EXPERIMENTAL INVESTIGATION OF MULTI- EFFECT MEMBRANE DISTILLATION (MEMD) MODULE FOR WASTEWATER TREATMENT

Bhausaheb L. Pangarkar

Chemical Engineering Department, Sir Visvesvaraya Institute of Technology, Chincholi, Nashik- 422 102, India.

blpangarkar78@gmail.com; pbl_1978@yahoo.com

Abstract - A novel multi-effect membrane distillation (MEMD) module for wastewater treatment was successfully developed. The effect of various main operating variables on the performance of 4-stage MEMD module was investigated. In all experiments, the excellent performance of the module was found in the separation of wastewater characteristics. The performance of 1 to 8- stage MEMD modules enables high efficient recovery of internal latent-heat.Also; it has great potential in the high permeation rate, thermal efficiency, and gain output ratio (GOR) and less specific energy consumption, which are the most important advantages for commercialization of the membrane distillation (MD) technology in the industry.

***Keywords*: Membrane distillation, Wastewater treatment, Heat recovery, multi-effect concept, water treatment**

I. INTRODUCTION

Membrane distillation (MD) is a thermal driven membrane technology. Presently, it has been attracting the interest of scientific and academic communities due to its excellent performance in the desalination and wastewater treatment [1] –[3]. The membrane used in the MD process is a microporous hydrophobic membrane. In MD process, the separation is based on the vapor pressure difference of the component across the membrane surface [4], [,5]. The MD process is operated under moderate temperatures and at non-pressurizedconditions, as compared to traditional membrane technologies. Hence MD can require only low grade energy such as waste heat or solar energy [6], [7].

In the traditional MD process have some limitations found in the literature such as high thermal energy requirement, low permeate flux, lacking in module design, low gain output ratio (GOR), and high cooling water consumption as compared to other conventional membrane technologies [8]-[14]. So for the commercialization purpose and overcome these above limitations, the multi-effect concept was added in the MD process by some researchers likememsys vacuum multi-effect membrane distillation (V-MEMD) [15]-[17]. The advantages of multi-effect membrane distillation (MEMD) process over the traditional MD are high product rate due to multi-stages in a single module, recovery of sensible heat of brine and latent heat of vapor during the condensation, low cooling water consumption, high GOR, low grade energy requirement, high stability, low maintenance cost and simple to operate. Hence, the aim of this work is to develop the MEMD process based on the air gap membrane distillation (AGMD) configuration for the application of wastewater treatment. AGMD is one of the configurations of MD among the four MD configurations. In AGMD the air gap is introduced at the permeate side between the membrane and condensation surface. The advantages of AGMD are low conductive heat losses, low chance to membrane wetting due to air-gap, possible latent heat recovery, and low temperature polarization effect [10], [12], [14],[18].

In this paper the multi- effect concepts such as heat recovery, multi stages, less cooling water consumption are added in a single AGMD module. The MEMD system with 4-stage module was installed, and the module performance for the application of wastewater treatment was discussed.

II. MATERIAL AND METHODS

A. *Membrane*

The flat sheet microporous hydrophobic membrane made of polytetrafluroethylene (PTFE) polymerwas used in MEMD module. These membrane sheets are commercially available and supplied by Madhu Chemicals Pvt. Ltd. Mumbai (India). Thecharacteristics of the PTFE membrane are shown in Table 1.

TABLE I

CHARACTERISTICS OF PTFE MEMBRANE

Parameter	**Characteristic**
Manufacturer	GmbH, Germany
Pore size	0.45 µm
Porosity	70%
Thickness	175 µm
Effective membrane area of single stage	80 cm^2

B. *MEMD module preparation*

The MEMD module was developed based on the air gap configuration. The detailed modeling of the 4-stage MEMD module was described in our earlier research paper [19]. The MEMD module was constructed by using the acrylic material. In the module, the cooling plates were made by the aluminum foil. The 4-stages were prepared in the module. It contains three feed channels; two cooling and fourair gap or permeates channels. The length and width of each channel in the module are about 100 and 80 mm respectively. The depth of the feed channel was kept and varied from 5 to 15 mm. The cooling channel depth was fixed about 5mm. The permeate channels or air gap thickness in the module was varied from 2 to 10 mm. The effective membrane area for the 4-stage MEMD module is about 0.032 m^2.The detail of the MEMD module internal channels and operated (block diagram) in a continuous mode with flow of water is illustrated in Fig. 1.

