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# Experimental evaluation of multistage direct contact membrane distillation system for water desalination

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**ABSTRACT**

The performance of a multistage direct contact membrane distillation system (MS-DCMD) is experimentally investigated using a laboratory-scale three stages system. The effects of operating conditions on the system performance are studied for parallel, series, and mixed flow stages connections for the feed and coolant streams. Results showed that the productivity of the parallel flow arrangement is well-higher than the series and mixed flow arrangements due to fewer temperature changes from stage to another. The experimental investigation showed that maintaining the feed and permeate temperatures at the required values required high energy consumption for heater and chiller circulation baths due to the high conduction heat transfer between feed and permeate sides across the membrane of the DCMD stages. Energy analysis showed lower specific energy consumption and higher gain output ratio for the parallel flow arrangement of the MS-DCMD system operating at feed temperature around 60°C. Salt rejection factor of 99.7% had been achieved for feed salts concentration of 35 g/L.

*Keywords:* Membrane distillation; Direct contact; Parallel and series multistage; Flux and energy analyses

## 1. Introduction

Due to the limitation of potable water resources and with the increase of the population, industry, and human activities, applying cost-effective and energy-efficient desalination technologies became a necessity to combat water scarcity [1,2]. Water desalination processes have high importance for human beings as they help to secure the potable water needed for drinking and also for industrial, agricultural, and domestic purposes [3,4]. Desalination technologies for large operations have significant capital costs and energy requirements.

Membrane distillation (MD) is a thermally-driven membrane separation technique in which a micro-porous hydrophobic membrane separates the hot feed solution stream and the cold permeate side. Due to the vapor pressure difference developed as a result of the temperature difference across the membrane, a driving force is generated to permeate the vapor in the feed solution across the membrane from the hot feed side to the cold side; where it condenses. MD operates with feedwater below boiling temperature (usually 50°C–90°C), so it can be operated utilizing low-grade waste heat from industrial processes or renewable energy sources such as geothermal and solar energies [5,6]. The European Union funded a project assessing the best available technologies for desalination in local areas [4]. This project assessed the current state of 11 different desalination technologies and mentioned the MD technology as a low cost and effective desalination technique. There are four main configurations for the MD: direct contact membrane

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distillation (DCMD); air gap membrane distillation (AGMD), vacuum membrane distillation (VMD), and sweeping gas membrane distillation (SGMD). These four configurations are classified based on the methods of vapor condensation and collection in the permeate side [8–10].

DCMD configuration has the simplest design and it is the most commonly used design in research and laboratory setups. In DCMD, the membrane is sandwiched between the hot feed solution stream and the cold permeate stream such that both streams are is in direct contact with the membrane surfaces. Evaporation takes place at the feed-membrane interface. The vapor is permeated by the virtue of vapor pressure difference across the membrane and condenses in the cold permeate stream inside the membrane module. However, the main drawback for this configuration is the high conduction heat loss between feed and permeate sides across the membrane [5].

In the 1960's, Findley was the first to introduce MD process with his work on DCMD [6]. His experimental results were based on different membrane materials and he also contributed to the basic theory of the MD technique. By the mid of the 90's, the number of publications that deal with the MD was doubled [7], and a large number of review papers wrote to evaluate the performance of the DCMD [8,6,17]. Martinez and Florido-Diaz [9] studied the MD process from a theoretical point of view, and evaluation for a model based on gas transfer in the porous media showed an agreement with experimental results on a DCMD conducted using two different membrane materials HVHP45 and GVHP22. Li et al. [10] conducted experiments on VMD and DCMD systems using two different microporous hollow-fiber membranes polyethylene (PE) and polypropylene (PP). The experiments showed that with the increase in the feed flow rate and temperature, the flux can increase significantly.

Lawal and Khalifa [11,12] predicted the output flux in DCMD using a theoretical model based on the analysis of the heat and mass transfer through the membrane and developed a statistical model using the analysis of variance technique to determine the significant effect of each operating parameter on the DCMD system performance. Using the Taguchi technique and applied regression, they determined that the maximum positive effect for the DCMD system input variables was for the feedwater temperature and the highest negative effect was for the coolant water temperature. Both the feed and coolant flow rates showed a small difference on the performance of the DCMD system. Khalifa et al. [13] studied experimentally and analytically the performance of a DCMD system. Their model validation with the experimental results showed a maximum error percentage <10%. They reported that the DCMD system has an ability to handle high salt concentration feeds (100 g/L) with a high salt rejection factor. Ahmad et al. [14] did experimental work on DCMD system showing that the salt rejection factor reached almost 100% after continues operation of the system for 48 h; while the gain output ratio (GOR) was between 0.8 and 1.2 for different values of feed inlet temperatures. Cath et al. [15] investigated experimentally a DCMD module to improve the water desalination process. With a turbulence flow regime, three microporous hydrophobic membranes evaluated with a feedwater temperature around 40°C. Their results showed that the careful design of the membrane module may result in a reduction in the temperature polarization and the permeability obstructions, leading to a huge increase in flux at low feed temperatures. Summers et al. [16] investigated the energy efficiency for different MD systems. They compared the GOR value as an indication of the energy utilization of the system. Increasing the feed temperature and the membrane length led to a tremendous increase in the GOR value for the DCMD and the AGMD while the GOR for the VMD was much lower than the other configurations.

Several attempts have been made at the industrialization of the MD systems and have repeatedly faced different challenges. Challenges include; permeate flux is still lower than well-established industrial techniques (multi-stage flash distillation, multi-effect distillation, reverse osmosis), membrane wetting problem, the absence of perfect energy recovery technique, lack of the perfect design of membrane cell (module). The multistage design of membrane distillation systems (MS-MD) can be a true solution for many industrial applications.

Lee et al. [17] assessed theoretically a hybrid multistage vacuum membrane distillation (MS-VMD) and a pressure-retarded osmosis system to produce freshwater and power. Pangarkar et al. [18] studied experimentally and theoretically the performance of a multi-effect AGMD system. The maximum flux of the system achieved was 166.38 $L/m^2h$, which is 3.2–3.6 times larger than the single-stage AGMD process. Lee et al. [19] made a comprehensive numerical analysis of productivity, the water product cost, and the membrane wetting problem to find the best arrangement for the system. He found that the mixed MVMD system with 20 stages, the highest productivity (3.79 $m^3/d$), lowest water product cost ($1.16/$m^3$), and lowest maximum trans-membrane pressure difference (93.8 kPa) in the studied arrangement. Geng et al. [20] investigated a multi-stage AGMD process for further concentrating RO brine and obtaining a high water recovery. In the 14 AGMD processes, the maximum value of the recovery and the minimum value of the flux were 82.2% and 3.9 $kg/m^2h$, respectively.

