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Applicability of ceramic membrane filters in pretreatment of coke-contaminated petrochemical wastewater: Economic feasibility study

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Abstract

Fouling and subsequent disruption of filter coalescers due to deposition of coke particles is a crucial concern for petrochemical and oil-refinery plants. Our previous study confirmed that the γ-alumina ceramic microfiltration membranes could successfully remove coke particles from petrochemical oily wastewater. The aim of the current study is preliminary design and economic evaluation for implementation of ceramic membrane unit (CMU), as a pretreatment for coalescer filtration unit, to elucidate the applicability of the process in petrochemical wastewater treatment. Using CMU not only increases the lifetime of the filter coalescers but also introduces a supplementary source for the production of dilution-steam-water (DSW). Two types of ceramic membranes, including 7- and 19-channel modules, were analyzed with the latter providing better performance for the full-scale application. Total number of the required membrane modules was calculated considering the fact that one flow pass through the tubular membrane is adequate for the reasonable elimination of coke particles from the feed. Accordingly, a continuous cross-flow filtration procedure provided with a system of concentrate recycle was suggested. Total capital investment elements were calculated for the CMU implementation. Economic studies showed that the break-even point (BEP) and payback period (PBP) are near 3% and 2 yr, respectively. The results indicated that the CMU is a potential pretreatment for coke removal from petrochemical effluents.

Keywords: Coke removal; Preliminary design; Economic evaluation; Ceramic membrane

1. Introduction

Coke particles are unfavorable by-products of the hydrocracking process in petrochemical industries. This unavoidable by-product causes some operational problems such as corrosion, loss of heat and mass transfer efficiency and especially, contaminated wastewaters [1]. Coke-contaminated wastewater is typically conducted to the coalescer filtration unit before disposal and/or reuse [2]. A coalescer filter is usually made of woven fabrics or cellulose derivatives sandwiched between rounded perforated supports with the ability to capture suspended particles from both gaseous and aqueous effluents. The coalescer filters are quickly clogged and disrupted due to coke deposition. This occurrence reduces working time and efficiency of the coalescer filtration unit. Therefore, reduction of coke loading in the effluents conducted to the coalescer filters is an important concern for the petrochemical plants [3,4].

Membrane filtration is a powerful alternative for the pretreatment of coke-containing effluents. Both organic and inorganic microfiltration membranes have been applied for the treatment of oily effluents; however, ceramic membranes offer several advantages over polymeric ones such as superior thermal, chemical and mechanical stabilities [5–7]. Generally, ceramic membranes can tolerate harsh operating conditions. Alumina and zirconia membranes have been applied for the filtration of oily wastewaters [6,8]. Coke elimination from the oily wastewater of the Marun Petrochemical Co. (Mahshahr Island, Iran) has been investigated in our previous works [9,10]. Single-channel γ-Al_2O_3 based ceramic MF membranes were applied for this purpose. The coke removal efficiency was almost 100% under operating conditions of 70 °C and 15 bar. The operating conditions were made in imitation of the actual operating conditions.

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In designing a new process, almost all the decisions are impacted by the economic factors. Therefore, it is critical to study process economics. Feasibility studies evaluate the potential of a proposed project based on pre-organized researches and well-based estimations to give full comfort to the decisions makers and suppliers. In its simplest terms, the two criteria to judge feasibility are preliminary design and economic potential estimation to be attained. Preliminary design should provide a background of the project operations and technical requirements. Economic evaluations however, give an estimate of total capital investment which includes fixed and working capitals.

