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Energy efficiency analysis of multi-effect membrane distillation (MEMD) water treatment

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Abstract : Traditional membrane distillation (MD) systems suffer from poor energy efficiency. Hence there is a need for improvement in the MD module in order to increase the energy efficiency and permeate flux. This paper presents a new modified energy efficient multi-effect membrane distillation (MEMD) module based on the air gap membrane distillation (AGMD) configuration for water treatment purpose. This 4-stage MEMD module with an energy recovery is implemented in this study. This MEMD module shows the high gain output ratio (GOR), low specific energy consumption, high thermal efficiency and product rate as compared to the traditional AGMD system. The maximum water vapor permeate flux of 42.75 L/m^{2}h, GOR of 1.19, specific energy consumption of 0.53 kWh/kg and thermal efficiency of 356.14% were obtained. Hence this module has great potential in increasing GOR and decreasing specific energy consumption, which is one of the important criteria for industrialization of the MD technology.
Keywords: Membrane distillation (MD); multi-effect membrane distillation (MEMD); energy efficiency; gain output ratio (GOR).

1. Introduction

Membrane distillation (MD) is relatively new and innovative membrane technology known since last 50 years. It has been widely studied for the various processes such as desalination of seawater or brackish water, concentration of solutions, removal of volatile organic compounds, removal of heavy metals and toxic elements from water and other separation and purification processes [1-3]. MD is a thermally driven separation process and it is economical in terms of energy, since low grade-waste heat energy for the process can be used because it has an advantage of performing at moderate temperature and pressure [4-6]. The working principle of MD is based on the vapor pressure difference between the two sides of hydrophobic membrane means the feed side and the permeate side. The vapor evolved from the feed solution passes through the pores of the membrane and is collected as the condensate. This depends on different MD configuration which are direct contact membrane distillation (DCMD), vacuum membrane distillation (VMD), air gap membrane distillation (AGMD) and sweep gas membrane distillation (SGMD); which have been well described in the literature [7-9]. In the literature many studies are found in the performance of the MD mainly on the membrane properties, operating conditions and module design [10-18].

The energy for the MD plants is generally supplied in the form of either thermal or electricity. Thermal energy is required to heating the feed and electrical energy required to run the circulation pump, vacuum pumps or compressors. The thermal energy requirement for MD process is more than the electrical energy, i.e. around 90% of the total energy. It can be accessed by using low grade waste heat [19]. Despite an attractive advantages of MD over other water purification technologies such as reverse osmosis (RO), till it has been not significantly implemented in the industry due to high energy consumption and lower flux as compared to RO process. Many researchers reported in their studies on the MD mainly investigate the temperature polarization phenomena, heat efficiency or heat transfer [20-22]. Only few studies are found on the energy requirement for the MD process [23-26]. There is need to optimize the process in order to maximize the permeate flux and minimize the energy requirement or reduce the temperature polarization phenomena. It is possible by carefully designed and optimized the MD membrane module configuration [24,26].

Since last two years, MD has emerged with numerous commercially oriented devices, especially in a new type of MD modules or high efficiency system such as vacuum multi-effect membrane distillation (V-MEMD) which was successfully developed by the Memsys (Germany) [27], multi-stage air gap membrane distillation module [28] and new AGMD module [29]. The MD process with either external or internal heat recovery has the characteristics of multi-effect operation. Hence the term multi-effect membrane distillation (MEMD) is used to describe an MD process with internal heat recovery and much more performance ratio [30].

The advantages of MEMD over the traditional MD are high product rate due to multi-stages in a single module, recovery of heat, low cooling water consumption, high gain output ratio (GOR) and stability, low consumption of heat, simple to operate and low maintenance cost. In this study, the multi- effect concepts such as heat recovery, less cooling water consumption, multi-stages of high water recovery are added in a single MD modular. Hence this process is called as the MEMD process. In this paper, the new type of MEMD system based on the air gap membrane distillation (AGMD) configuration with 4-stage module was installed. This new type of module shows huge potential in increasing the GOR and reducing the thermal energy requirement. The performance indicator parameters such as GOR, energy consumption and thermal efficiency of this 4-stage MEMD system were discussed. The higher the GOR, low consumption of energy and high thermal efficiency with a high product rate is the better the performance of the MD system [31].