Gilron et al. [21] and He et al. [22] designed a cascade of a crossflow multistage DCMD system to maximize energy recovery. The GOR reached 20 in the system but with low terminal temperature differences for the DCMD and the heat exchangers, and they improved the system to maintain a good energy recovery rate by using inter-stage heating of brine between each cascade. Lee et al. [23] presented a theoretical analysis of the monthly average, daily, and hourly performances of a solar-powered multistage direct contact membrane distillation (MS-DCMD) system. The number of module stages used by the dynamic operating scheme changes dynamically based on the inlet feed temperature of the successive modules. They found that the monthly average daily water production increases from 0.37 to 0.4 $m^3$/day and thermal efficiency increases from 31% to 45% when comparing systems both without and with the dynamic operation.

In this paper, the performance of the MS-DCMD system is experimentally investigated at different operating parameters and with different flow stages connections (parallel, series, and mixed arrangements). Furthermore, the power consumed by the MS-DCMD system is measured and analyzed for different cases. As MD technology for water desalination is slowly moving out of laboratories to industrial applications, the benchmark data presented in the current study would be useful for researchers looking for scaling MD systems for field testing.

## 2. Experimental Work

The layout of the three-stage DCMD system is shown in Fig. 1. The system consists of two water closed cycles, hot and cold, connected to the three MD modules. The system includes a circulation water chiller which supplies cold water flow at a specified temperature and flow rate, an electric heater circulating bath to supply the hot feedwater stream at the desired temperature and flow rate, connection pipes and valves, and the three DCMD modules where the water vapor separation and condensation process takes place. The two cycles are manually controllable using a set of valves to change between different flow arrangement (parallel, series, and mixed). Thermocouples installed at the inlet and exit of each module chamber to measure the temperature of the feed and permeate streams. Furthermore, the flow rates of the feed and permeate streams are measured using rotameters and turbine flow meters. Pressures are monitored at the inlet and exit of each stage using pressure gages. The electric power consumed by the heater and the chiller is measured using power transducers. All sensors are connected to a National Instruments data acquisition system for monitoring and recording using a LabVIEW code. As the vapor condensation process occurs in the three modules, the permeate volume level increases in the chiller bath. A small tube is installed at a certain level in the chiller bath to continuously take the condensed vapor out of the chiller bath for measurement.

Fig. 2 shows a photo of the experimental multistage DCMD system and the details of the MD single module (stage) design. High-Density-Poly-ethylene material is used to fabricate two chambers in each cell with total dimensions of 210 mm width, 210 mm length, and 40 mm thickness. The MD module chambers are feed chamber and cooling chamber, with two flow channels in each chamber. Rubber gaskets, with 1.5 mm thickness, are inserted between the module components to prevent internal and external leakage. The module flow channels were machined using a computer numerical control machine. Three different flow connections/arrangements (Parallel, Series, and Mixed) between system stages are investigated in this study as shown in Fig. 3. In parallel flow stages-connection (Fig. 3a), both feed and permeate waters are pumped in parallel to all modules such that the inlet temperatures to all modules are equal. In the series flow arrangement (Fig. 3b), the feed and permeate streams are pumped to the first module chamber on each side. The flow goes from the first module to the second then to the third one and then returns to the circulation bath. For the mixed flow stages connection, the feed stream