This paper challenges the feasibility of the ceramic membrane unit (CMU) implementation as a pretreatment for the coalescer filtration unit for the purpose of coke elimination from oily effluent produced in PET zone of the Marun Petrochemical Co. (Mahshahr, Iran). Preliminary design and economic evaluations were performed. Finally, financial viability of the project was judged based upon the following parameters:

- Projected flow diagram
- Total estimated investment of the project
- Economic potential and payback time
- Saving and profitability

2. Experimental

Feed samples of oily wastewater containing coke particles were supplied by PET zone of the Marun Petrochemicals, Mahshahr, Iran. The feed samples contained water, gasoline and coke particles (~1 wt%). Operating pressure and temperature were 15 bar and 80 °C, respectively. Single-channel γ-Al_2O_3 ceramic MF membranes were used for the experiments due to ease of application, control and scale up. Specifications for the ceramic membrane alternatives (one, 7 and 19-channel tubular modules) are depicted in Table 1. Full description of the experimental procedure and the applied setup were reported elsewhere [9]. Briefly, a typical cross-flow filtration batch-concentration procedure was applied. The TMP and permeate volume were continuously measured during filtration. The effluent was fed in to the ceramic membranes through their channels i.e., inside to outside flow pattern. The solution was penetrated through the membrane and collected in the housing free space then, allowed to exit the cell and recycled to the feed tank. Concentrated solution passed through the channels and returned to the feed tank. All the experiments, necessary for the evaluation of the ceramic membranes performance, have been conducted and their corresponding results reported in our prior works [7,9,10].

3. Result and discussions

Separation performance of the alumina-based ceramic membranes was studied in our prior work [9]. The current work utilizes the experimental results for the purpose of scale up and full-scale design. Economic information seems necessary for decision makers and suppliers to make sense about the feasibility of a projected plan. Preliminary design and economic assessment are principle criteria for the feasibility studies. Preliminary design is a practical tool by which an estimative process flow diagram is simulated, mainly by using simple calculations and well-based rule of thumbs instead of straightforward detailed calculations (required for full-scale design). The latter is required after final consolidation for the preparation of detailed PFD and P&ID.

3.1. Preliminary design

3.1.1. Number of required membranes

From industrial point of view, 7-channel and 19-channel ceramic membranes (see Table 1), are better alternatives, compared to single-channel ones, on account of efficient utilization of the footprint and economic considerations. Maximum volumetric flow rate of the streaming feed was measured as 222,000 l/h. Active filtration areas of 7-channel and 19-channel ceramic membranes are 0.12 and 0.24 m^2, respectively (Table 1). The minimum permeated water flux for the 7-channel and 19-channel ceramic membranes (Table 1) is reported by the supplier as 500 l/h m^2. Based on the experimental results, single pass of the feed flow through the membranes is enough for a significant coke elimination to obtain. Accordingly, maximum number of 7-channel and

Table 1
Specifications for different types of ceramic membranes[a].

Number of channels		Single channel	7-channel	19-channel
Dimensions	Out dia. (mm)	10	25	30
	Channel dia. (mm)	6	6	4
	Thickness (mm)		1.5~2	
	Length (m)		1	
	Specific area (m^2/m)	0.03	0.12	0.24
Parameters	Porosity of support (%)		> 35	
	Average pore size (µm)		0.05, 0.1, 0.2, 0.5	
	Breaking strength (MPa)		> 50	
	Distilled water flux (l/m^2 h)		> 500	
Material			Al_2O_3	
Operating Condition		Max. pressure 800 °C		pH: 0 ~14

[a] Reported by manufacturer agency in Iran (Iran Membrane Co.).

Table 2
Alternatives for ceramic membranes and housings selection.

Alternatives	7-channel membrane		19-channel membrane	
37-capacity housing	N_m[a]$=2500$ Membrane system cost=361,000 $	N_h[b]$=68$	$N_m=1250$ Membrane system cost=197,550 $	$N_h=34$
99-capacity housing	$N_m=2500$ Membrane system cost=321, 200 $	$N_h=26$		
91-capacity housing			$N_m=1250$ Membrane system cost=172,550 $	$N_h=14$

[a]Number of total ceramic membrane modules.
[b]Number of required housings.

19-channel ceramic membranes is calculated as follows:

$$n_{\max} = \frac{F}{Q_{\min} A} = \frac{F}{F_m} \tag{1}$$

where F and F_m are feed flow rate and permeated water flow rate (m^3/h), respectively, $Q_{\min}$ is minimum permeated water flux (m^3/h m^2), and A is the membrane active surface area (m^2). Using Eq. (1), the maximum number of the modules for 7 and 19-channel ceramic membranes is obtained as 3700 and 1850, respectively.