2. Experimental

2.1. Membrane

The flat sheet microporous hydrophobic membrane made of polytetrafluroethylene (PTFE) polymer which is the commercially available membrane was used. The membrane sheet was supplied by the Madhu Chemicals Pvt. Ltd. Mumbai (India). The detailed characteristic of the membrane is shown in Table 1.

Table 1. Characteristics of PTFE membrane

Parameter	Characteristic
Manufacturer	GmbH, Germany
Pore size	0.45 μm
Porosity	70%
Thickness	175 μm
Membrane area of AGMD module	80 cm^2
Membrane area of 4-stage MEMD module	320 cm^2

2.2. Preparation of MEMD module

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 [32]. The acrylic material was used for the construction of the module. The aluminum foil was used as cooling plates. The 4-stage module contains, three feed channels, two cooling and four permeate or air gap channels. The length and width of each channel in the module are about 100 and 80 mm respectively. The depth of the feed channel varied from 5 to 15 mm. The depth of the cooling channel was fixed about 5 mm. The air gap thickness also varied from 2 to 10 mm. 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. The effective membrane area for the 4-stage MEMD module is about 0.032 m^2.

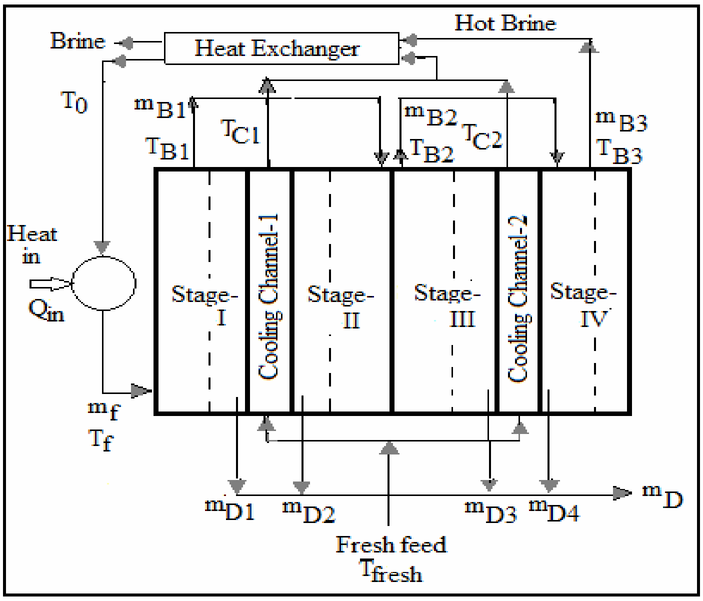

Fig.1. Block diagram of 4-stage MEMD module (Q_{in} is the heat input, m_f is mass flow rate of feed, m_B mass flow rate of brine, m_D is the mass flow rate of permeate, T_f is the temperature of feed circulate through the 1st feed channel, Tc is the output temperature of cooling channel, T_B is the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

The MEMD module is of varying capacity due to changing the number of stages in a module. One cooling channel is used commonly in the two stages successively. The fresh feed was circulated through the cooling channels for cooling purpose of the permeate vapor. The permeate vapor was condensed on the surface of the aluminum foil. The picture of internal arrangement of 4- stage MEMD module is shown in fig. 2(a) and the assembled module is shown in fig. 2(b).

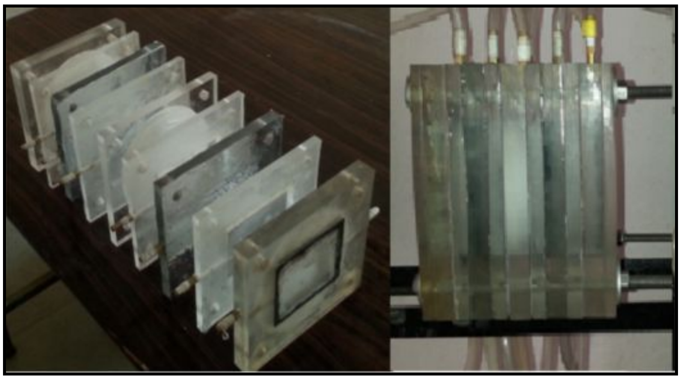

Fig.2. (a) Picture of internal arrangement of MEMD module and (b) Picture of assembled MEMD module

2.3. Experimental setup and procedure

The schematic of 4-stage MEMD system is shown in fig. 3. A 20 liter capacity of the first feed tank (cooling tank) contained fresh feed water, which is used as coolant circulates through the cooling channels of the module. The internal latent heat of vaporization is added in the cooling water (fresh feed) during the condensation of water vapor. After that sensible heat is recovered in the heat exchanger from the hot brine solution. Then external heat is supplied to the second feed tank. The feed is circulated from the feed tank to the first feed channel by using the circulation pump (0.5 hp). The Rotameter is used to measure the flow rate of the feed. The inlet and outlet temperature of feed and cooling channels were measured by thermocouples of pt100 sensors.