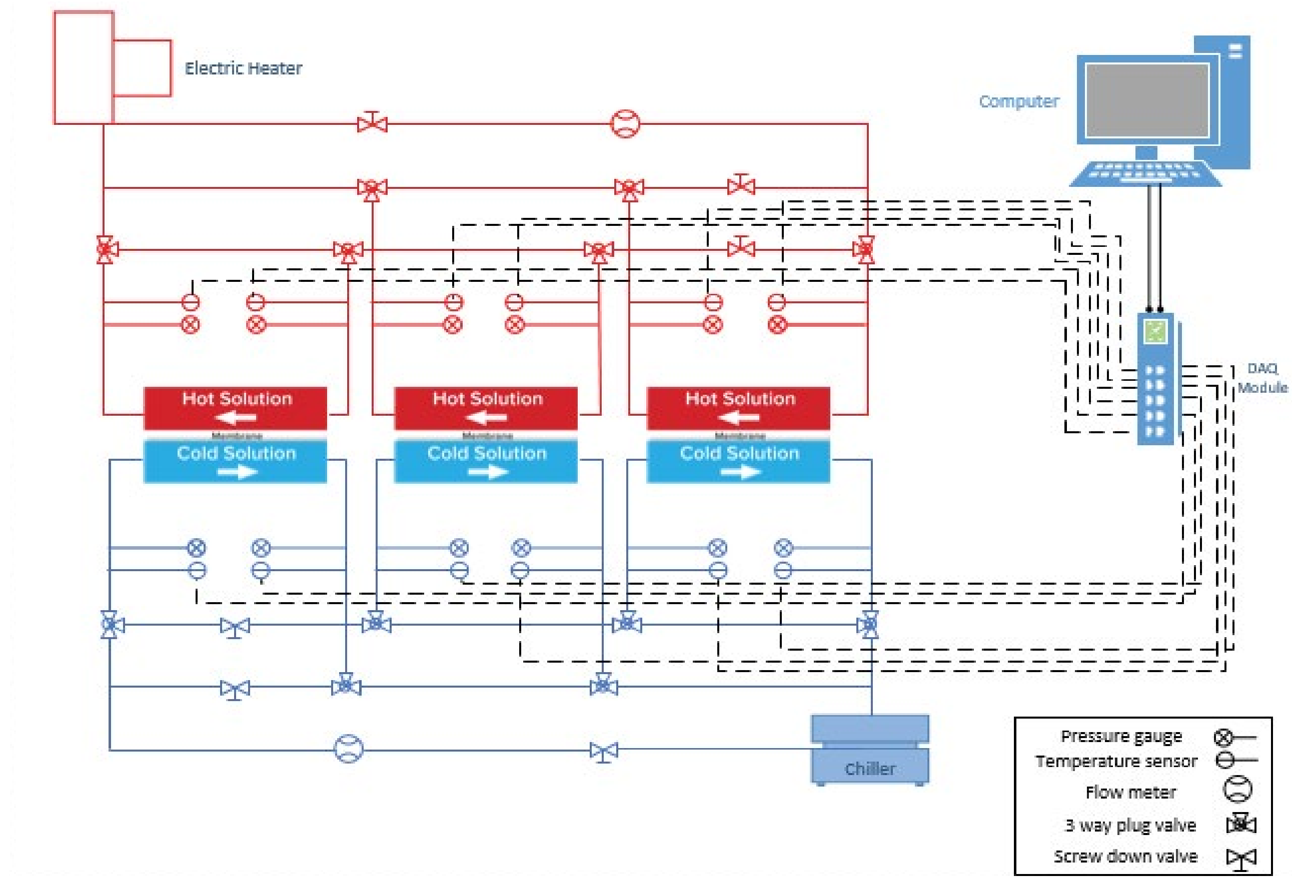
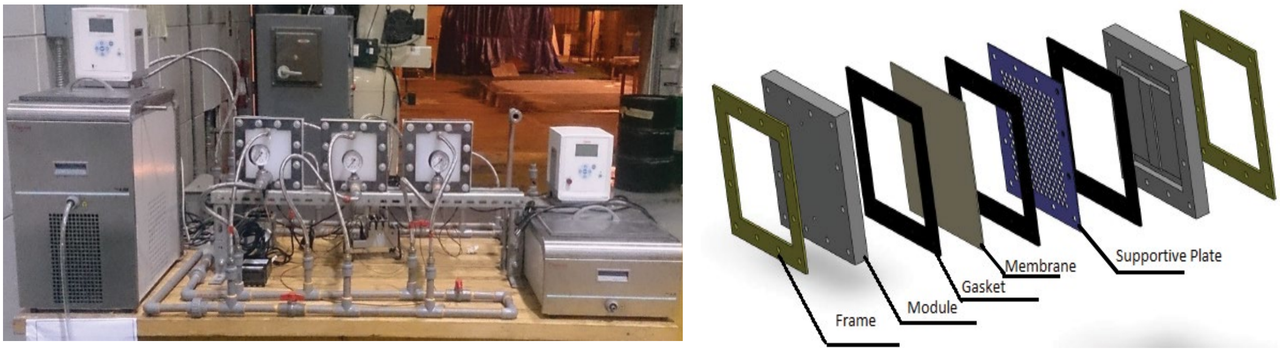
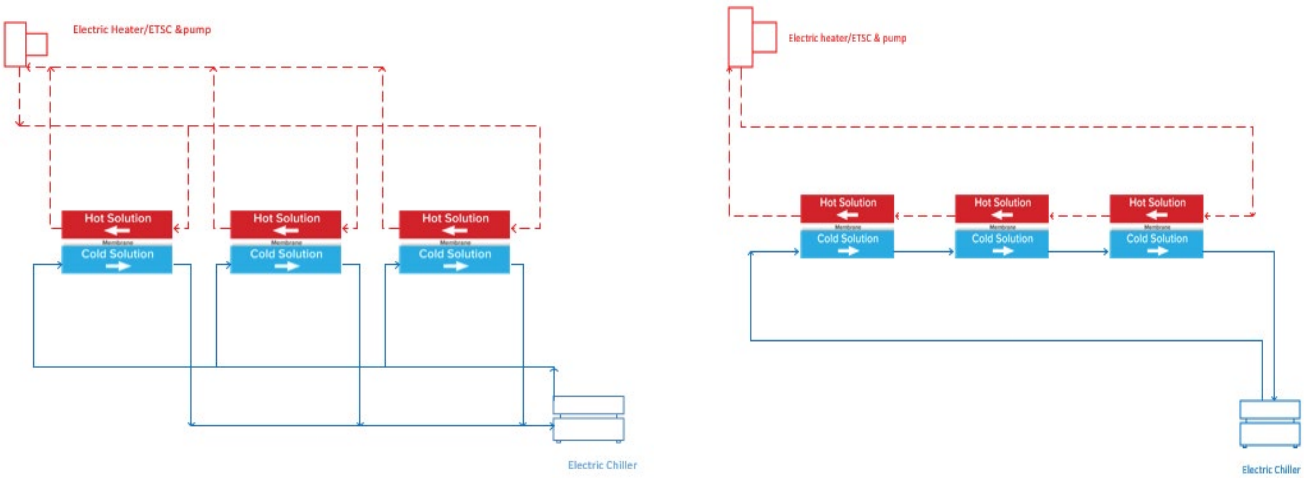



Fig. 1. Layout of the multistage DCMD system.

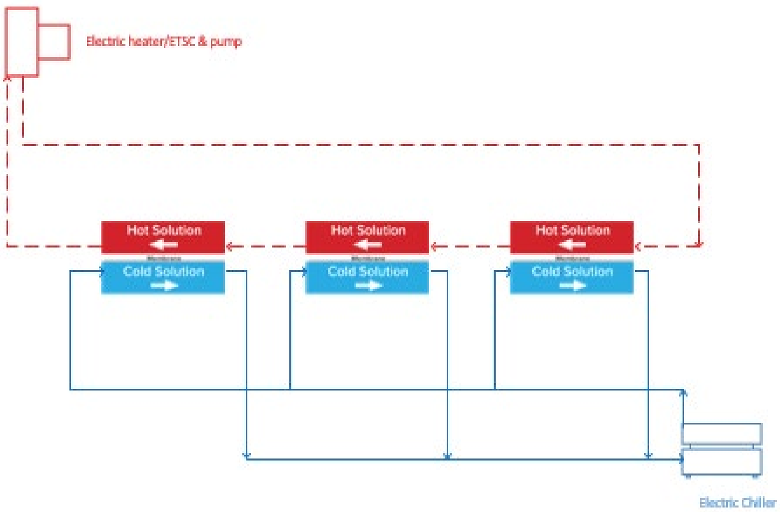



(a) Experimental setup (b) Stage design

Fig. 2. Experimental setup and components of a single-stage DCMD module. (a) Experimental setup and (b) stage-design.




(a) Parallel flow stages connection (b) Series flow stages connection




(c) Mixed flow stages connection

Fig. 3. (a) Parallel, (b) series, and (c) mixed flow arrangements for feed and permeate streams.

is connected in series with the three MD modules, while the permeate stream is connected in parallel with the three MD modules; Fig. 3c.

The operating parameters that are investigated are the feed temperature, feed flow rate, permeate temperature, permeate flow rate, and feed concentration. The experiments are conducted by studying the effect of changing one of these variables with different flow arrangements. The experimental plan is presented in Table 1.

