International Journal of Engineering Research and Technology. ISSN 0974-3154 Volume 10, Number 1 (2017)

Economic assessment of multi-effect membrane distillation (MEMD) for water treatment

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Abstract
In this study, a novel MEMD process was developed and investigated for the purpose of wastewater treatment. The MEMD module was developed based on the air gap membrane distillation (AGMD) configuration. The traditional MD systems suffer from poor energy efficiency and not economical due to high energy consumption. Hence in this study, economical assessment of the novel 4-stage MEMD pilot plant was presented. The water production cost (WPC) of 4-stage MEMD pilot plant of membrane area about 0.5 m^2 was found to be 771 Rs/m^3. But it was reduced if the thermal energy i.e. waste heat is available in the plant, then the WPC was obtained as about 331 Rs/m^3. As compared to the literature WPC of the MD process, the 4-stage MEMD was an economical process which is one of the important criteria for industrialization of the MD technology.

Keywords: Membrane distillation (MD); multi-effect membrane distillation (MEMD); economical assessment; water treatment

Introduction
Membrane distillation (MD) is a thermally driven separation process and comparatively innovative membrane technology known since last 50 years. The principle of MD is based on the vapor pressure difference between the two sides of hydrophobic membrane. It has some advantages of performing at low temperature and pressure. Hence low grade or waste heat can be used in the MD process [1-4]. But the MD has been not significantly implemented in the industry due to high energy consumption and lower flux as compared to traditional reverse osmosis process. Hence the multi-effect concept is needed to add in a traditional MD process. The MD process with either external or internal heat recovery has the characteristics of multi-effect operation [5,6]. The advantages of MEMD over the traditional MD are high product rate, recovery of heat, low consumption of heat, low cooling water consumption, high gain output ratio (GOR), simple to operate and low maintenance cost [7].

In the economic analysis of the MD process, the costs of MD process equipments and its component like MD module are not yet known precisely. Also, the MD technology is still under test and not fully implemented in the industry, and there is wide dispersion in the energy consumption [8]. Hence the water production cost (WPC) of MD process was not determined precisely.

Some of the following studies on the economical analysis for the determination of WPC of MD process since last 20 years are described as:

About 20 years ago Hogan et al. [9] studied the feasibility of a solar-powered MD pilot plant with heat recovery for the supply of domestic drinking water in the arid/rural regions of Australia. They optimized solar collector area, membrane area and heat recovery to achieve low capital cost and high water production. For a production capacity of 50 kg/day the optimum configuration was a solar collector area of around 3 m^2, membrane area of 1.8 m^2 and a total heat exchanger area of 0.7 m^2 with a capital cost of $3500 (Australian in 1991).

Bouguecha et al. [10] estimated the annual cost of 17 l/day by using AGMD configuration using sensible heat of geothermal water resource. The capital cost ($110/$m^3$) of the plants as well as the costs of operation and maintenance ($20/$m^3$) was taken into consideration. The obtained WPC was $130/$m^3$.

Sarti et al. [11] estimated the cost of benzene removal from wastewater (1000 ppm of benzene) by VMD plant with 5 stages. The capital cost of the plant was $247,000 designed for 99% benzene removal with heat recovery. They considered the capital depreciation, labor cost, module replacement and energy consumption to estimate the treatment cost per unit volume of wastewater. They considered the labor cost about 10% of the capital cost per year, the assumed membrane life was 3 years, the membrane cost was $450/$m^2$ in module, the depreciation was 15% of capital cost per year, the pump efficiency was 0.8, the operation time was 7200 h per year, the electricity cost was 0.085 $/kWh, and the steam at low pressure was 0.013 $/kg. The estimated WPC was $4.04/$m^3$ [11].