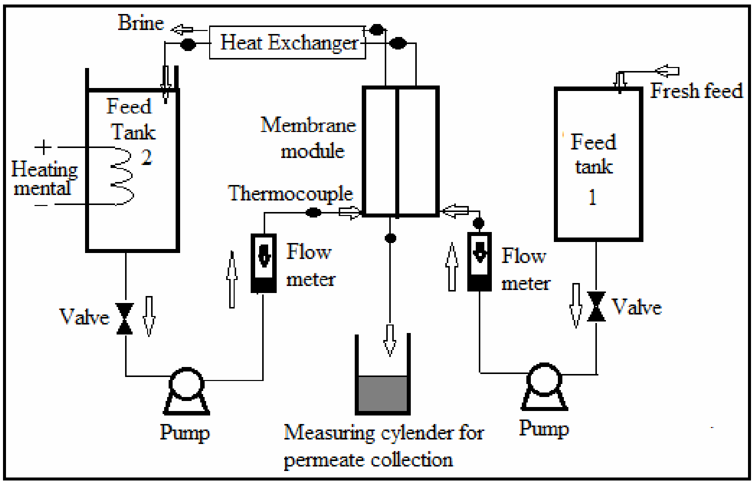

Fig.3. Schematic diagram of MEMD experimental setup

The experiment was carried out for the treatment of synthetic wastewater having TDS of 4630 mg/L and conductivity of 14350 µs/cm. The performance of the 4-stage MEMD process was analyzed in terms of the GOR, energy consumption and thermal efficiency. Also the results are compared with the traditional AGMD system which is a first stage of this system. The effects of module geometry and operating conditions like feed temperatures and flow rates on the GOR of 4-stage MEMD module were studied. The permeation rate is used to evaluate the performance of the module. The calculations of the performance parameters of the module such as permeate flux; GOR, specific energy consumption and thermal efficiency of the module are shown in Table 2.

Table 2. MEMD performance parameter calculations

Parameter	**Calculation equation**
Permeate flux, J_D (L/m^{2}h)	$= \frac{V}{A\,t}$
% 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

3. Results and discussion

3.1. Effect of feed flow channel depth on GOR of 4-stage MEMD module

MD module geometry and design can have a dramatic effect on the GOR [31]. Hence the precise design of the module is an important for the MD module performance. The effect of feed flow channel depth of 4-stage MEMD module on GOR and permeate flux results are shown in fig.4. The GOR were calculated for without heat recovery, and also with recovery of internal latent heat of water vapor and hot brine sensible heat. The feed flow channel depth of each stage varied from 5 to 15 mm. The input energy requirement was decreased due to the recovery of heat in the module. Hence the GOR was increased by the heat recovery in the system. The Reynolds number of the feed in the feed flow channel increases due to decreasing the hydraulic diameter or depth of the channel. The permeate water rate increases due to increasing the Reynolds number of feeds and hence GOR increases. The maximum GOR of 4-stage MEMD module after all heat recovery was achieved about 1.19 at the feed flow channel depth about 5 mm. The maximum flux was achieved about 42.75 L/m^{2}h. During all the experiment, the TDS and conductivity removal of water was found about > 99.6%.