Calculation of actual number of the ceramic membrane modules is necessary for the economic analysis. Permeated water flux through a membrane is in tune with its active surface area [5,7]

$$\frac{Q_1}{Q_2} \approx \frac{A_1}{A_2} \tag{2}$$

Ignorable deviation in Eq. (2) may be related to the overlap of the permeating area of neighboring channels in a multi-channel tubular membrane. Actual volumetric flux for single-channel membrane, obtained at operating conditions simulated as actual ones (15 bar and 70 °C), was tabulated as 12.85 l/h. According to Eq. (2), actual flux quantities for the 7- and 19-channel ceramic membranes are 90 and 180 l/h, respectively. After substitution of the actual water flux values in Eq. (1), the actual numbers of the 7- and 19-channel ceramic membranes were obtained as 2467 and 1234, respectively. These values were rounded to 2500 and 1250 for simplicity and considering a safety limit for the subsequent calculations. Available commercial housings for 7- and 19-channel ceramic membranes are listed in Table 2. The number of the required membranes and housings for the available alternatives were computed and reported in Table 2.

3.1.2. Projected flow diagram

Based on the experimental results [9], single pass of the feed through the membranes is adequate for perfect coke elimination. Accordingly, a parallel set of membrane cartridges with recycling the concentrated solutions was suggested as illustrated in Fig. 1. Feed is distributed among the cartridges each of which containing several number of membrane modules according to the housings capacity. The problem of coke contamination can be solved by using such a simple strategy as applied by other researchers [11,12]. Mass balance principles showed that the total permeate flow rate should be balanced with the feed flow rate to satisfy the requirement of the system continuousness (Fig. 2).

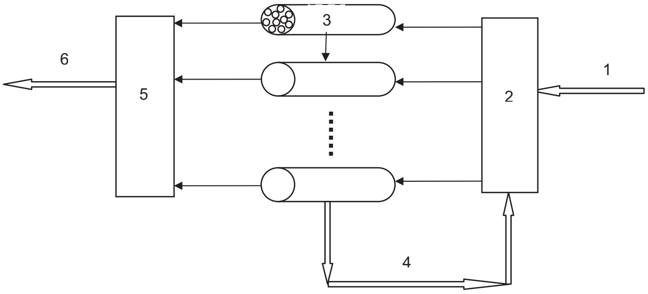

Fig. 1. Process flow diagram for the ceramic membrane unit. (1) Feed stream, (2) flow distributer, (3) membrane housing, (4) recycled concentrate, (5) permeate collector and (6) filtrated water.

3.2. Economic evaluation

The total capital investment for the ceramic membrane unit includes fixed capital and working capital investments [13,14]. Fixed capital investment comprises both direct and indirect costs. Direct costs include investments for:

a) Main operating system (ceramic membrane systems).
b) Installation of main systems (15% of a)
c) Instrumentation and controls (6% of a)
d) Electrical (10% of a)
e) Installation (30% of a)
f) Buildings, yard and auxiliary (15% of a)
g) Land (6% of a)

Indirect costs however, include:

- Engineering and supervision (30% of a)
- Contractor's fees (5% of direct cost)
- Construction expenses (10% of direct costs)
- Contingency (8% of fixed capitals)

Direct costs are evaluated based upon the main operating systems (here, the membrane system) costs. It is obvious that the key parameter for the economic analysis is the total price of the membrane system required for the operation.

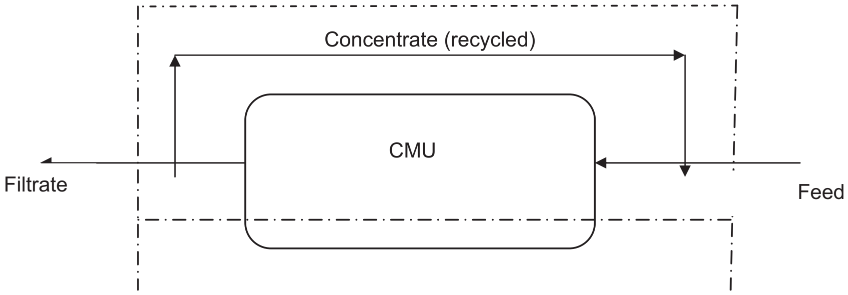

Fig. 2. CMU boundary limit.