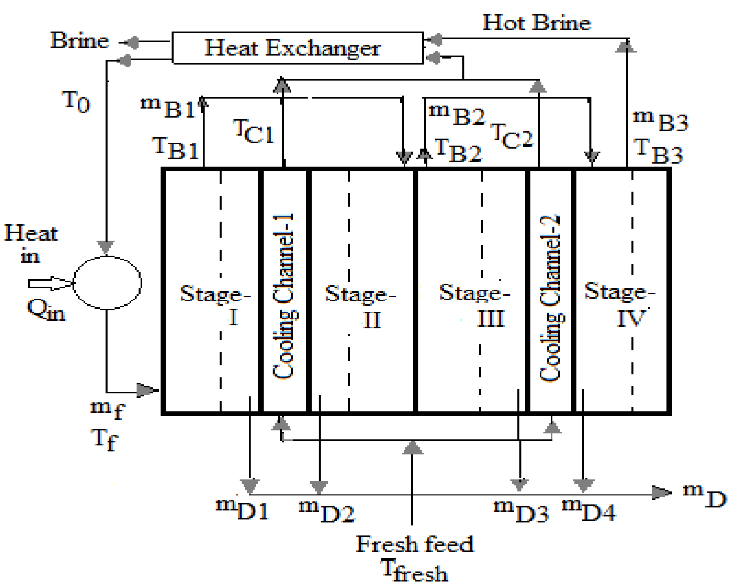

Fig.1. Block diagram of 4-stage MEMD module (Q_{in} is the heat input, mf is mass flow rate of feed, m_B mass flow rate of brine, m_D is the mass flow rate of permeate, T_f is the temperature of feed circulate through the 1st feed channel, Tc is the output temperature of cooling channel, T_0 is the temperature of feed water after recovery of hot brine heat, T_{fresh} is fresh feed water)

The MEMD module can be varying capacity due to changing in the number of stages. In MEMD module one cooling channel is used commonly in the two stages successively. The fresh feed water was circulated through the cooling channels and it is used for cooling purpose of the permeate vapor. In the permeate channels, the permeate vapor was condensed on the surface of the aluminum foil and collected as permeates. The picture of internal arrangement of 4- stage MEMD module is shown in Fig. 2(a) and the assembled moduleis shown in Fig. 2(b).

Fig. 2. (a) Picture of internal arrangement of MEMD module and (b) Picture of assembled MEMD module

C. *Experimental setup and procedure*

The experimental setup of MEMD system is shown in Fig.3. The first feed tank (20 lit. capacities) contained fresh feed water which is used for cooling purpose and circulatesthrough the cooling channels of the module. The internal latent heat of vaporization during the condensation of permeate vapor is added in the cooling water. After that sensible heat is recovered in the heat exchanger from the hot brine solution. Then the external heat is supplied to the second feed tank (20 lit. capacities). The feed is circulated from the feed tank to the first feed channel by using the circulation pump (0.5 hp). The inlet and outlet temperature of feed and cooling channels were measured by thermocouples of pt100 sensors. The feed flow rate is measured by using the Rotameter.

The performance parameters such as permeate flux, energy consumption, GOR and thermal efficiency of the module were evaluated. The equations used for calculations of the performance parameters are shown in Table II.