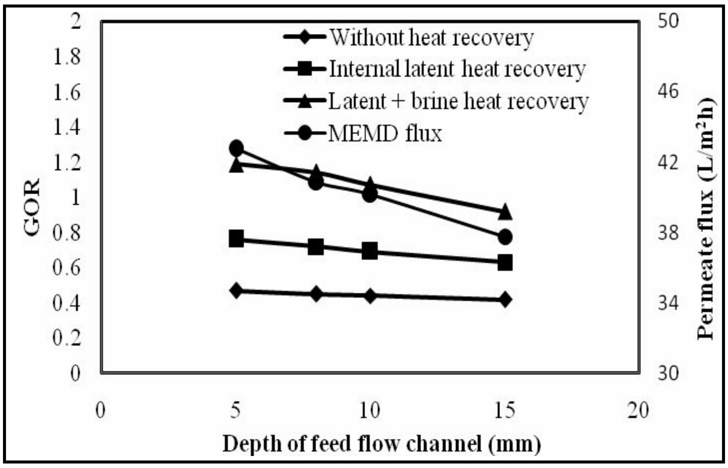

Fig.4. Effect of depth of feed flow channel on GOR and permeate flux of 4-stage MEMD (feed flow rate = 0.5 L/min, T_f = 80 ^{0}C, coolant flow rate in each channel = 0.25 L/min, T_{fresh} = 27 ^{0}C, air gap thickness = 2 mm)

3.2. Effect of air gap thickness on GOR of 4-stage MEMD module

Air gap separation is an important effect on the permeate flux. In the AGMD process, the air gap is an extra mass transfer resistance added in the overall resistance. Hence increasing the air gap thickness, decreases the permeate flux. The less resistance in the flow channel increases the Reynolds number and convective heat transfer coefficient, decreases the heat transfer resistance in the channel. The decrease of an air gap thickness increasing the permeate flux, it has a positive effect on the GOR. The effect of air gap thickness on the GOR and permeate flux of 4-stage MEMD module was shown in fig. 5. As increasing the air gap thickness the GOR of 4-stage MEMD system was decreasing. The GOR were calculated after the internal latent heat and hot brine sensible heat recovery. The GOR decreases from 1.19 to 0.25 when the air gap in each channel increases from 2 to 10 mm. The lower air gap thickness in the MEMD module gives advantages as high GOR and permeates flux, low heat transfer resistance and high convective heat transfer hence high internal latent heat recovery.

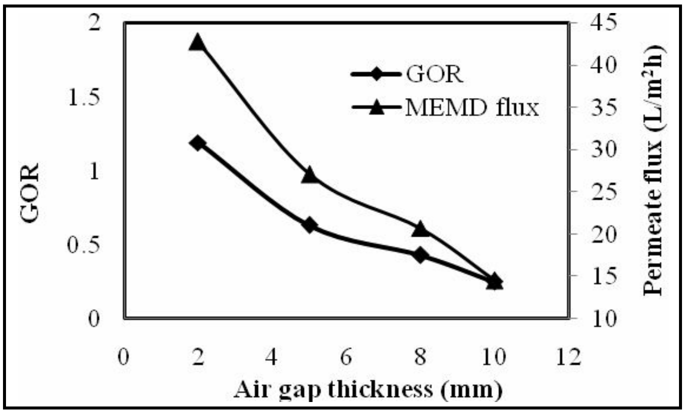

Fig.5. Effect of air gap thickness on GOR and permeate flux of 4-stage MEMD module (feed flow rate = 0.5 L/min, T_f = 80 ^{0}C, coolant flow rate in each channel = 0.25 L/min, T_{fresh} = 27 ^{0}C, depth of feed flow channel = 5 mm)

3.3. Effect of feed temperature on GOR of 4-stage MEMD module

The varying operating temperatures on the GOR and permeate flux of 4-stage MEMD module is shown in fig. 6. As increasing the feed temperature, increases the GOR. But increasing the feed temperature increases the demand on the heater. As recovery of the internal latent heat of water vapor and sensible heat of brine, decreases the demand on the heater. Also, the permeate flux increases due to increasing the feed temperature. The greater flux increases the water production rate for a net increase on GOR. The feed temperature varies from 40 to 80 ^{0}C. The GOR of 4-stage MEMD system after all heat recovery was achieved about 1.19 at feed temperature about 80 ^{0}C.