3.2.1. Selection of membrane system

Based on Table 2, there are four alternatives for the membrane system selection. Each alternative includes a specific ceramic membrane together with the potential housings which are available for the membrane. Prices of membranes and housing are reported by the manufacturer agency in Iran (Iran-Membrane Co., Golestan, Gorgan, Iran), based on 2012 index. Total membrane system cost includes membranes and housings prices

$$\text{Main system cost} = (\text{number of membrane} \times \text{price of one module}) + (\text{number of housings} \times \text{price of one housing}) \quad (3)$$

According to Eq. (3), main system cost can be obtained for the possible alternatives and reported in Table 2. In this step, the membrane system alternatives could be compared according to their total cost. It is obvious from the results that 19-channel ceramic membranes with 91-capacity housings are economically preferred to the other alternatives. After selection of the main system, fixed capital investment can be computed. Table 3 shows the details for the fixed capital cost elements.

Table 3
Fixed capital investment elements.

Component	Costs (US $)
Main operating system	172,550
Installation of main systems	25,882
Instrumentation and controlling devices	10,353
Electrical	17,255
Installation	51,765
Buildings, yard and auxiliary	25,883
Land	10,353
Sum of direct costs	**314,041**
Engineering and supervision	51,765
Construction expenses	31,404
Contractor's fees	15,702
Sum of indirect costs	**98,872**
Contingency	33,033
Fixed capital investment	**445,945**

3.2.2. Total capital investment

Working capital investment includes the following elements [13]:

- Deprecations and amortization (calculated based on Vebena model [15])
- Energy consumption (4% of fixed capital)
- Maintenance (4% of fixed capital)
- Operation and performance (2% of fixed capital)
- Laboring (3% of fixed capital)

Based on the Vebena model, deprecation cost is computed as follows:

$$\text{Depreciation costs} = \left(\frac{1}{30}\right)\text{maintenance costs} + \left(\frac{1}{15}\right)\text{engineering and supervision} + \left(\frac{1}{5}\right)\text{membrane system} \quad (4)$$

Detailed discussions about backwashing (cleaning) of ceramic membranes including cleaning procedure, backwashing period and applied cleaning agents may be found in our previous publications [7,10]. Economic analysis of these parameters would also be performed in 'detailed design' of the process which is not within the scope of the current study. However, all the cost related to the filtration operation, performance and process maintenance (including regeneration-dependent costs) are implicitly accounted in 'operation and performance' and 'maintenance' costs as a percentage of the fixed capital investment. The main goal of the current manuscript (estimative design and economic evaluation) is to provide a dependable perspective of the general feasibility of the process for decision makers. Table 4 summarizes working capital components and total capital investment for the CMU.

3.2.3. Feasibility clarification

In essence, lifecycle costing only considers costs and benefits to the point where they balance, instead of considering them over the entire life of a project. The accounting method of calculating break-even point (BEP) does not include cost of working capital. This economical parameter represents the economical potential of a project and is defined as [13]:

$$\text{BEP}(\%) = \{(\text{Fixedcapitals}) \div (\text{Total profit} - \text{Working capitals})\} \times 100 \quad (5)$$

The purpose of the economic feasibility assessment is to determine the positive economic benefits that the proposed system will provide. It includes identification and quantification

Table 4
Working capital and total capital investment elements.

Component	Costs (US $)
Deprecations	31,427
Energy consumption	17,838
Maintenance	17,837
Operation and performance	8919
Laboring	13,378
Working capital	**89,399**
Fixed capital	**445,945**
Total capital investment	**535,344**

of all the benefits expected. This assessment typically involves a cost/benefits analysis.