Reynolds number is a dimensionless number representing the ratio of inertia forces to viscous forces.

$$\mathrm{Re} = \frac{VD_h}{\upsilon} \quad (1)$$

where $V$ is the mean flow velocity, $D_h$ is the hydraulic diameter of the non-circular flow channel, and $\upsilon$ is the fluid kinematic viscosity which is mainly a function of fluid temperature. Re varies with the water flow rate and water temperature.

Based on our module design, the internal flow rectangular channels dimensions are 60 mm width and 5 mm height.

Considering the flow rate and temperature ranges investigated in the current study as shown in Table 1, the Re values are always less than 2,300 in all test combinations of operating conditions, and thus the flow in the module is always laminar.

It should be mentioned that due to the capabilities of the used setup, heater, and chiller internal pumps, the maximum flow rates of hot feed water and coolant water are limited to laminar flow situations.

The hydrophobic membranes used in all experiments are 0.22 μm polytetrafluoroethylene (PTFE) membrane hydrophobic membranes acquired from Tisch Scientific. Table 2 shows the measured properties of the used membranes. It is worth noting that PTFE membrane is composed of two layers, a thin active layer, and a support layer. The measured properties included the actual overall thickness ($\delta_{membrane}$), the active layer thickness ($\delta_{active}$), the mean pore size ($d_p$), the porosity ($\varepsilon$), the water contact angle ($\theta$), and the liquid water entry pressure (LEP).

We have three identical modules in our setup. The membrane surface area is the same in each module with an effective permeation area of 0.006534 m$^2$, and thus the total membrane surface area for the three modules = 0.019602 m$^2$. The flux of each module was calculated based on the module area, and the system flux of the three modules is calculated based on the membrane areas in the three modules.

Table 1
Experimental plan

| Variable | Range |
|---|---|
| Feed temperature | 40°C–90°C |
| Coolant temperature | 15°C–25°C |
| Flow rate of feed (parallel) | 5–7 L/min |
| Flow rate of feed (series) | 1.67–3 L/min |
| Flow rate of coolant (parallel) | 4–6 L/min |
| Flow rate of coolant (series) | 1.3–3 L/min |
| Feed concentration | 150; 3,550; and 35,000 mg/L |

## 3. Results and discussion

The multistage direct contact MD system performance is studied by investigating the effect of different operating conditions such as feed temperature, permeate temperature, feed flow rate, permeate flow rate, and feed concentration on the system output permeate flux. The performances of different flow arrangements (parallel, series, and mixed) are examined and compared in terms of output flux at different operating conditions. Furthermore, the electric power consumption is used for the energy analysis of the MS-DCMD system. The permeate flux of the MS-DCMD system is calculated based on the permeate volume collected over the experiment time and the effective permeation membranes area of the three stages system. For each experimental run, the system needs to reach thermal equilibrium before data collection. Thermal equilibrium is reached when system temperature probes show stable readings. Minimum sampling time of 15 min was adopted after reaching the thermal steady-state condition.

### *3.1. Effects of system operating conditions*

#### *3.1.1. Effect of feed water temperature at different feed flow rates*

The effects of feed water temperature at different feed flow rates ($q_f$) are studied for the MS-DCMD. Fig. 4 shows the effect of varying feed temperature at different feed flow rates on the permeate flux for the three stages in the MS-DCMD system in case of the parallel and series flow arrangements. The feed temperature is changed from 40°C to 90°C with 1°C increment. Permeate side temperature is kept at 25°C and feed concentration of 3,500 mg/L is used.

For parallel stage connections (Fig. 3a), the total feed flow rate entering the three stages is changed from 5 to 7 L/min with 1 L/min increment; while the total permeate flow

Table 2
Measured properties of the PTFE membranes

| | Membrane characteristics | | | | | |
|---|---|---|---|---|---|---|
| Membrane type | $\delta_{membrane}$ (μm) | $\delta_{active}$ (μm) | $d_p$ (nm) | ε (%) | θ (°) | LEP (bar) |
| PTFE-SF17385 (0.22 μm) | 159 ± 18 | 8 ± 2 | 236 ± 6 | 76 ± 5 | 138 ± 2 | 3.3 ± 0.1 |

$\delta_{membrane}$, membrane thickness; $\delta_{active}$, thickness of membrane active layer; $d_p$, mean pore size; ε, porosity; θ, water contact angle; LEP, liquid water entry pressure.

rate is set at 6 L/min (so, 2 L/min for each stage). In the parallel flow arrangement, the total flow supplied for feed and permeate sides is divided equally between stages. Testing of the system showed negligible maldistribution of flow between the three stages. The measurement of the system flux (from the three stages) started when the steady-state operating conditions are reached. As shown in Fig. 4a, the permeate (vapor) flux increases with the increase in feed temperature and feed flow rate. Increasing the feed temperature increases the vaporization rate in the feed side and consequently the vapor pressure difference across the membrane (the transmembrane potential). For instance, the percentage increase in the permeate flux due to change the feed temperature from 40°C to 90°C at total feed flow rate 7 L/min is 374.34% while the percentage increase in the permeate flux due to change the feed flow rate from 5 to 7 L/min at 90°C feed temperature is 31.04%. It should be noted that for parallel stage flow arrangement each stage is receiving the same flow rate at the same temperature for both feed and permeate sides. This means that each stage will have the same temperature drop between the inlet and outlet of each flow stream, and eventually, each stage will produce the same amount of distilled water. Thus, one can multiply the productivity on one stage by three to get the total amount of distilled from the multistage parallel flow DCMD system.

For the series flow arrangement (Fig. 3b), the feed flow rate entering stages in series is changed from 2 to 3 L/min with 0.5 increments. This range of flow rate was selected to be very close to the single-stage flow rate of the parallel connections for the sake of comparison. Note that the maximum experimental flow rate in series connections is reduced due to friction in the feed and coolant channels of the three stages. Permeate flow rate passing the modules in series is fixed at 2 L/min. Fig. 4b shows the effects of varying the feed temperature and feed flow rate on the permeate flux for the three stages of the MS-DCMD system in case of the series flow arrangement. A similar trend of flux increasing with the increase in feed temperature and feed flow rate. Percentage-wise, flux increased by 336.4% when changing feed temperature from 40°C to 90°C at a total feed flow rate of 3 L /min, and about 35.59% increase in flux when changing feed flow rate from 2 to 3 L/min at 90°C feed temperature. However, the slope of flux increase is lower compared to parallel stage connections. This behavior is due to the fact that the feed temperature drops continuously from stage to stage and the permeate temperature is increasing continuously from stage to stage in the series connection that results in decreasing the productivity as we go from the first stage to the last stage. If one compares the measured flux for both connections, parallel and series, at 2 L/min flow rate for each stage (total of 6 L/min in the parallel case and 2 L/min for series), the flux is about 80 kg/m$^2$.h for the parallel connection and about 55 kg/m$^2$ h for the series connections.