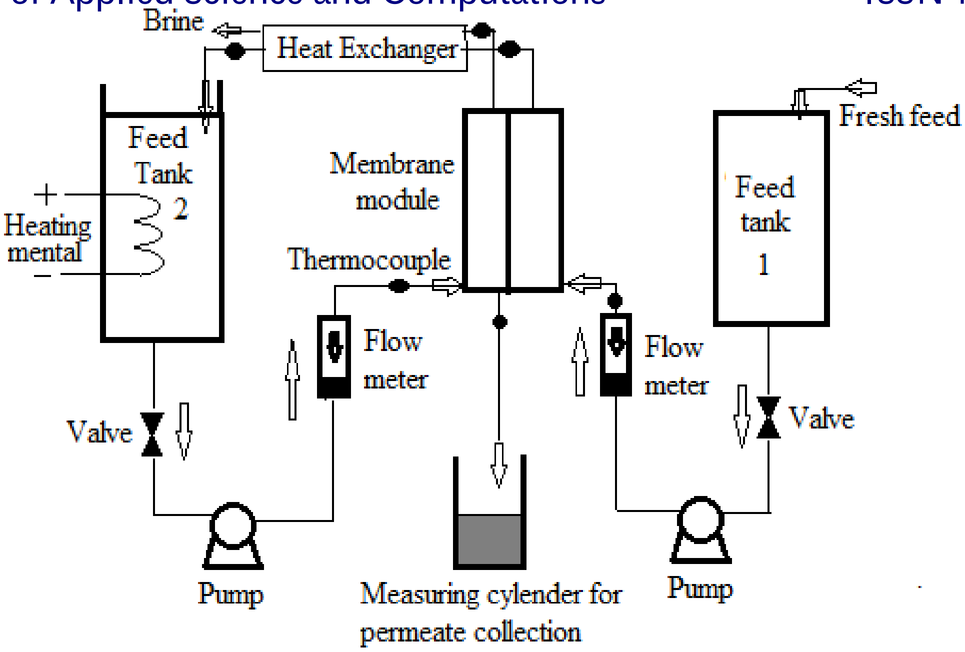

Fig.3. Schematic diagram of MEMD experimental setup

TABLE III

MEMD PERFORMANCE PARAMETER CALCULATIONS

Parameter	Calculation equation
Permeate flux, J_D (L/m^{2}h)	$= \frac{V}{At}$
% Separation factor	$= \frac{C_f - C_p}{C_f} x\, 100$
Specific energy consumption (kWh/kg)	$= \frac{m_f C_{pf}\ (T_f - T_o)}{m_D}$
GOR	$= \frac{m_D \Delta H_v}{m_f C_{pf}\ (T_f - T_o)}$
Thermal efficiency, η (%)	$= \frac{m_D \Delta H_v}{m_f C_{pf}\ (T_f - T_{B3})}$
Where V (L) is volume of permeate collection in time t (h), A (m^2) is membrane area, C_f and C_p is the concentration in feed and permeate respectively, m_f and m_D (Kg/s) is mass flow rate of feed and permeate water respectively, T_f, T_0&T_{B3} are the temperature of feed circulate through the 1st feed channel, water after recovery of hot brine heat and output brine water from module respectively, C_{pf} (KJ/kg ^{0}C) is specific heat capacity of water, ΔH_v (KJ/kg) is heat of vaporization of water	

D. *Wastewater sample and analysis process*

The synthetic wastewater samples were prepared by adding soluble organic and inorganic components like glucose (2.5 g/L), sodium chloride (2 g/L) and malathion (0.4 ml/L) in untreated tap water.The samples were freshly used for physico-chemical analysis and were stored at room temperature. Table III shows the main physico-chemical characteristics of the fresh feed wastewater sample which were analyzed in our laboratory. The water analysis kit (Systronics, Type-371) was used for analysis of the characteristics of samples such as pH, total dissolved solid (TDS), turbidity, conductivity. The chemical oxygen method (COD) was measured by using a standard titration method [20]. Total organic carbon (TOC) was measured by using HACH TOC analyzer in the industrial R&D laboratory located in Nashik city (India).

TABLE IIIII

PHYSICO-CHEMICAL ANALYSIS OF FEED WASTEWATER SAMPLE

Parameter	Unit	Value
pH	--	8.5
TDS	mg/l	4630
COD	mg/l	1680
TOC	mg/l	415
Conductivity	µs/cm	14350
Turbidity	NTU	88

III. MATERIAL AND METHODS

A. *Effect of feed flow channel depth on the 4-stage MEMD module performance*

The effect of feed flow channel depth on the permeate flux of 4-stage MEMD module were measured and the results are shown in Fig. 4. Here the feed flow channel depth was changed from 5 to 15 mm. Hence the hydraulic diameter of the feed flow channel was changed between 0.0094 m and 0.025 m. In this test, the feed flow rate and temperature were kept constant about 0.5 L/min and 80 ^{0}C respectively. The coolant flow rate in each coolant channel was about 0.25 L/min. The temperature of the fresh feed is about 27 ^{0}C, which is used as a cooling purpose. The air gap thickness in each permeate channel was kept constant about 2 mm.

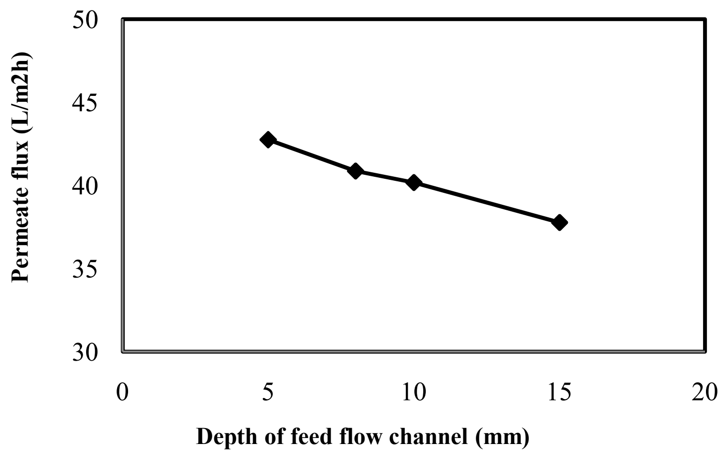

Fig.4. Effect of feed flow channel on 4-stage MEMD module (feed flow rate = 0.5 L/min, T_f= 80 ^{0}C, coolant flow rate in each channel = 0.25 L/min, T_{fresh} = 27 ^{0}C, air gap thickness = 2 mm).

When the feed flow channel depth increased from 5 mm to 15 mm, the permeate flux was decreased about 11.6 % in 4-stage MEMD process. This is due to decreasing the Reynolds number of the feed from 3182 to 1199 in the feed flow channel. Hence the turbulences of the feed water were decreasing due to increasing the feed flow channel depth. Hence the flux depends on the geometry of feed channels of the module. The maximum flux of 4-stage MEMD module was measured about 42.74 L/m^{2}h at each feed flow channel depth constant at 5 mm.

