installed between the feed line and the CMF-S unit, just above the top of the submodules; the inside (filtrate side) of the membranes is then placed under suction by the filtrate pump. Filtration takes place from the outer surface of the fiber to the hollow inner core. The feed liquid passes through the porous wall of the fiber and the suspended matter remains on the feed side. This filtration process removes solids larger than approximately 0.2 μm. As a guide, bacteria are typically larger than about 1 μm. As deposits build up on the fibers, filtration flow resistance increases resulting in a drop in the filtration flow rate. To reduce the flow resistance and restore the filtration flow rate, the membrane is backwashed. During backwash, filtration is stopped, and the outside of the fibers is exposed to strong air. A small amount of the filtrate is pushed through the fibers (from inside to out) to further remove deposits from the outer surface of the fibers. The tank is then drained to transport any dislodged deposits to the backwash drain lines. The tank is then refilled with feed prior to commencing of filtration. Feedwater enters the bottom of each cell via a central feed channel, and then passes over and around the microporous hollow fiber membranes. Clean water is drawn through the membrane wall by a suction pump into the center of each fiber. The filtrate flow passes from the top of each filtration module rack to a filtrate pump, which incorporates a variable speed drive to enable flow control. The flow from the pump is manifolded into a treated water outlet and passes under pressure to filtrate tank.

The membranes operate in a direct flow using nominal 0.2-μm polypropylene membranes. The CMF-S backwash uses a low pressure air scour and liquid backwash that remove the solids built up on the membrane surface at regular intervals. The key to its success is a proprietary design that allows the air to be delivered evenly into the depths of a highly packed membrane module. Periodically, a chemical cleaning procedure, chemical in place is used to restore membrane performance. A PLC allows the operator to control the operation of the unit. Table 1 presents the

Table 1
Filtration modules specifications

Type	S10
Membrane types	Polypropylene
Membrane area	13 m^2 each
Filtration direction	Outside in
Nominal bubble point	200 kPa
Fiber outside diameter	650 μm + 30 μm
Fiber inside diameter	390 μm + 20 μm
Exposed fiber length	1,050 mm
Number of fiber	14,500 nominal
Length overall	1,186 mm
Diameter overall	131 mm
Weight (dry); (wet)	2.7 kg; 5.6 kg
Volume (lumens)	2.01

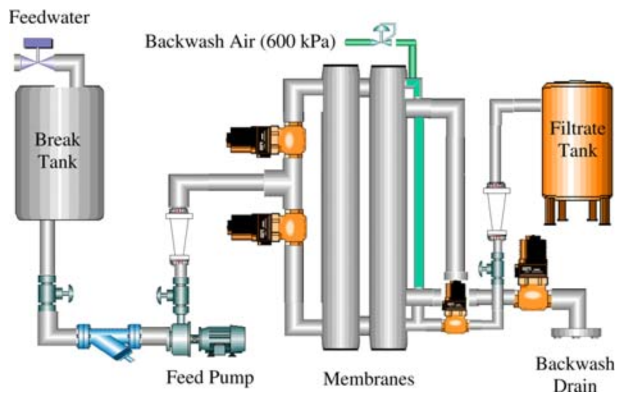

Fig. 2. A schematic diagram of CMF system.

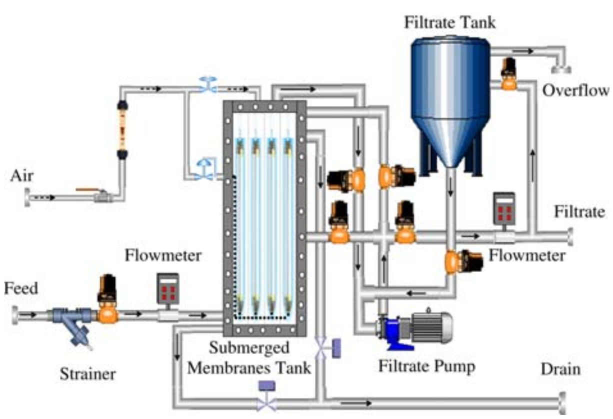

Fig. 3. A schematic diagram of CMF-S system.