The percentage increase in permeate flux when changing the stages flow connection from series to parallel is shown in Fig. 4c when the feed and permeate flow rates are set at 2 L/min for each stage. On average, one can report a 40% increase in flux in favor of parallel stage connections over series connections. The lower productivity of series stage connections is attributed to the temperature changes

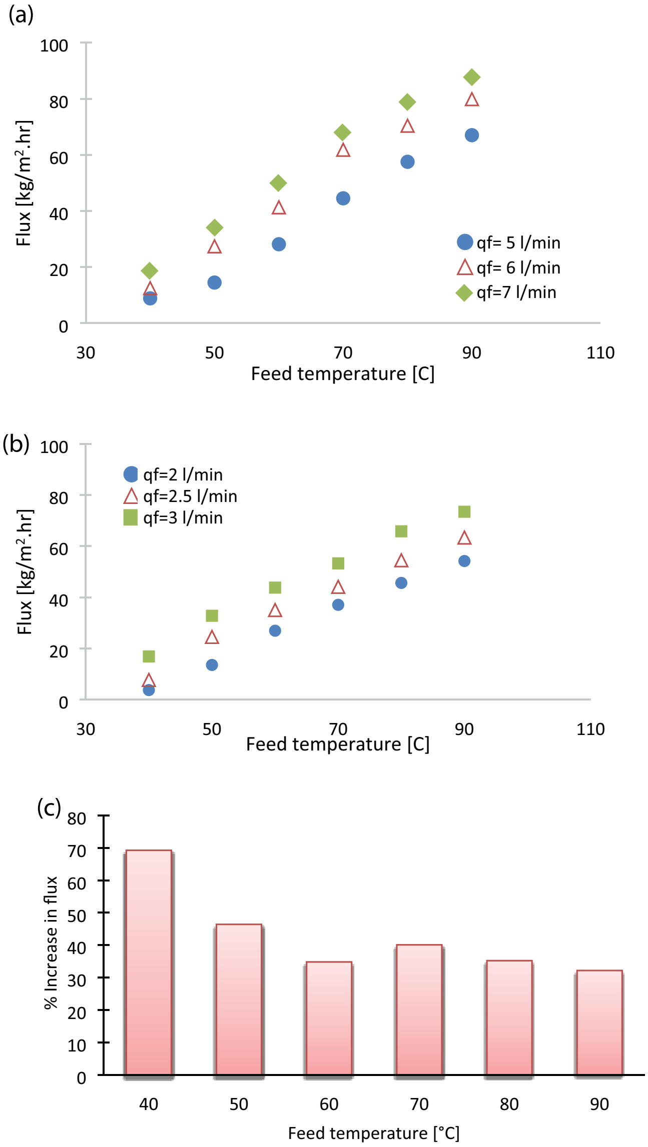



Fig. 4. Variation of multistage system flux with feed temperature at different feed flow rates. Conditions: Permeate temperature 25°C, feed salinity 3,500 mg/L, and permeate flow rate of 2 L/min for each stage. (a) Parallel flow arrangement, (b) series flow arrangement, and (c) percentage increase in flux when changing from series to parallel connections of stages.

from stage to stage which reduced the transmembrane potential for vapor permeation in the progressive stages.

*3.1.2. Effect of feed temperature at different permeate flow rates*

The variations of the permeate flux with the feed temperature are shown in Fig. 5, at different permeate flow rates ($q_p$) for parallel and series flow stage connections. Increasing the permeate flow rate of the MS-DCMD leads to higher values of the mass and heat transfer coefficients in the permeate side of the stages, and that improves the transmembrane potential of vapor permeation. For instance, the percentage

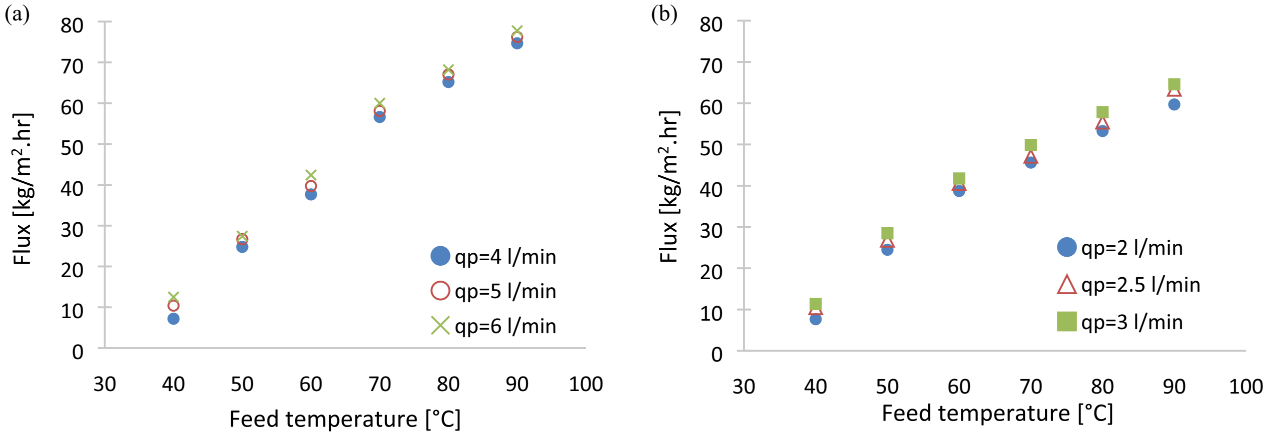



Fig. 5. Variations of flux with feed temperature at different permeate flow rates ($q_p$) for the (a) parallel and (b) series flow arrangements. Conditions: permeate temperature 25°C, feed salinity 3,500 mg/L, and feed flow rate of 2 L/min for each stage.

increase in the flux due to changing permeate flow rate from 4 to 6 L/min at 90°C feed temperature is 4.1% for the parallel flow stages connections. For series flow arrangement, flux increased by 8.2% when the permeate flow rate increased from 2 to 3 L/min, at 90°C feed temperature. It is noted that the effect of increasing permeate flow rate is much less than the effect of increasing feed flow rate as presented earlier in Fig. 4.