B. *Effect of feed flow rate on 4-stage MEMD module performance*

The flux of MD increases when the feed flow rate increases. A higher feed flow rate increases the heat transfer coefficient in hot feed streams and reduces the temperature and the concentration polarization effect [21]. Thus, it can increase the driving force of the MD process. If the feed flow rate is higher than the needed, the energy consumption for preheating the feed will be more and it will be wasted and also it will produce extra unnecessary high temperature brine.

At low feed rate, produces the over concentrated feed and crystallization may occur inside the module. Hence life span of the module may be reduced [15]. Thus, it is necessary to adjust the feed flow rate more precisely.

In this test, the feed temperature was kept constant about 80 ^{0}C, coolant flow rate and temperature about 0.25 L/min in each coolant channel and 27 ^{0}C respectively. The feed channel depth and air gap in each stage was kept constant about 5 mm and 2 mm respectively. Fig. 5 shows that when the feed flow rate increased from 0.3 to 0.5 L/min, the 4-stage MEMD flux was increased by 25.47 %. Also, the total flux was increased by 26.35 %, when the feed flow rate increased from 0.3 to 1 L/min. Hence, after increasing the feed flow rate from 0.5 to 1 L/min the flux was very slightly increases due to the fewer membrane area.

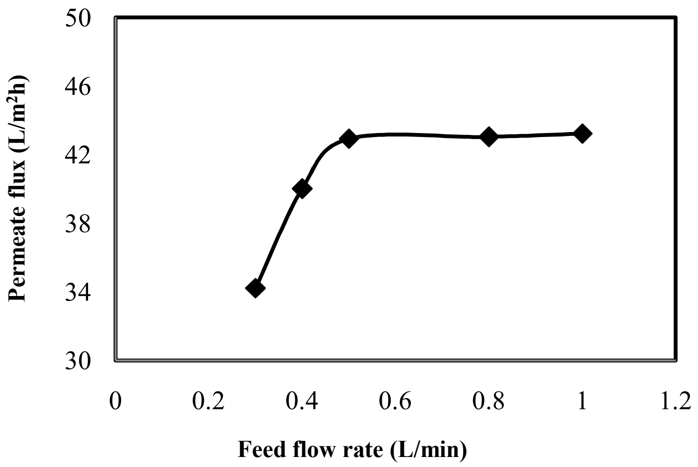

Fig.5. Effect of feed flow rate (T_f= 80 ^{0}C, coolant flow rate in each channel = 0.25 L/min, T_{fresh} = 27 ^{0}C, air gap thickness = 2 mm, feed channel depth = 5 mm).

Also in this performance, the brine temperature of 4-stage MEMD module was tested for different feed flow rate (0.3, 0.4 and 0.5 L/min) as shown in Fig.6. At a low feed flow rate about 0.3 L/min, the temperature of the brine was fluctuating due to insufficient feed fill up in the feed channel and it causes the unstable brine flow. At the feed flow rate about 0.4 and 0.5 L/min, the brine temperature remains constant throughout the operating period. Hence the brine temperature also depends on the geometry of feed channel of the module. The feed flow rate about 0.5 L/min was fixed in the further experiment.

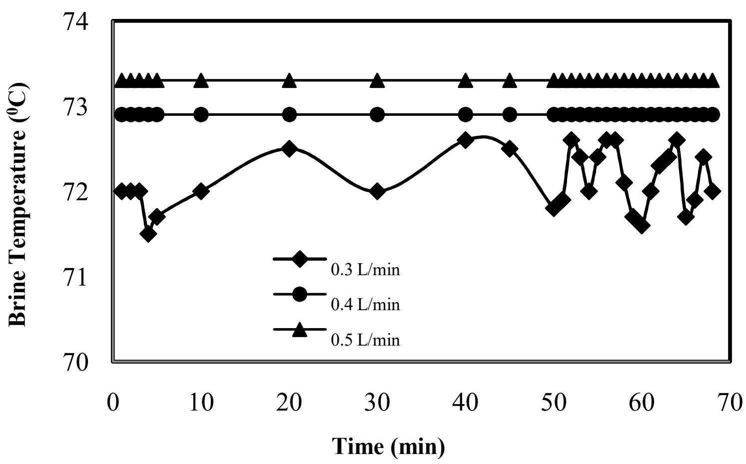

Fig.6. Effect of feed flow rate on brine temperature with time (T_f= 80 ^{0}C, coolant flow rate in each channel = 0.25 L/min, T_{fresh} = 27 ^{0}C, air gap thickness = 2mm, feed channel depth = 5mm).

C. *Effect of cooling water flow rate on 4-stage MEMD module performance*

Fig. 7 shows the effect of cooling water flow rate on the permeate flux of 4-stage MEMD module. If the cooling water flow rate in each cooling channel was increased from 0.15 L/min to 1 L/min, the maximum rise in the flux was about 2.6%. This increase of flux was only when the cooling water flow rate increases from 0.15 to 0.25 L/min. Further increasing the cooling water flow rate was not effected on the permeate flux.