Al-Obaidani et al. [12] made calculations for a DCMD plant with a capacity of 24,000 m^3/day, with and without heat recovery. They found the minimum WPC obtained by them was $1.23/$m^3$ for the feed inlet temperature of 55 °C (permeate outlet temperature of 25 °C) for DCMD without heat recovery. And the minimum WPC was $1.17/$m^3$ when the feed inlet temperature was 60 °C and the permeate outlet temperature was 30 °C for DCMD with heat recovery. It was reported that the membrane cost contributed about 50% of the capital cost and 30% of the cost of O&M in the DCMD plant. Al-Obaidani et al. [12] found that the estimated water cost of MD plant by using a heat recovery system is 1.17 $/m^3$ and it is reduced to 0.64 $/m^3$ if MD plant is operated with lower grade-waste heat.

Banat and Jwaied [13] made economic evaluation of two solar driven AGMD plants using spiral wound membrane module(s) with heat recovery (Fraunhofer ISE, Germany). The obtained WPCs were $29.9/m^3$ and $36/m^3$ for the compact and large AGMD plants, respectively. Also, it was reported that this cost was for very pure water and the production cost of drinkable water with a salt content of 500 ppm would decrease the WPC to one half, $15/m^3$ for the compact unit and $18/m^3$ for the large unit [13].

Hence, in this paper the economical 4-stage MEMD process for water treatment was developed on the laboratory scale and present here the economical assessment of MEMD pilot plant.

WPC determination process of MD

The MEMD process equipment is the most costly items that depend upon the plant capacity. In the process equipment, the cost considered the membrane module, heat exchanger and pumps. And in the auxiliary equipments are considered as open intake, pipe lines, valves, storage tanks, generators and transformers, electric wiring, and brine disposal line etc. Many researchers are assumed the different MD membrane cost due to the membrane is still under development [14,15]. Macedonio et al. [16] and Al-Obaidani et al. [12] assumed membrane cost as $90/m^2$. Drioli et al. [17] was considered higher membrane cost as $116/m^2$. While Banat and Jwaied [13] considered a less membrane cost as $36/m^2$. However the prices of the membrane may be depend on the type of membrane, manufacturer and the quantity purchased.

WPC of MEMD palnt was divided into two groups namely, Capital Cost (CC) and Annual Operating Cost (AOC). The detailed cost elements needed to determine the WPC of MD process is shown in figure 1. The capital cost again divided into two groups like Direct capital cost (DCC) and Indirect capital cost (ICC). The ICC is depending on the DCC. The ICC may be considered as in the range of 5 – 15% of DCC [8].

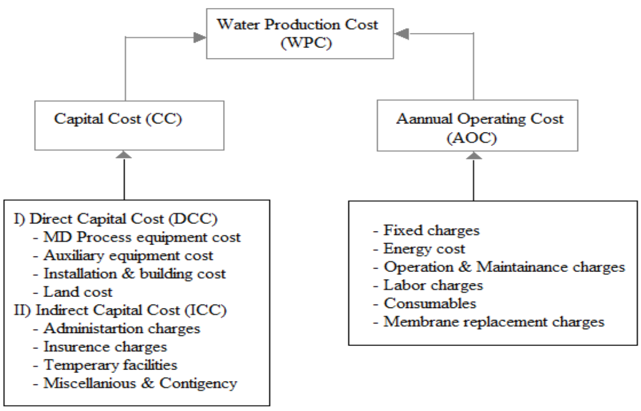

Figure 1: Cost elements needed to determine WPC of MEMD pilot plant

The AOC are the total yearly costs of operating a plant including the energy cost, labor costs, fixed charges, operation and maintenance (O&M) costs, membrane replacement costs, consumables etc. In general, the membrane life is considered about 4-5 years. The membrane replacement cost was 20% of membrane module cost. Also, considered the maintenance cost as 2% of the capital cost (CC) [13,18].

The annual fixed charges (C_{fixed}) can be estimated from the CC by using the following equation as [222]:

$$C_{fixed} = aDCC \quad (1)$$

Where a is the amortization factor and which is determined as:

$$a = \frac{i\,(1+i)^n}{(1+i)^n - 1} \quad (2)$$

Where i is the annual interest rate (%), n is the lifetime of the plant in year.