specifications of the membranes modules for the two systems. Fig. 2 presents a schematic diagram of the MF system process; whereas, Fig. 3 shows a schematic diagram of the CMF-S system. This paper evaluates the treatment of secondary treated wastewater effluent using both the CMF and CMF-S techniques. Potential saving in capital and operation expenses is expected from such treatment aiming at water reuse. Both units were installed at the Riqqa wastewater treatment plant. The unit treatment capacity is 144 m^3/d and was connected to the secondary effluent. Riqqa Wastewater Treatment Plant is the second largest sewage treatment facility in the State of Kuwait; its design capacity is 180,000 m^3/d, and it serves a population of 220,000. The plant was constructed in 1982, and upgraded in 1995. Wastewater treatment at the Riqqa plant is accomplished through three stages: primary, secondary, and tertiary.

4. Results and discussion

A total of 44 samples, which included 22 feed and 22 filtrate water samples for both CMF-S and CMF units, were collected and analyzed. The results of these analyses are summarized in Tables 2 and 3, where Table 2 presents the chemical and biological analysis for CMF system of the feed and filtrate and Table 3 presents the chemical and biological analysis for CMF-S system of the feed and filtrate.

The analytical results for CMF-S revealed that the feedwater turbidity ranged between 5.08 and 5.34 FTU, whereas the turbidity of the filtrate water ranged between 0.155 and 0.255 FTU. Also, the TSS values of the feedwater ranged between 9.93 and 15.6 mg/l, whereas the total suspended solid (TSS) values of the filtrate water ranged between 0.4 and 0.86 mg/l. It can be seen from Table 3 that CMF-S was capable of reducing the average feedwater turbidity and TSS from 5.23 to 0.184 FTU, and from 13.0 to 0.62 mg/l, respectively.

Similarly, the analytical results for CMF revealed that the feedwater turbidity ranged between 4 and 36 FTU, whereas the turbidity of the filtrate water ranged

Table 2
Chemical and biological analysis of feed and filtrate water for CMF system

	CMF					
	Feedwater			Filtrate water		
Parameter	Max	Min	Ave	Max	Min	Ave
TDS (mg/l)	1,092	628	860	800	580	690
Electrical conductivity (μs/cm)	1,763	1,086	1,424.5	1,759	1,084	1,421.5
PH	7.3	5.81	6.55	7.61	68	7.2
Turbidity (FTU)	36	4	20	10	1	5.5
Total suspended solid TSS (mg/l)	81.4	5.6	43.5	21.4	1	11.2
Bio-Chem: Oxygen Demand BOD_5 (mg/l)	14.62	3.15	8.8	8.5	0.93	4.71
COD (mg/l)	28	11	19.5	22	6	14
Total Bacterial Count (Heterophic) (coloni/100 ml)	3.30E+1	9.20E+5	1.59E+9	3.26E+6	8.46E+2	1.2E+6
E-coli (coloni/100 ml)	4.0E+5	9.6E+4	2.4E+5	0	0	0
Fecal coliform bacteria (coloni/100 ml)	4.44E+6	1.48E+3	2.79E+5	1.5E+4	0	1.65E+3

Table 3
Chemical and Biological analysis of feed and filtrate water for CMF-S system