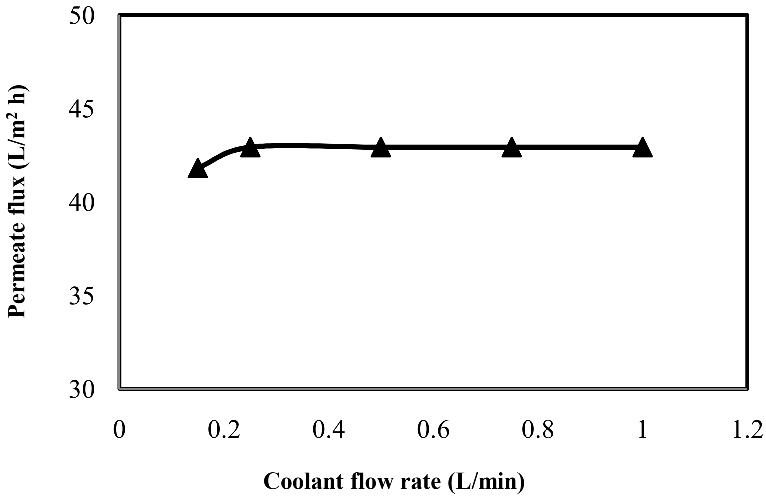

Fig.7. Effect of cooling water flow rate (feed flow rate = 0.5 L/min, T_f= 80 ^{0}C, T_{fresh} = 27 ^{0}C, air gap thickness = 2 mm, feed channel depth = 5mm).

In this performance, the output temperature of the cooling water from the cooling channel was also measured at various cooling water flow rates. At low cooling water flow rate, the residence time of the water in the channel increases, due to this increasing the cooling water inlet-outlet temperature difference. The effect of the cooling water flow rate on the coolant inlet-outlet temperature difference was shown in Fig.8. The inlet temperature of the coolant water was kept constant about 27 ^{0}C. The feed temperature and feed flow rate was about 80 ^{0}C and 0.5 L/min respectively. The result shows that the maximum temperature difference of the coolant water was achieved about 15 ^{0}C at a coolant water flow rate of 0.25 L/min. The maximum temperature difference means the maximum internal latent-heat recovery by the coolant water during the permeate water vapor condensation process. The heat recovery is an important parameter in the multi-effect concept. The coolant water flow rate about 0.25 L/min was fixed in each coolant channel for the further experiment.

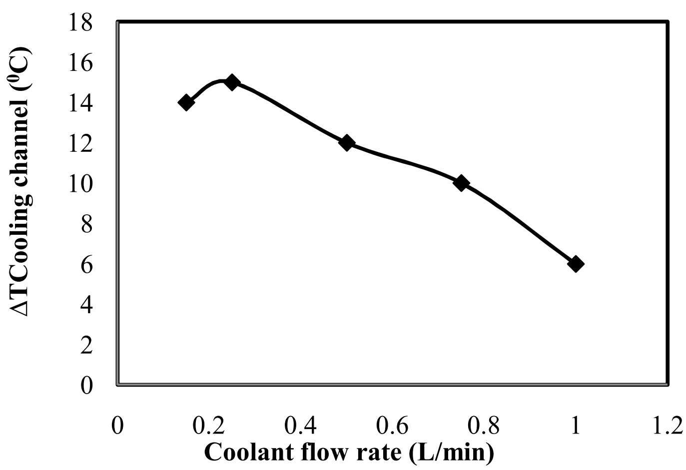

Fig.8. Effect of cooling water flow rate on cooling channel inlet-outlet temperature difference (feed flow rate = 0.5 L/min, T_f= 80 ^{0}C, T_{fresh} = 27 ^{0}C, air gap thickness = 2 mm, feed channel depth = 5mm).

D. *Effect of feed temperature on 4-stage MEMD module performance*

The effect of feed temperature on the permeate flux of the 4-stage MEMD module was shown in Fig. 9. It shows that the permeate flux was enhanced due to increase of the feed temperature and hence increases the temperature difference between the feed and coolant water. Temperature is the main factor affecting on the permeate flux in the MD process. The vapor pressure of the feed solution increases with increase in feed temperature and hence increases the driving force across the membrane surface. The temperature gradient between the membrane surfaces will affect the diffusion coefficient positively with feed temperature, which leads to increased vapor flux. If the MD process handled at high temperature, the mass transfer coefficient increases. In addition, temperature polarization decreases with increasing feed temperature.

During the experiment, the feed temperature was increased from 40 to 80 ^{0}C and coolant temperature was kept constant about 27 ^{0}C. The feed flow rate was about 0.5 L/min and coolant flow rate in each coolant channel was about 0.25 L/min. As increasing the feed temperature from 40 to 80 ^{0}C, leads to increase the permeate flux about 177 % in the 4-stage MEMD process. Hence the permeate flux is sensitive to feed temperature. The maximum permeate flux was recorded to 42.92 L/m^{2}h at 80 ^{0}C feed temperature.