#### *3.1.3. Comparison between parallel, series, and mixed flow arrangements*

The mixed flow arrangement (series feed—parallel permeate) of the MS-DCMD system has been tested and compared to both the parallel and series flow arrangements as shown in Fig. 6, at different feed temperatures (Fig. 6a) and feed flow rates (Fig. 6b). In this experiment, hot feed water is supplied in series through system stages at 2 L/min, while cold permeate is supplied in parallel with a total flow rate of 6 L/min such that 2 L/min of permeate is delivered to each stage. The output permeate flux of the MS-DCMD system with parallel flow arrangement is greater than both the mixed and series flow arrangements. This is due to the higher temperature difference across the membrane applied to each stage in the parallel flow arrangement compared to the other two arrangements. Under those test conditions, 20% increase in the permeate flux was recorded due to changing the flow arrangement from series to mixed, and 32.18% when changing from series to parallel, at feed temperature of 90°C, Fig. 6a. Similar behavior was observed with variable feed flow rate at constant feed temperature of 50°C as shown in Fig. 6b. At feed flow rate 2.3 L/min, flux increased by 17.5% when flow arrangement was changed from series to mixed, and 28.76% when changed from series to parallel flow arrangement. At constant feed temperature, increasing the feed flow rate from 1.7 to 2.3 L/min (37% increase in feed rate) resulted in 140% increase in flux for parallel, series, and mixed flow connections of the three stages. This considerable enhancement in MS-DCMD system flux with a relatively small increase in feed flow rate proves the important effects of flow rates on the performance of DCMD system, as well as the temperatures of hot and cold streams.

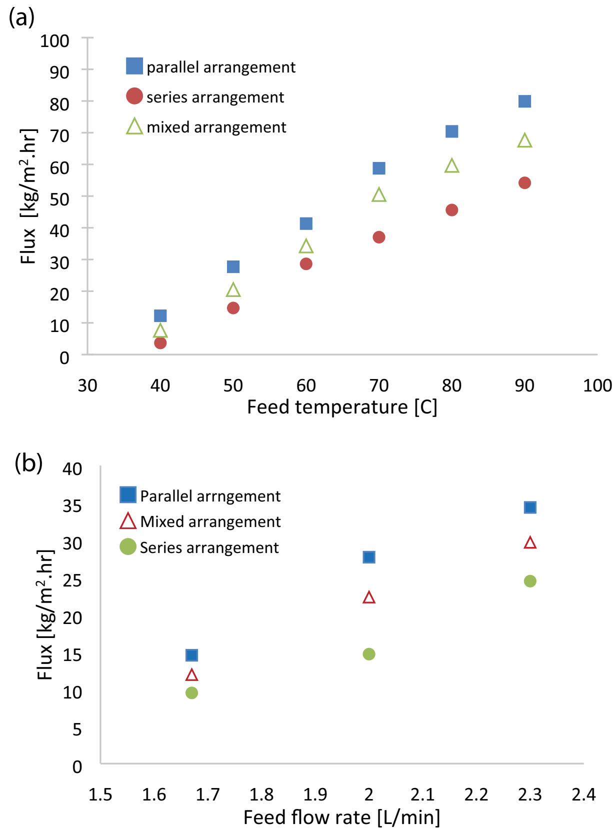



Fig. 6. Comparison between parallel, series, and mixed flow arrangements. Conditions: permeate temperature 25°C, feed salinity 3,500 mg/L, feed and permeate flow rates of 2 L/min for each stage. (a) Effect of feed temperatures, (b) effect of feed flow rate—feed temperature 50°C.

#### *3.1.4. Effects of feed temperature on system flux at different flow and temperature ratios*

Based on data presented above, it is believed that the flow and temperature ratios between hot feed and cold permeate streams determine the performance and control the output flux of the 3-stages DCMD system. Better design options of the operating conditions and understanding of the MS-DCMD performance and flux variation can be represented with variable flow rate ratio ($q_f/q_p$) and temperature ratio ($T_f/T_p$). Fig. 7 shows the variation of flux with feed temperature at different flow ratios of hot and cold streams. The tested range of flow ratios represents the setup limits with the stable flow in all stages without flow maldistribution where minimum flow rate and pressure are required. The increase in the flow ratio causes an increase in the permeate flux at different feed temperature for both the parallel and series flow arrangements. Flow rate ratio shows higher effects in the case of parallel connections of flow between stages due to the fixed temperature difference across membranes of all stages.

Fig. 8 shows a combined effect of flow ratio and temperature ratio on MS-DCMD flux. Operating the system at higher flow and temperature ratios is definitely recommended. Higher temperature ratio means higher permeation potential across the membrane while higher flow rate ratio means higher heat and mass transfer coefficients in the MD system. Again, the effect of temperature ratio is more effective for parallel stages of flow connections. The optimum flow ratio should be investigated for a given design of MD system to avoid increasing the flow rates without real improvement in flux while energy consumption increases with flow rate for a given inlet temperature.

### 3.1.5. Effect of feed salts concentration on the permeate flux

The effect of feed salts concentration on the permeate flux of MS-DCMD system is shown in Fig. 9. The three flow connections, parallel, series, and mixed arrangements, have been tested with three feed concentrations of 150; 3,550; and 35,000 mg/L. The system operating conditions are listed below Fig. 9, where the feed and permeate flow rates are adjusted to 2 L/min for each stage for the three flow arrangements. We can observe from Fig. 9a that flux decrease with the increase in feed salinity for the three flow arrangements. Increasing feed salts concentration reduces the vapor