Parameter	CMF-S					
	Feedwater			Filtrate water		
	Max	Min	Ave	Max	Min	Ave
TDS (mg/l)	797	691	707.6	796	690	714
Electrical conductivity (μs/cm)	1,199	1,040	1,107	1,196	1,037	1,104
PH	7.40	6.24	7.01	7.65	6.42	7.06
Turbidity (FTU)	5.34	5.08	5.23	0.255	0.154	0.184
Total suspended solid TSS (mg/l)	15.60	9.93	13.00	0.86	0.40	0.62
Bio-chem: oxygen demand BOD_5 (mg/l)	5.20	3.0	4.49	2.47	1.0	1.67
COD (mg/l)	24.0	13.0	17.57	18	6.70	7.93
Total bacterial count (Heterophic) (coloni/100 ml)	6.18E+6	4.09E+6	5.04E+6	2.7E+5	1.6E+5	2.2E+5
E-coli (coloni/100 ml)	4.0E+5	9.6E+4	2.4E+5	118	0	104
Fecal coliform bacteria (coloni/100 ml)	5.68E+5	4.53E+5	5.26E+5	107	0	103

between 1 and 10 FTU. Also, the TSS values of the feedwater ranged between 5.6 and 81.4 mg/l, whereas the TSS values of the filtrate water ranged between 1 and 21.4 mg/l. It can be seen from Table 3 that CMF was capable of reducing the average feedwater turbidity and TSS from 20 to 5.5 FTU and from 43.5 to 11.2 mg/l, respectively.

Chemical analysis for both the systems' samples indicated that MF had no significant effect on other constituents of wastewater such as phosphate, nitrite, fluoride and total dissolved solid (TDS). Biological analysis of both feed and filtrate water showed that CMF-S significantly reduced the average total bacterial counts and fecal coliforms from 5.04E+6 to 2.2E+5 (colonies/100 ml), and from 5.26E+5 to 103 (colonies/100 ml) respectively. Also, CMF-S reduced the values of biological oxygen demand (BOD) and chemical oxygen demand (COD) from 4.49 to 1.67 mg/l and from 17.57 to 7.93 mg/l, respectively. The analysis showed no *Salmonella* present in neither feed nor filtrate water.

The treated wastewater contained impurities, which resulted in the accumulation of impurities on the surface of the membranes during operation. Thus, the flux decreased with time, the filtrate pressure decreased, and the transmembrane pressure (TMP) increased. Fig. 4 shows the increases in TMP (i.e. from 25 to 140 kPa). At this point, the unit was stopped, and chemical cleaning of the CMF membrane was carried out to restore the performance of the membranes and avoid fouling. After cleaning, the TMP was improved to 62 kPa. The membranes were chemically cleaned eight times during the operation of the CMF unit. The CMF-S unit was cleaned only once during operation using treated wastewater effluent as shown

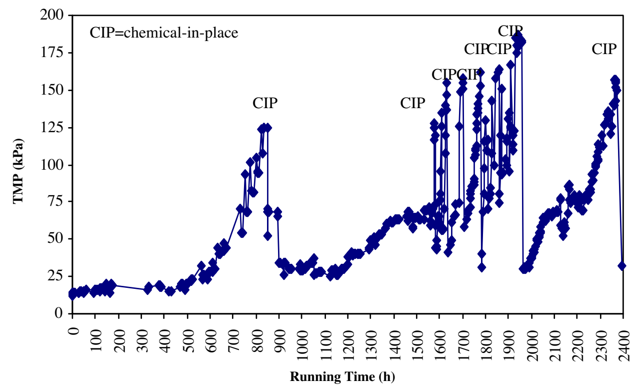

Fig. 4. Running hours vs. TMP of CMF unit.

in Fig. 5. The cleaning was performed, as recommended by the CMF manufacturer. Table 4 shows the shutdown time, the reason for shutdown and the availability of both systems. It can be seen that 87.66 and 98.73% are the availabilities of CMF and CMF-S, respectively. The lower availability of CMF is due to frequent membranes fouling which required several chemical cleaning of the modules.

TMP is the average applied pressure from the feed to the filtrate side of the membrane. TMP is calculated by subscripts

$$\mathrm{TMP(bar)} = \frac{P_f - P_R}{2} - P_F$$

where P_f = the feed pressure, P_R = the retentate pressure, and P_F = the filtrate pressure.