The operation and maintenance cost ($C_{O\&M}$) is the maintenance of the plant, staff cost, spare cost etc. It may be determined by using the following equation as:

$$C_{O\&M} = 0.2C_{fixed} \quad (3)$$

Also, in the AOC the annual labor cost (C_{labor}) can be estimated as:

$$C_{labor} = l\ f\ M\ 365 \quad (4)$$

Where l is the specific cost of the operating labor and which is considered as $0.05 /m^3$ [16], f is the plant availability which is the working time of the plant, M is the plant capacity (m^3/day).

The annual brine disposal cost (C_{brine}) can be estimates as:

$$C_{brine} = b\ f\ M\ 365 \quad (5)$$

Where b is the specific brine disposal cost and which was considered as 0.0015 $/m^3$. [16].

The annual electric power cost ($C_{electric}$) was calculated by using the following equation as:

$$C_{electric} = c\ w\ f\ M\ 365 \quad (6)$$

Where c is the electric cost (Rs/kWh) and w is the specific consumption of the electric power (kWh/m^3).

Hence, the total cost (C_{total}) calculated as:

$$C_{total} = C_{fixed} + C_{IC} + C_{O\&M} + C_{labor} + C_{brine} + C_{electric} + C_{memb\ rane} \quad (7)$$

The WPC of the MEMD plant can be determined by using the following equation as:

$$WPC = \frac{C_{total}}{f\ M\ 365} \quad (8)$$

Experimental

Membrane

The flat sheet microporous hydrophobic membrane made of polytetrafluroethylene (PTFE) membrane was used. The membrane sheet was supplied by the Madhu Chemicals Pvt. Ltd. Mumbai (India). The pore size, thickness and porosity of the membrane was 0.45 µm, 175 µm and 70% respectively. The single sheet membrane area was 80 cm^2.

MEMD module and experimental performance on the lab scale

The MEMD module was developed based on the air gap configuration. The detailed modeling and experimentation of the 4-stage MEMD module was described in our earlier research paper [19,20]. The 4-stage module contains, three feed channels, two cooling and four permeate or air gap channels. The acrylic material was used for the construction of the module. The aluminum foil was used as cooling plates. The internal arrangement of 4- stage MEMD module is shown in figure 2.

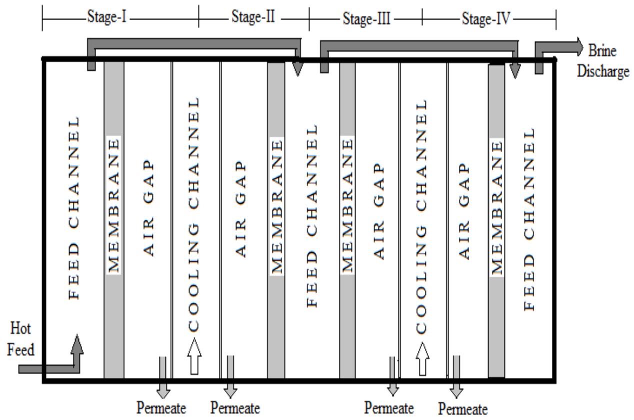

Figure 2: Different internal channels and flow of water in 4-stage MEMD module

Figure 3 shows the schematic of 4-stage MEMD system. The first feed tank (cooling tank) contained fresh feed water circulates through the cooling channels of the module. The latent heat of vaporization of water vapor is added in the cooling water (fresh feed) during the condensation process. The sensible heat is recovered in the heat exchanger from the hot brine solution. Then external heat is supplied to the second feed tank. The inlet and outlet temperature of feed and cooling channels were measured by thermocouples of pt100 sensors.