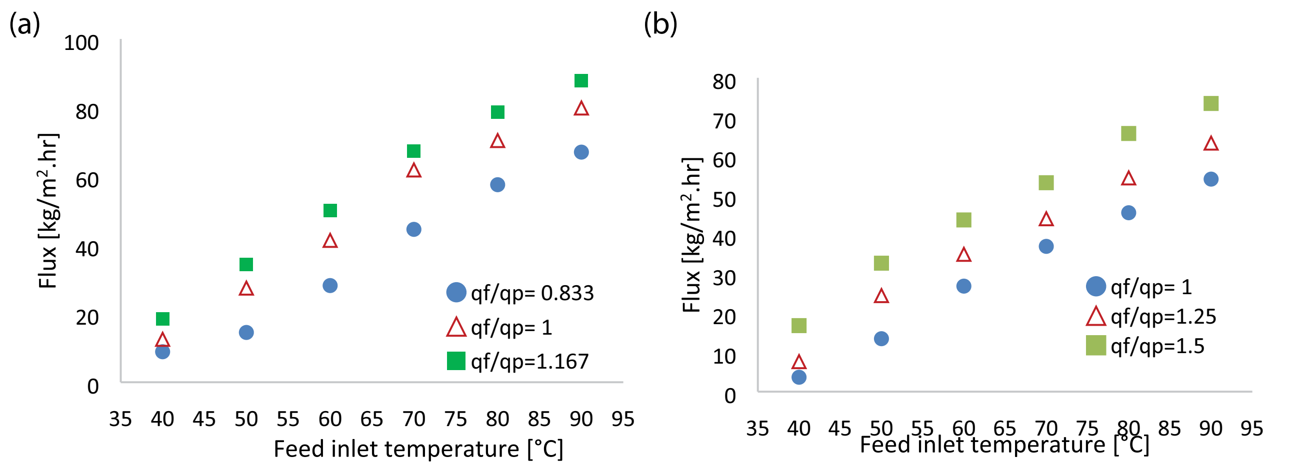



Fig. 7. Effects of feed temperature on system flux at different flow ratios. Conditions: permeate temperature 25°C, feed salinity 3,500 mg/L, and permeate flow rate of 2 L/min for each stage. (a) Parallel flow arrangement and (b) series flow arrangement.

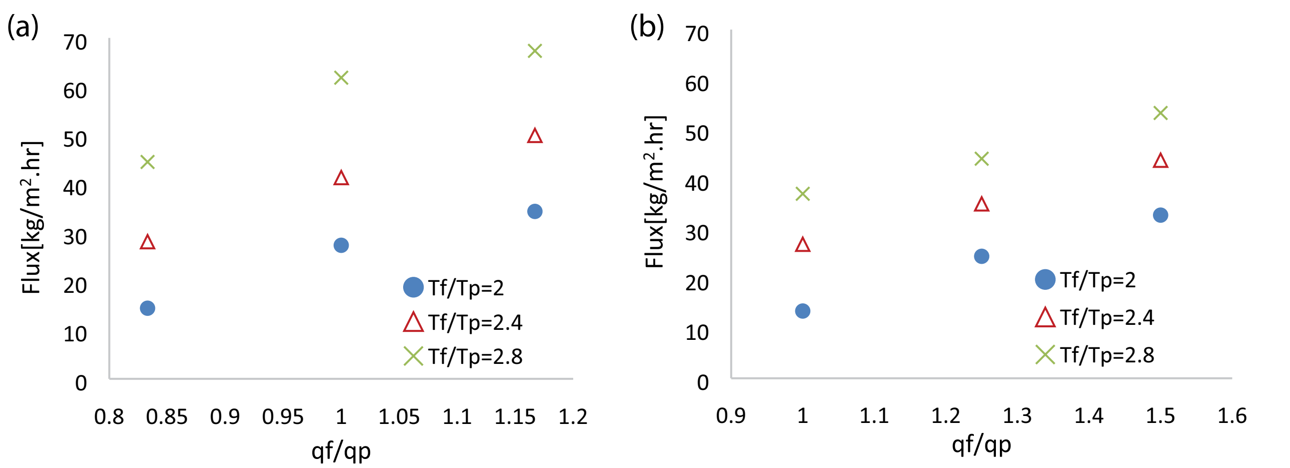



Fig. 8. Variations of flux with flow rate ratio at different temperature ratios. Conditions: permeate temperature 25°C, feed salinity 3,500 mg/L, and permeate flow rate of 2 L/min for each stage. (a) Parallel stages flow connection and (b) series stages flow connection.

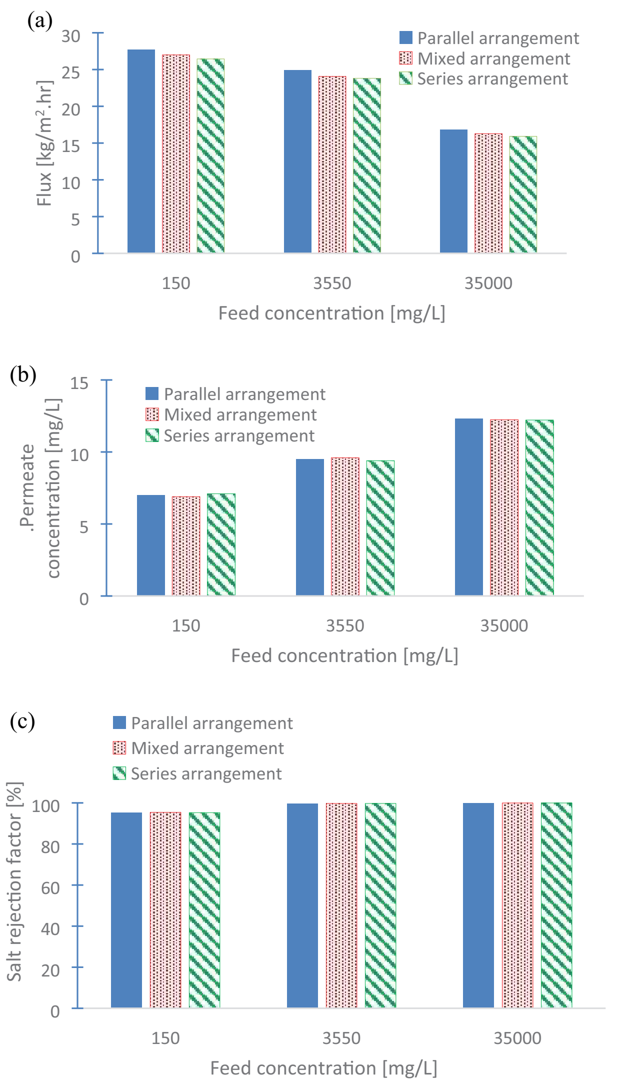



Fig. 9. (a–c) Effect of feed salinity concentration on the permeate flux. Conditions: feed temperature 50°C, coolant temperature 25°C, and feed and permeate flow rates of 2 L/min for each stage.

pressure in the feed channel, in addition to increasing the concentration polarization effects. Those effects add a concentration resistance layer (concentration polarization) on the membrane surface and reduces the vapor transfer through the membrane. Fig. 9b presents the effect of feed concentration on the quality of permeate for the three flow arrangements. The obtained distilled has salts concentration between 6 and 12 mg/L (ppm) which is in the high-quality range. The three different flow arrangements show almost the same results on the permeate concentration as the feed salts concentration increase.