The most important factor causing membrane fouling is the quality of the feedwater. In this study, the

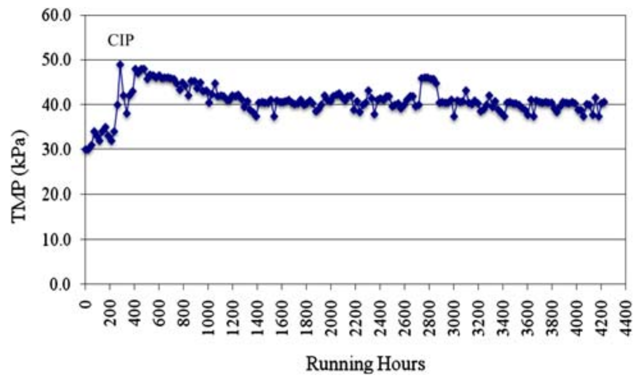

Fig. 5. Running hours vs. TMP of CMF-S unit.

silt density index (SDI) was used as an indicator for feed water quality. The SDI test is used to predict and then prevent particulate fouling on the membrane surface. Other names for it are the Kolloid-Index or the Fouling-Index. The test is defined in ASTM Standard D4189, the American Standard for Testing Material. SDI can be calculated using the following equation:

Table 4
Shut-down time, reasons and availability of the CMF and CMF-S system

Reasons for shut-down	Total time of shut-down (h)
CMF system	
Membranes chemical cleaning	288
Solenoid valve maintenance	2
Solenoid valve replacement	2
Feed pump electric contactor replacement	1
Air filter replacement	1
Feed line pipe replacement due to vibration	2
Total running hours (h)	2,400
Total shut-down (h)	296
Availability (%)	87.66
CMF-S system	
Membranes chemical cleaning	48
Air filter replacement	1
Tank low-level switch maintenance	2
Online conductivity meter maintenance	2
Total running hours (h)	4,200
Total shut-down (h)	53
Availability (%)	98.73

$$SDI_T = \frac{\%\ P_{30}}{T} = \frac{\left[1 - \frac{t_i}{t_f}\right]100}{T}$$

where $\%\ P_{30}$ = percent at 207 kPa (30 psi) feed pressure, T = total elapsed flow time, min (usually 15 min), t_i = initial time required to collect 500 ml of the sample; t_f = time required to collect 500 ml of the sample after, and test time T (usually 15 min).

The effluent produced at the Riqqa Wastewater Treatment Plant varies according to the plant's condition. The SDI of the feedwater measured was high (over 6%), but could not always be measured. The results showed that when the CMF unit was fed with water with a high SDI, a high SDI was also measured on the filtrate side. Fig. 6 shows that the average SDI value during this study was 4.26% whereas, the SDI values when using the submerged type of MF (CMF-S) was 3.0% as shown in Fig. 7. To improve the productivity of both units, regular backwashing of the membranes must be carried out to dislodge and remove foulants from the membranes surfaces. To investigate the effect of backwashing on the membrane flux and productivity, a set of experiments was performed. In these tests, variations in the backwashing sequence were made by setting it to 15, 10 and 25 min, while keeping all other variables constant, including the feed flow rate of 1.0 m^3/h. The results indicated that the best time interval for backwashing the membranes of both units was 25 min.

5. Techno-economic evaluation

The estimates of the unit costs of treated water produced using both techniques are in Table 5. The estimated unit costs of treating water using CMF and

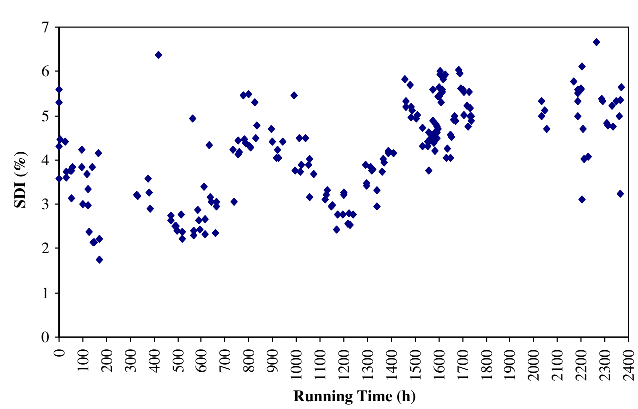

Fig. 6. SDI of the filtrate of CMF unit vs. running hours.