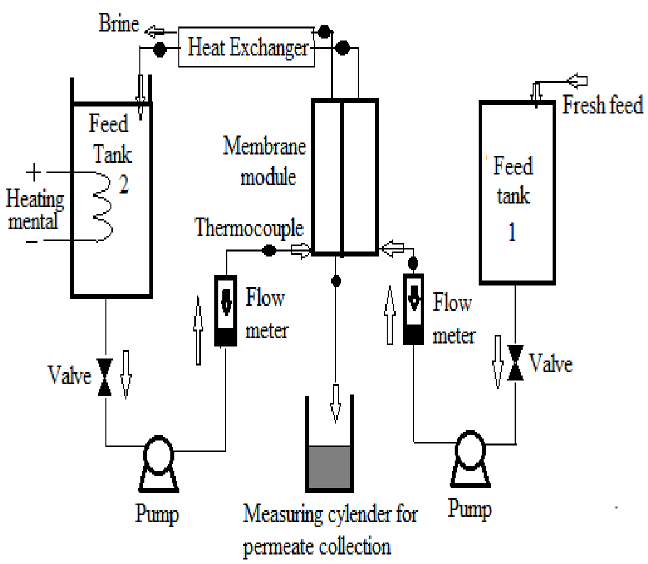

Figure 3: Schematic diagram of MEMD experimental setup

The lab scale experiment was carried out for the treatment of saline wastewater having TDS of 4630 mg/L and conductivity of 14350 µs/cm. The performance of the 4-stage MEMD process was analyzed and determined the permeate flux. The permeation rate is used to evaluate the performance of the module. the permeate flux was obtained as 42.5 L/m^{2}h at feed temperature of 80 ^{0}C, feed flow rate of 0.5 L/min, cooling water temperature of 27 ^{0}C and cooling water flow rate of 0.25 L/min. The feed and cooling channel depth was 5 mm and air gap thickness in each stage was 2 mm. This lab scale result was used in the determination of WPC of the 4-stage MEMD pilot plant.

WPC determination of the MEMD pilot plant

The pilot plant of the MEMD was considered for determination of the WPC by theoretically. In the large scale pilot plant, increases the membrane area in the module. Hence to increase the size of the module like length and width of the flow channels means increases the hydraulic diameter of the channels.

Table 1 shows the operating parameters considered for determination of the performance of the MEMD pilot plant for the wastewater treatment by theoretically. In these conditions the small lab scale 4-stage MEMD process (with a membrane area of 0.032 m^2) obtained a production rate 1.36 L/h for the feed rate of 30 L/h for saline wastewater. Using these results the production rate of a scaled-up 4-stage MEMD pilot plant (with membrane area of 0.5 m^2) was estimated to be around 21.25 L/h and the plant capacity was 0.51 m^3/day. Hence a large MEMD pilot plant is able to achieve a recovery ratio of about 70.8 %. The detailed block diagram of the plant capacity was shown in figure 4.

Table 1: Operating conditions considered for 4-stage MEMD pilot plant

Parameters	**Operating conditions**
Feed temperature	80 ^{0}C
Feed flow rate	0.5 L/min
Fresh feed (Cooling water) temperature	27 ^{0}C
Cooling water flow rate in each cooling channel	0.25 L/min
Effective membrane area of 4-stage	0.5 m^2
Feed flow & cooling channel depth	5 mm
Air gap thickness	2 mm

The cost elements of the MEMD pilot plant are considered as shown in Table 2, which are used for determination of the WPC of the MEMD pilot plant. The theoretical cost of the MEMD pilot plant was determined by using the above procedure described in the section 2. The theoretical cost determined of the cost elements were shown in Table 3.