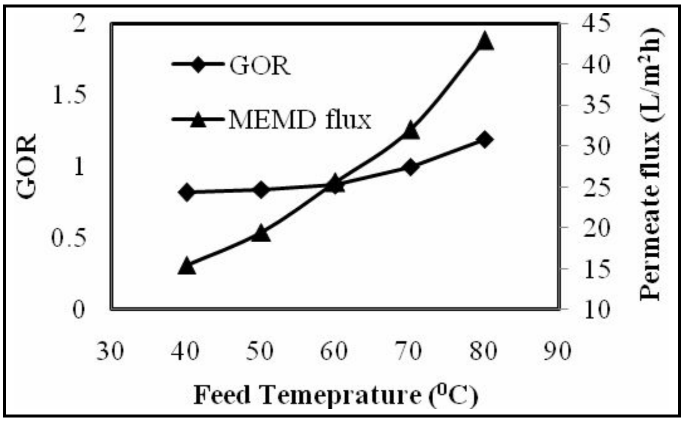

Fig.6. Effect of feed temperature on GOR and permeate flux of 4-stage MEMD (feed flow rate = 0.5 L/min, coolant flow rate in each channel = 0.25 L/min, T_{fresh} = 27 ^{0}C, air gap thickness = 2 mm, depth of feed flow channel= 5mm)

3.4. Effect of feed flow rate on GOR of 4-stage MEMD module

The feed flow rate is a sensible parameter which has to be adjusted pore precisely [27]. Fig. 7 shows the effect of feed flow rate on the GOR of 4-stage MEMD system. The results show that the GOR can be maximized at the low feed flow rate. Feed flow rates under about 0.5 L/min in each feed flow channel yield relatively high GOR greater than unity. After feed flow rate about 0.6 L/min in each feed flow channel the GOR goes below 1 and decreases slowly. This indicates that, GOR is high at low feed flow rate due to lower heat required to raise the temperature of the feed to its top temperature. But at very low feed rate and temperature, the production rate of water is very low. Hence, to adjust the feed flow rate such that the extra high temperature brine and over concentrated feed should not be produced at higher and lower feed flow rate respectively. In this 4-stage MEMD module, the feed flow rate about 0.5 L/min in each feed flow channel gives the best results, and GOR and flux can be obtained about 1.19 and 61.07 L/m^{2}h respectively.

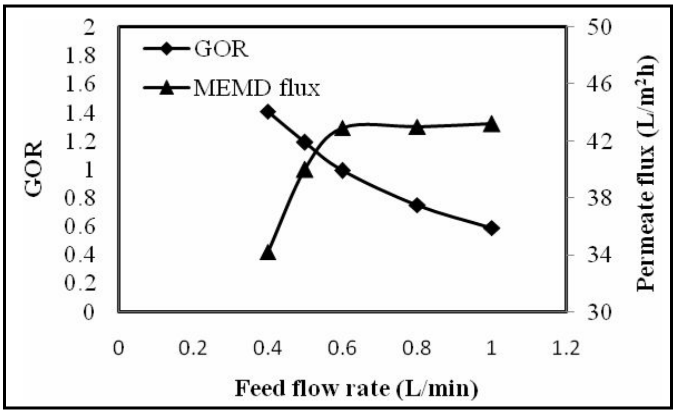

Fig.7. Effect of feed flow rate on GOR and permeate flux of 4-stage MEMD ($T_f = 80\ ^0C$, coolant flow rate in each channel = 0.25 L/min, $T_{fresh} = 27\ ^0C$, air gap thickness = 2 mm, depth of feed flow channel = 5mm)

3.5. Energy consumption in 4-stage MEMD system

The requirement of specific thermal energy in the MEMD system is evaluated in this section. Before feed flow thorough the 1st stage of MEMD, the feed was preheated from the ambient temperature to the higher temperature and then partially evaporated. Hence the energy consumption is high. If the feed temperature is naturally higher, then the requirement of energy is low for increasing the feed temperature to reach the top temperature level. This is possible when proper recovery of the heat in the module. In this MEMD module, the latent heat of vaporization of water vapor during the condensation process was recovered in the feed water, which is used as cooling water flow through the cooling channels. After that the sensible heat of hot discharged brine also recovered in the heat exchanger. Hence the less energy is required to increase the feed temperature after heat recovery.

Fig. 8 shows this data as a function of feed temperature. The specific energy consumption in the 4-stage MEMD module was increased with increasing the feed temperature when there is no heat recovery. If the internal latent heat and sensible heat was recovered in the feed water, then the opposite trend was observed in the specific energy consumption. It was decreases with a rise in the feed temperature. The specific energy consumption respectively was about 1.354 kWh/kg and 0.53 kWh/kg when without heat recovery and after all heat recovery in the module at a higher feed temperature about 80 ^0C.