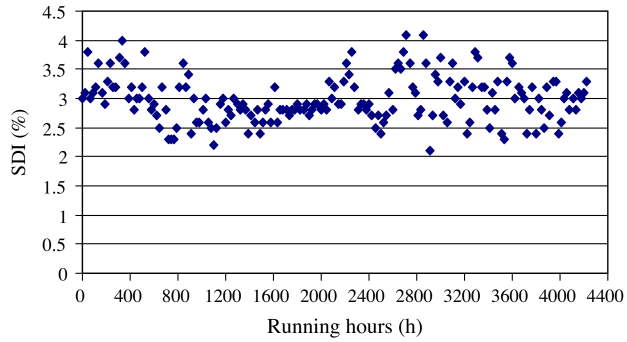

Fig. 7. SDI of the filtrate of CMF-S unit vs. running hours.

CMF-S are KD 0.357/m^3 and KD 0.2096/m^3, respectively.

6. Sensitivity analysis

Table 5 shows the estimated unit costs using a small experimental plant's operating data. A scale-up approach will be used to determine the cost of a large capacity plant (such as the Riqqa Wastewater Treatment Plant). Due to economies of scale, the unit cost for a larger plant is likely to be lower than in a smaller one. The following formula will be used to scale-up the unit cost of the pilot plant:

$$C_x = C_y (Q_x/Q_y)^{\eta}$$

Table 5
Estimates of unit costs of primary and secondary wastewater treatment using CMF for a small experimental pilot plant

Cost		Treatment (KD[a])	
		CMF	CMF-S
A.	*Total unit capital cost (depreciation)*	**0.257**	**0.1294**
A.1	Machinery – MF unit	0.137	0.0801
A.2	Membranes	0.118	0.0481
A.3	Civil work	0.0012	0.0012
	Concrete base and Kirby shade	0.0012	0.0012
B.	*Total unit operating cost*	0.001	**0.0802**
B.1	Manpower	0.101	0.0000
B.2	Electricity unit cost = $(E/Q) * R$	0.013	0.0003
B.3	Chemicals unit cost	0.009	0.0000
B.4	Air compressor (backwash)	0.009	0.0333
B.5	Maintenance and spares (2.5%)	0.069	0.0467
Total unit cost (A + B)		0.357	0.2096

[a]KD 1 equivalent to US$ 3.55.

where C_x = the capital cost for a large plant with a specific capacity, C_y = the capital cost for a small pilot with its actual capacity, Q_x = the capacity of a large plant (120,000 m^3/d), Q_y = the capacity of a small pilot; and η = a parameter representing economies of scale.

The value of η is unknown due to lack of relevant information. So in the study, different assigned values will be used (η = 0.95, 0.90, and 0.95), which imply a modest to reasonable level of economies of scale. Not all the cost components are affected to the same degree by the plant capacity. The most affected component is the capital cost, so for simplicity, an assumption will be made that no economies of scale exist in other components.

Tables 6 and 7 show the variation of the unit cost with different values of η for both the systems. When the economies of scale increase, the estimated unit cost decreases.