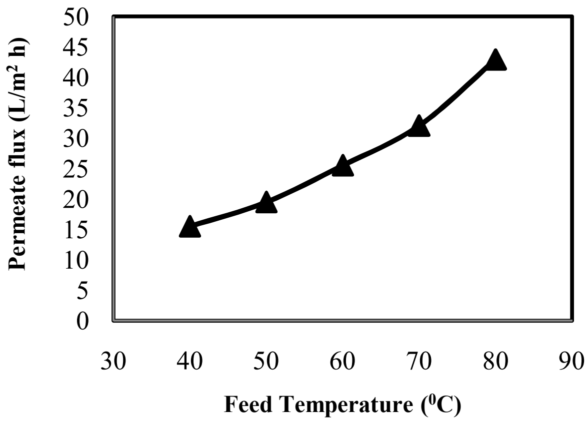

Fig.9. Effect of feed temperature (feed flow rate = 0.5 L/min, coolant flow rate in each channel = 0.25 L/min, T_{fresh} = 27 ^{0}C, air gap thickness = 2 mm, feed channel depth = 5mm).

E. *Effect of time on 4-stage MEMD module performance*

Fig.10 shows the permeate fluxes obtained by the 4-stage MEMD process for wastewater as a function of time. The experiment was carried out at feed and coolant temperature about 80 ^{0}C and 27 ^{0}C respectively for about 80 h operations. The fresh feed water was used as cooling water and the flow rate in each coolant channel was kept constant about 0.25 L/min. The feed flow rate was about 0.5 L/min. The initial permeate flux was recorded about 42.92 L/m^{2}h. The flux was decreased about 10.92% within the first initial period of about 9 h continuous operations. Also the flux was continuously decreasing further and remains constant nearly at 34.49 L/m^{2}h. The total decline of the flux was about 19.56 % within the period of 80 h operation. The flux decline is due to the fact that the membrane surface fouling due to the deposition of the soluble components on the membrane surface. Hence the membrane fouling is the major issues found in MD process. Generally fouling is caused due to the deposition of soluble salts [22,23], biological compounds like protein[24], and carbohydrates [25] on the membrane surface.

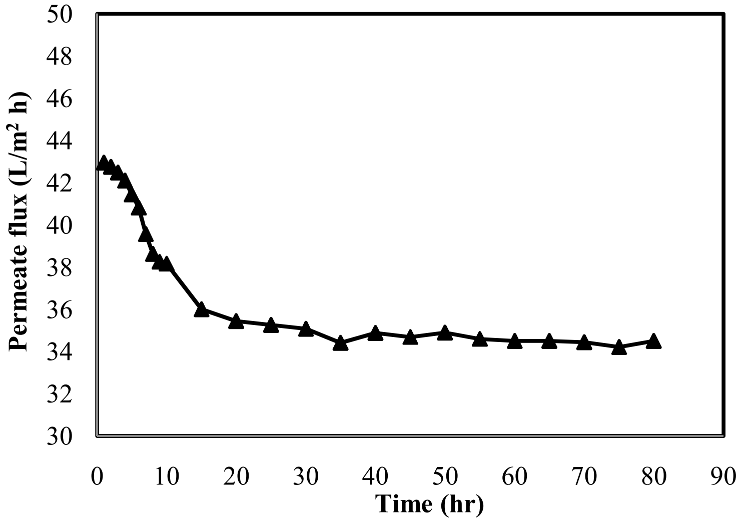

Fig.10. Effect of operating time (feed flow rate = 0.5 L/min, T_f= 80 ^{0}C, coolant flow rate in each channel = 0.25 L/min, T_{fresh} = 27 ^{0}C, air gap thickness = 2 mm, feed channel depth = 5mm).

F. *Water quality analysis*

Fig.11 shows the main character analysis of the permeate water. The removal of malathion component from the water were measured in terms of the COD removal of the water. The COD removal efficiency of the module was about 98.97%. The TDS and TOC removal efficiency of 4-stage MEMD process was shown >99.6%. Also, it is found that the same TDS and TOC removal efficiency in each stage even increases the TDS and TOC of the brine after each stage. With respect to the turbidity separation efficiency, 98.64% reduction could be achieved by this process. The conductivity of the permeate water was found to be about 3 µs/cm. With this excellent performance of the 4-stage MEMD module for the treatment of the wastewater, the high quality distillate produced and could be reused in the industrial process.

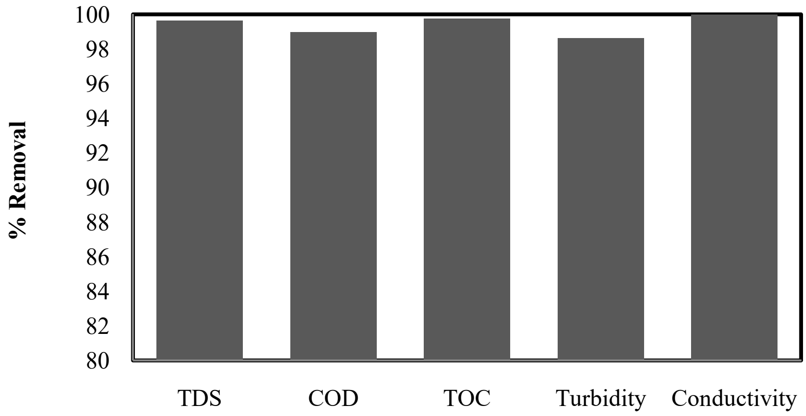

Fig.11. Removal efficiency of MEMD module.