Using ceramic membranes increase the life-time of the filter coalescers. It means that fewer numbers of the filters are needed to be purchased yearly. There are 28 filter coalescers available in the operating line of the wastewater treatment. Price of one filter coalesce is near 300 $ based on what reported by the petrochemical company. The filter coalescers should be replaced bimonthly in the absence of the ceramic membrane unit. In other words, 672 filters per year should be purchased without CMU. Normal life-time for a filter coalescer is almost three months when applied in normal operating conditions. This life-time is likely attainable where coke particles are removed from the feed by the CMU. CMU can reduce the number of the required filter coalescer from 672 to 112 per year. Running under standard treatment procedures and cleaning protocols provide the conditions for the application of ceramic membrane without any significant deterioration and failure in performance for a very long time. This fact implies that entire investment will be paid back (here, over payback period of 2 yr) prior to the requirement of membrane replacement. It is worthy of mention that the feasibility studies are carried out for the period between implementation commencement up to the payback time of the project. Therefore, a part of the project profit can be obtained by yearly saving in the purchase cost of 560 filter coalescers

$$\text{Saving in filtercoalescers cost} = (560) \times (300\ \$) = 168,000\ \$$$

It is not the entire profit. The coke-free filtrated water can be reprocessed in the dilution steam generators (DSG) to produce dilution steam water (DSW). In thermal cracking, DSW is added to reduce the partial pressure of the hydrogen and shift the equilibrium to produce more ethylene.

The effluent is produced in the petrochemical plant with the maximum capacity of 220 ton/h for only one month (maximum loading) and with the capacity around 70 ton/h for the remaining months. Considering 330 working-day per year and 24 working-hours per day, filtrate production capacity (FPC) can be calculated as

$$\text{FPC} = \frac{330}{360}\left\{1\text{month} \times 220\frac{\text{ton}}{\text{h}} \times 24\frac{\text{h}}{\text{day}} \times 30\frac{\text{day}}{\text{month}} + 11\text{month} \times 70\frac{\text{ton}}{\text{h}} \times 24\frac{\text{h}}{\text{day}} \times 30\frac{\text{day}}{\text{month}}\right\} \approx 650000\frac{\text{ton}}{\text{year}}$$

Average price of the filtrated water is near 0.15 $/ton. Thus, the minimum possible gain is around 97,500 $ for the first year after the start of the CMU. Total profit is sum of the saving and marketing benefits

$$\text{Total profit} = (168,000\ \$) + (97,500\ \$) = 265,500\ \$$$

Finally, the BEP was obtained near 3% using Eq. (5). A plan is economic when BEP is less than 40%. For BEP in the range of 40% to 55% more detailed study is required and, for BEP higher than 55% the project is economically rejected [16]. Therefore, CMU implementation is quite economic with a satisfactory confidence limit.

The payback period (PBP) of an investment is essentially a measure of how long it takes to break even on the cost of that investment. The required time for the compensation of the CMU investments can be computed using the following relation:

$$\text{PBP(year)} = (\text{Total capital investment}) \div (\text{Total profit per year}) \tag{6}$$

PBP was obtained around 2 yr for the CMU implementation. It means that normally 2 yr lasts for repaying of all the original investments from the resulting profits of the process. Based on the economic analysis results (BEP and PBP), it is concluded that the ceramic membrane unit (CMU) is a feasible and completely economic pretreatment for the coalescer filtration unit. In addition, removing coke contaminants from the wastewater helps the company to meet better environmental protection standards when effluent disposal is considered.

4. Conclusions

The current study shows that the economic potential of the ceramic membrane unit for the pretreatment of coke-contaminated effluents produced by petrochemical plants. Using CMU offers several advantages such as increasing the coalescer filters life-time, providing DSW and environment protection from coke contamination. 19-channel membranes with 91-capacity housings were selected among available membranes/housing alternatives with respect to the economic considerations. Total capital investment was obtained near 535,300 $ whereupon, reasonable economic potential in terms of break-even point (~3%) and payback time (~2 yr) was obtained. Generally, the current study provided a conductive and statistically defensible picture of the CMU implementation as a potential pretreatment for the coalescer filtration unit in petrochemical wastewater processing.

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