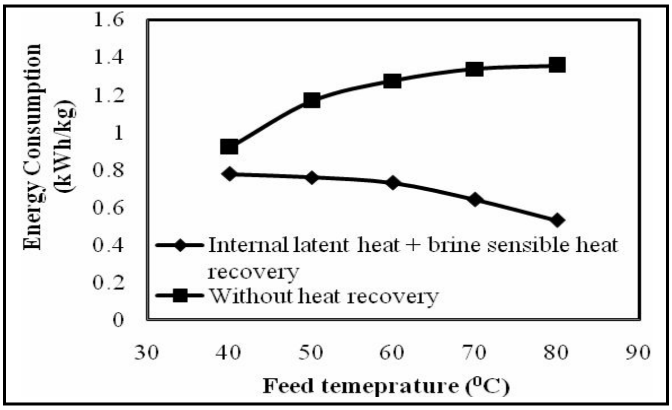

Fig.8. Effect of feed temperature on specific energy consumption in 4-satge MEMD system

3.6. Thermal efficiency of 4-stage MEMD module

Thermal efficiency in the MD module is the ratio of the latent heat of vaporization to the total heat. The thermal efficiency of the MD process can be improved by increasing the feed temperature, feed flow rate and membrane thickness [33]. Fig. 9 shows the effect of the feed temperature on the thermal efficiency of 4-stage MEMD system. The result shows that the thermal efficiency of the system was increased with the feed temperature. In this system the latent heat of vaporization is higher than the heat by conduction and it is increased by increasing the feed temperature. Also, at high feed temperature the permeate flux was increased and this also gives higher thermal efficiency. The maximum thermal efficiency of the 4-stage MEMD module was reached about 356.14% of feed temperature about 80 ^{0}C. The thermal efficiency was increased by 97% by increasing the feed temperature from 40 to 80 ^{0}C due to increasing the permeate flux and latent heat of vaporization.

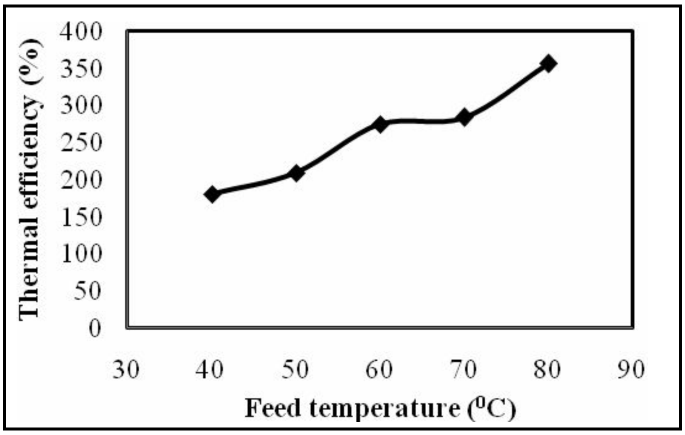

Fig.9. Effect of feed temperature on thermal efficiency of 4-stage MEMD module

3.7. Comparative study of the performance of 4-stage MEMD module with traditional AGMD module

In this study, the MEMD module was prepared based on the AGMD configuration. The fig. 10(a) shows the comparative results of the performance of 4-stage MEMD and traditional AGMD process. The permeate flux of the AGMD process was about 44.64 L/m^{2}h and 4-stage MEMD process about 42.75 L/m^{2}h. But the permeation rate of 4-stage MEMD module was nearly 4 times of the traditional AGMD module. The permeate flux of the 4-stage MEMD module was slightly lower than the traditional AGMD module due to increasing the membrane area and also temperature drop of the feed in each stage.

Fig. 10(b) shows the comparison of GOR between 4-stage MEMD and AGMD module. The GOR is calculated for both the module for without heat recovery, internal latent heat recovery and the latent along with sensible heat recovery. The maximum GOR of the 4-stage MEMD module was reached about 1.19 and the traditional AGMD module about 0.17 after all heat recovery. Due to the high permeation rate of 4-stage MEMD module the GOR was greater than the traditional AGMD module. Also, larger membrane areas have achieved higher GOR values [31].