G. *Effect of number of stages in MEMD module performance*

The number of stages in the MEMD module is a critical parameter because it has an effect on the thermal efficiency, energy consumption, gain output ratio (GOR), product rate, size and investment cost of the whole system. The experimental performance of the MEMD module for wastewater treatment with a number of stages was shown in Table 4. When increasing the number of stages from 1 to 8-stages, the permeate flux was slightly decreased due to decreasing the temperature in each stage, increasing the TDS of brine and the membrane area, butincreases the rate of productionof permeate water. Hence the product rate was dependent on the number of stages. The temperature drop in 4-stage MEMD module was found from 80 ^{0}C to 73$\pm$2 ^{0}C.

In this investigation, the fresh feed was used as cooling water. Hence the latent heat was recovered during the condensation of the permeate water vapor. The average cooling water temperature increases from 27 ^{0}C to 47$\pm$2 ^{0}C. After that the sensible heat of the hot brine also recovered by using the heat exchanger in the feed water. The temperature of the feed water after recovery of the sensible heat of hot brine was found nearly 59$\pm$2 ^{0}C in the 4-stage MEMD module. The specific energy consumption in the first stage of MEMD about 3.72 kWh/kg, which decreases with increasing the number of stagesand it was about 0.53 kWh/kg in 4-stage MEMD and 0.35 kWh/kg in 8-stage MEMD process. The GOR of the MEMD process was increased with increasing the number of stages. The maximum GOR reached about 1.19 in 4-stage and 1.81 in 8-stage MEMD process. The thermal efficiency of the module was also increased by increasing the number of stages.

TABLE IVV

PERFORMANCE COMPARISON OF THE MEMD SYSTEM WITH DIFFERENT NUMBER OF STAGES

Parameter	1-stage	2-stage	4-stage	6-stage	8-stage
Membrane area (m^2)	0.008	0.016	0.032	0.048	0.064
Flux (L/m^2h)	44.64	44.37	42.74	42.11	41.91
Specific energy consumption (kWh/kg)	3.72	1.89	0.53	0.42	0.35
GOR	0.17	0.35	1.19	1.54	1.81
Thermal efficiency (%)	162.64	258.77	356.61	409.4	443.99
Cooling water consumption/ permeate water	0	0	0	0.42	0.35

In this test, the output water of first 02 coolant channels, after brine heat recovery and pre-heating, was passed through the first feed channel. Hence there was no cooling water consumption found up to 4-stage of MEMD process. But after 4-stages excess cooling water was required, hence the ratio of consumption of cooling water per permeate water seemsto increase. Also, it was observed that the internal latent heat recovered by cooling water in the 6th and 8th stage of the MEMD module was wasted. Hence the number of stages optimization in the design of the module has a significant effect on the module performance. More stages has affects the higher investment cost, but it has advantages for the specific energy consumption and product rate. H. Geng et al.[26] found that the water recovery reached to 82.2% after the 14-satges of AGMD desalination.

IV. CONCLUSION

In this study, a novel 4-stage MEMD module based on the air-gap configuration was developed for wastewater treatment with internal heat recovery. The performance of the 4-stage module was experimentally demonstrated under different operating conditions like feed flow rate, temperature, cooling water flow rate and operating time. In the design of the module, the effect of feed flow channel depth on the permeate flux of 4-stage MEMD module is discussed and it is observed that the lower depth of the feed flow channel (5 mm) gives the best performance of the module. During all the experiment, the module gives the higher separation efficiency of the characteristics of wastewater. The effect of number of stages (1 to 8 stages) on the MEMD module performance was demonstrated experimentally. It was found that the multi-stage MEMD module has higher thermal efficiency and GOR, and low specific energy consumption. Also, 4-stage module does not require cooling water consumption. Hence multi-stage MEMD module has a great potential for commercialization of the MD technology in the industry for wastewater treatment.

ACKNOWLEDGMENT

We are deeply indebted to the SavitribaiPhule Pune University, Pune (India) for sanctioned the grant for this research project.

REFERENCES

[1] Alklaibi A.M., Lior N.,Membrane –distillation desalination: status and potential, Desalination,vol. 171, pp.111-131, 2004

[2] Alkhudhiri A., Darwish N., Hilal N.,Treatment of saline solutions using air gap membrane distillation: Experimental study, Desalination,vol. 323, pp.2–7, 2013.