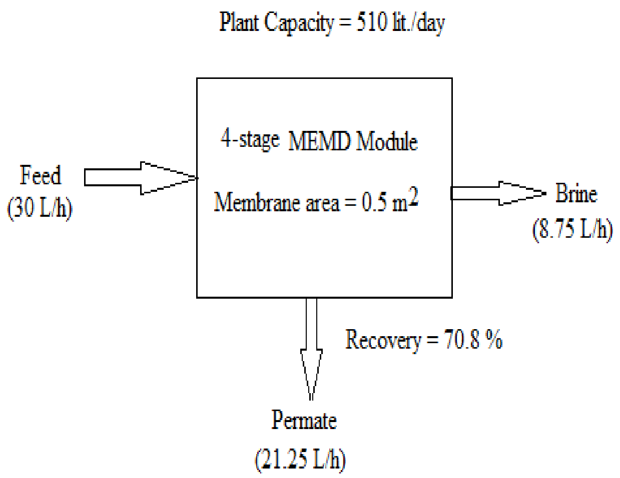

Figure 4: Detailed block diagram of MEMD pilot plant capacity

Table 2: Consideration of economic evaluation of MEMD plant

Cost element	Cost considered
Membrane cost	Rs. 8438 /0.125m^2 /sheet
MEMD module	19 % of total plant
ICC	10 % of DCC
Membrane life	5 year
Membrane replacement cost	10% of membrane module cost
Annual interest rate	8 %
Plant life	20 year
O&M cost	20 % of fixed cost
Plant availability	90 % of year
Electric cost	Rs. 3/kWh
Heater steam cost	Rs. 0.2 /lb (0.44 Rs/Kg)
Specific labor cost	Rs. 4 /m^3
Specific brine disposal cost	Rs. 0.105 /m^3

The WPC of the MEMD pilot plant were calculated for heat recovery in the module and also for when the waste heat is available in the plant. The WPC of the MEMD pilot plant is about 771 Rs/m^3 (0.77 Rs/lit.) water production when internal heat recovery. If the waste heat is available in the industry, the thermal cost required for heating the feed water will be reduced. Hence, the WPC is reduced and it is about 331 Rs/m^3 (0.33 Rs/lit.) water production.

Table 3: Theoretical cost of large MEMD pilot plant

Parameter	Cost (Rs)
Direct capital cost	140750=00
Indirect capital cost	14075=00
Annual fixed charges	14215=00
Annual operation & maintenance cost	2843=00
Labor cost	670=00
Electrical cost	17616=00
Thermal energy cost	73715=00
Membrane replacement cost	6075=00
Total Annual cost	129227=00
WPC with heat recovery (Rs/m^3)	**771=00**
WPC without thermal energy (Rs/m^3)	**331=00**

The WPC estimated for the various MD systems are summarized in the Table 4. As can be seen that the WPC values are vary in large magnitude from 220 Rs/m^3 to 8934 Rs/m^3. This is happened due to change in the different MD module, configuration and membrane used. As compared to the 4-stage MEMD pilot plant, WPC is less than other literature values. Hence 4-stage MEMD process is an economical and comfortable for the commercialization and industrial implementation for the water treatment.

Table 4. Comparison of literature estimated water production cost (WPC) of different MD systems with 4-stage MEMD pilot plant

WPC (Rs/m^3)	Year	Observations	Ref.
220	2003	VMD - single stage, flux: 0.7 l/m^{2}h	[21]
8934	2005	AGMD- use of geothermal energy, water production: 17 l/day	[10]
1031-2055	2008	AGMD - solar driven plant, water production: 0.1 m^3/day	[13]
1237-2474	2008	AGMD- solar driven plant, water production: 0.5 m^3/day	[13]
771	**2016**	**4-stage MEMD pilot plant-heat recovery**	**Current study**
331	**2016**	**4-stage MEMD pilot plant- when waste heat is available in the plant**	

Conclusion

In this paper, the economical analysis of the 4-stage MEMD pilot plant was done along with the comparative study of the current process with the traditional MD process and literature study. The pilot plant was considered for 0.5 m^2 membrane area. The complete WPC determination procedures were explained and the WPC of the 4-stage MEMD pilot plant obtained about 771 Rs/m^3. But it was reduced if the thermal energy i.e. waste heat is available in the plant, then the WPC was obtained as about 331 Rs/m^3. As compared to the literature WPC of the MD process, the 4-stage MEMD was an economical process.

Acknowledgement

We are deeply indebted to the Savitribai Phule Pune University, Pune for financially support to this research project.

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