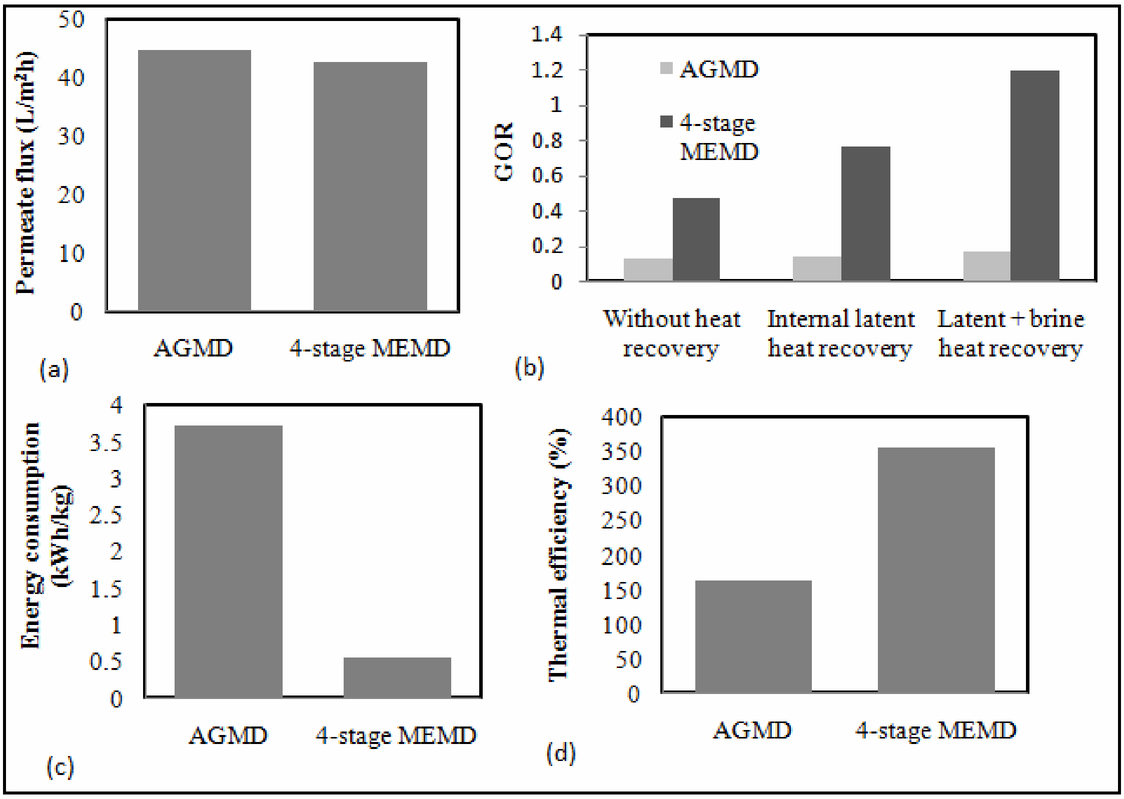

Fig.10. Comparison between traditional AGMD and 4-stage MEMD process for (a) Permeate flux, (b) GOR, (c) energy consumption and (d) thermal efficiency

Also the comparison between both the module for the specific energy consumption and thermal efficiency were shown in figs. 10(c-d). The specific energy consumption in 4-stage MEMD module was found about 0.53 kWh/kg and in AGMD module about 3.72 kWh/kg. Hence the specific energy consumption was lower in 4-stage MEMD as compared to the traditional AGMD process due to the high permeate rate and heat recovery. Similarly, the thermal efficiency of the 4-stage MEMD module was about 356.14% and the AGMD module about 162.64%. This is due to the high evaporation of feed water in the 4-stage MEMD as compared to the traditional AGMD process. The membrane area of 4-stage MEMD module is 4 times greater than the traditional AGMD module.

4. Conclusion

A new 4-stage MEMD module for water treatment with internal latent heat and brine sensible heat recovery was successfully developed, and the performance indicator parameters of the MD was experimentally demonstrated under the different module geometry and operating conditions. The following conclusions were drawn:

1. The energy of the MEMD module was recycled effectively and the GOR of 1.19 of 4-stage MEMD module was obtained.
2. The minimum specific energy consumption of 0.53 kWh/kg was obtained after the heat recovery.
3. The thermal efficiency of 356.14% of 4-stage MEMD module was obtained in all the experiments.
4. The maximum permeate flux of 42.75 L/m^2h of 4-stage MEMD module was obtained which is nearly equal to the traditional AGMD module. But the cumulative permeate rate of 4-stage MEMD module was nearly 4 times of traditional AGMD module.
5. This 4-stage MEMD module was enabled high energy efficient during the comparison with the traditional AGMD system. Hence this system has great potential for implementation of MD technology in the industry.

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