[3] El-Abbassi A., Hafidi A., Khayet M., Garcia-Payo M.C.,Integrated direct contact membrane distillation for olive mill wastewater treatment, Desalination,vol. 323, pp. 1-38, 2013.

[4] Lawson K.W., Lloyd D.R., Membrane distillation, J. Membr. Sci.vol. 124, pp. 1-25, 1997.

[5] Curcio E., Drioli E.,Membrane distillation and related operations- A review, Separation and Purification Reviews,vol., 34, pp.35-86, 2005.

[6] Mannella G.A., Carrubba L., Brucato V., Charecterization of hydrophobic polymeric membranes for membrane distillation process, Int. J. Material Forming, vol. 3, no. 1, pp.563-566, 2010.

[7] Li N.N., Fane A.G., Ho W.S., Matsuura T., "Advanced membrane technology and applications", 394, John Wiley and Sons, Inc., Hoboken. New Jersey, 2008.

[8] Khalifa A., Lawal D., Antar M., Khayet M., Experimental and theoretical investigation on water desalination using air gap membrane distillation, Desalination, vol. 376, pp. 94-108, 2015.

[9] Geng H., Wu H., Li P., He Q., Study on a new air-gap membrane distillation module for desalination, Desalination, vol. 334, pp. 29-38, 2014.

[10] Cipollina A., Disparti M.G., Tambarlni A., Micale G., Development of a membrane distillation module for solar energy seawater desalination, Chemical Engineering Research and Design, vol. 90, no. 12, pp. 2101-2121, 2012.

[11] Alsaadi A.S., Gaffour N., Li J.D., Gray S., Francis L., Maab H., Amy G.L.,Modeling of air-gap membrane distillation process: A theoretical and experimental study, J. Membr. Sci., vol. 445, pp.53-65, 2013.

[12] Liu G.L., Zhu C., Cheung C.S., Leung C.W., Theoretical and experimental studies on air gap membrane distillation, Heat Mass Transfer, vol. 34, pp. 329-335, 1998.

[13] Harianto R.A., Aryapratama R., Lee S., Jo W., Lee H.J., Surface treatment of air gap membrane distillation (AGMD) condensation plates: Techniques and influences on module performance, Applied Sci. and Convergence Technology, vol. 23, no.5, pp.248-253, 2014.

[14] Al-Anezi A. A., Sharif A.O., Sanduk M.I., Khan A.R., Potential of membrane distillation- a compressive review, Int. J. of water, vol. 7, no.4, pp.317-346., 2013.

[15] Zhao K., Heinzl W., Wenzel M., Buttner S., Bollen F., Lange G., Heinzl S, Sarda N., Experimental study of the memsys vacuum-multi-effect membrane distillation (V-MEMD) module, Desalination,vol. 323, pp.150-160, 2013.

[16] LuS.J., Gao Q.J., LuX.L., Device and process study on vacuum multiple-effect membrane distillation, Advanced Materials Research, vol. 573, pp.120-125, 2012.

[17] Liu R., Qin Y., Li X., Liu L., Concentrating aqueous hydrochloric acid by multiple-effect membrane distillation, Frontiers of Chemical Science and Engineering, vol. 6, no. 3, pp.311-321, 2012.

[18] Warsinger D.E.M., Swaminathan J., LienhardJ.H., Procedding of the 15th Int. Heat Transfer Conf., IHTC-15, pp. 10-15, 2014.

[19] Pangarkar B.L., Deshmukh S.K., Theoretical and experimental analysis of multi-effect air gap membrane distillation process (ME-AGMD), J. Environ. Chem. Eng.,vol. 3, pp.2127-2135, 2015.

[20] Method 508, Standard Methods for the Examination of Water and Wastewater, 550, 14th Edition, 1975.

[21] *Gujit C.M., Meindersma G.W., Reith T., de HaanA.B., Air gap membrane distillation 1. Modelling and mass trabsger properties for hollow fiber membranes, Sep. Purif. Technol.,vol. 43, pp. 233-244, 2005.*
[22] *GrytaM., 2008. Alkaline scaling in the membrane distillation process, Desalination, 228:128-134.*
[23] *He F., Gilron J., Lee H., Song L., Sirkar K.K., Potential for scaling by sparingly soluble salts in crossflow DCMD, J. Membr. Sci., vol. 311, pp. 68-80, 2008.*
[24] *Goh S., Zhang Q., Zhang J., McDougald D., Krantz W.B., Liu Y., Fane A.G., Impact of a biofouling layer on the vapor pressure driving force and performance of a membrane distillation process, J. Membr. Sci.vol. 438, pp. 140-152, 2013.*
[25] *Mokhtar N.M, Lau W.J., Ismail A.F., Veerasamy D., Membrane distillation technology for treatment of wastewater from rubber industry in Malaysia, Procedia CIRP vol. 26, pp. 792-796, 2015.*
[26] *Geng H., Wang J., Zhang C., Li P.,Chang H.High water recovery of RO brine using multi-stage air gap membrane distillation, Desalination, vol. 355, pp.178-185, 2015.*