For modest economies of scale (η = 0.95), the unit cost of CMF is estimated to be KD 0.223/m^3 and for greater economies of scale (η = 0.85), the unit cost is estimated to be KD 0.155/m^3. Comparing the last unit cost with the one for a conventional wastewater treatment plant (Al-Riqqa with a capacity of 120,000 m^3/d), which is KD 0.165/m^3 assuming an estimated capital cost of KD 39.2 million from Abdel-Jawad [9], with a plant life of 20 years and a unit operating cost of 0.120/m^3 obtained from the Ministry of Public Work (MPW). As a result, using CMF in a large commercial plant has a lower unit cost than the unit cost of using conventional wastewater treatment.

Similarly, for modest economies of scale (η = 0.95), the unit cost of CMF-S is estimated to be KD 0.202/m^3 and for greater economies of scale (η = 0.85), the unit cost is estimated to be KD 0.132/m^3. Comparing the last unit cost with the one for a conventional wastewater treatment plant (Al-Riqqa with a capacity of 120,000 m^3/d), which is KD 0.165/m^3 assuming an

Table 6
Estimates of unit costs of secondary treatment of wastewater using CMF and conventional systems for a large commercial-sized plant (120,000 m^3/d) capacity

Parameter	Economies of scale		
	$\eta = 0.95$	$\eta = 0.90$	$\eta = 0.85$
Capital cost (CMF plant)	0.123	0.082	0.055
Operating cost (CMF plant)	0.101	0.101	0.101
Total unit cost (CMF plant)	0.223	0.183	0.155
Total unit cost (conventional treatment plant)[a]		0.165	

[a]The cost of the conventional treatment is already has been analyzed in pervious techno-economic study (Abdel-Jawad, 1999).

Table 7
Estimates of unit cost of secondary level treatment of wastewater using CMF-S system for a large commercial size plant

	Economies of scale		
	$\eta = 0.95$	$\eta = 0.90$	$\eta = 0.85$
Capital cost (CMF-S plant)	0.122	0.079	0.052
Operating cost (CMF-S plant)	0.080	0.080	0.080
Total unit cost (CMF-S plant)	0.202	0.160	0.132
Total unit cost (conventional plant)[a]		0.165	

[a]The cost of the conventional treatment has been analyzed already in a previous techno-economic study [9].

estimated capital cost of KD 39.2 million from Abdel-Jawad [9], with a plant life of 20 years and a unit operating cost of $0.120/m^3$ obtained from the MPW. As a result, using CMF-S in a large commercial plant has a lower unit cost than the unit cost of using a CMF system.

The techno-economic study revealed that the CMF-S system is a cost-effective system for treating secondary wastewater when compared with the CMF system. The cost of treated wastewater by CMF-S will reduce the cost of the conventional treatment by 20 and 6% when using the CMF system.

7. Conclusions

Based on the results of this study, conclusions are made as follows:

- The chemical analysis revealed that both systems significantly improved the quality of the secondary treated wastewater effluents, with an overall average turbidity of 5.5 and 0.184 for CMF and CMF-S, respectively.
- The CMF-S has the capacity to reduce the BOD and COD from the treated secondary effluent by 62.8 and 54.9%, respectively. It also has the capacity to reduce the TSS and total bacteria count by over 95% and the fecal coliform bacteria by over 99.98%.
- Overall, the results confirmed that CMF-S can be operated efficiently on a municipal scale to consistently and reliably produce highly clarified water of a quality suitable for indirect reuse. Therefore, water produced from a CMF-S system could be considered to be safe for agriculture, industry and other indirect human reuse.
- The CMF-S process could offer several benefits over conventional treatment including smaller space requirement and better solids removal.
- The chemical analysis of this study would suggest that the submerged type of MF (CMF-S) could produce better quality of filtrate than the pressure-driven CMF unit.
- Excellent availability was demonstrated under comparable conditions of two systems which is 87.66 and 98.73% for CMF and CMF-S, respectively.
- The techno-economic study revealed that CMF-S is a cost-effective system for secondary wastewater treatment when compared with CMF system. MF can be used as a pretreatment technique for RO system in the field of wastewater treatment.
- MF (CMF-S) can be used to treat wastewater inside local areas for *in situ* reuse.

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