The salt rejection factor is a parameter used to report the quantity of salt removal from the feed water stream and is defined as:

$$\text{SRF} = \frac{\text{Feed Concentration} - \text{Permeate Concentration}}{\text{Feed Concentration}} \times 100 \quad (2)$$

Fig. 9c presents the effect of feed concentration on the rejection factor for the three stages of flow arrangements. With the increase in the feed concentration between the values 150; 3,550; and 35,000 mg/L, the salt rejection also increased to reach 99.96% for the case of 35,000 mg/L feed concentration.

### 3.2. Energy Analysis

The performance of the multistage direct contact MD system is mainly measured by both the flux output and the energy consumption and efficiency. Direct contact MD modules are characterized by high heat transfer across the membrane from the hot feed side to the cold permeate side. The hydrophobic membranes are designed to be thin to increase the flux (by reducing vapor mass transfer resistance across the membrane) but this feature increases the heat transfer between the hot and cold streams in the module and results in higher temperature drop in the feed channel and higher temperature increase in the permeate channel of the DCMD stages. The end results are higher energy consumption to run the MS-DCMD system. The flow arrangement, parallel or series, in the MS-DCMD system is expected to affect the total energy consumption in a way similar to its effect on flux.

In the present system, electrical power is used for heating the feed water and cooling the permeate (using heater and chiller). To measure the power consumed by the electrical heater and chiller, power transducers are installed in-line and are connected to the data acquisition system to record the electrical power consumption for parallel and series flow arrangements of the MS-DCMD system. The set values of feed temperature, permeate temperature, feed flow rate, and permeate flow rate control the system electrical power consumption. It worth mentioning that feed and permeate streams are recirculated as shown in Figs. 1–3.

The power consumption for heating and cooling may be calculated from the temperature changed of the feed and permeate stream; respective, as $Q = \dot{m} \times c_p \times \Delta T$. For the series arrangement, by measuring the temperature change between inlet and outlet of each stream across each module of the MS-DCMD system, one can calculate the energy consumed by each module; assuming constant mass flow rate and specific heat of the stream. For the demonstration, Fig. 10 shows the inlet temperatures of the feed stream for each module when the series arrangement is applied. Fig. 10 shows the significant drop in feed temperature across each stage when the feed inlet temperature of the MS-DCMD system is high. This is due to the high heat transfer between feed stream and cold permeate stream, and high heat loss to the surrounding associated with high feed inlet temperatures.

Fig. 11 compares the power consumption of the system heater as a function of feed water temperature (Fig. 11a) and water chiller consumption as a function of the permeate temperature (Fig. 11b), for parallel and series flow connections between stages. Feed and permeate flow rates of 2 L/min for each stage were adjusted for both parallel and series arrangements. Measurements showed that heater power for the parallel flow arrangement is always less than series arrangement at any feed temperature in the tested range, under similar operating flow rates. The differences in power consumption

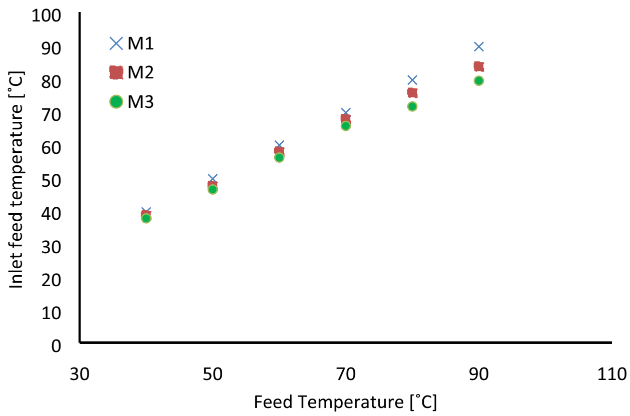



Fig. 10. The inlet feed temperature of each stage in a series arrangement. Conditions: permeate temperature 25°C, feed salinity 3,500 mg/L, feed and permeate flow rates of 2 L/min for each stage.

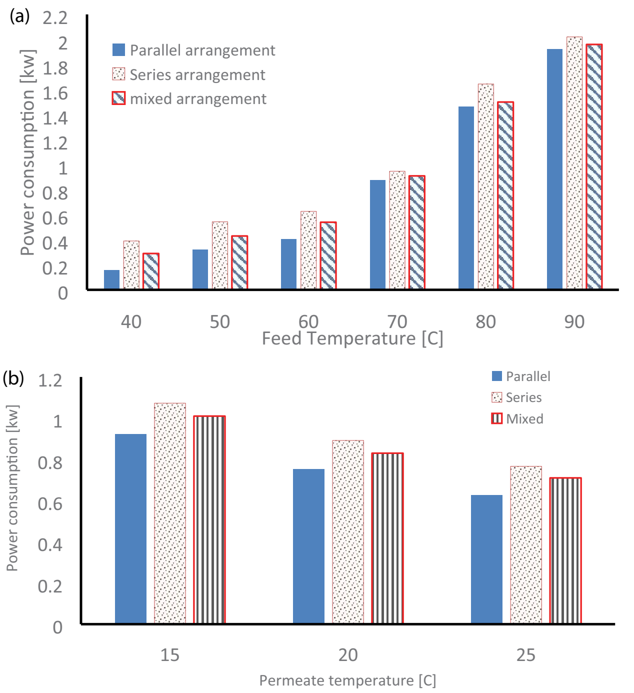



Fig. 11. Power consumption of the MS-DCMD system—effect of inlet temperatures. (a) Heater power at permeate temperature 25°C, and (b) chiller power at permeate temperature 50°C.

between series and parallel flow arrangements increase with reducing the feed temperature as it is controlled by the temperature drop in each stage. For an instant, the power consumed by the heater was 1.92 KW in case of parallel flow arrangement and 2.02 KW in case of series flow arrangement at feed temperature 90°C and permeate temperature 25°C. Similar behavior was measured by the water chiller where cooling power consumed increase with reducing permeate temperature, and consumption by series flow arrangement is 15% to 22% higher than parallel flow arrangement, depending on set value of permeate temperature. For example, 0.92 KW was consumed by parallel flow arrangement and 1.07 KW by series flow arrangement at permeate temperature 15°C. One should also consider higher heat loss to surrounding in cases of high feed and low permeate temperatures through pipelines, connections, and MD modules.

The effects of feed flow rate and permeate flow rate on the electrical power consumption by the heater and the chiller were measured and presented in Fig. 12. In general, the power consumption increases with increasing the flow rate, for given inlet temperatures, due to higher energy transfers with the bulk flow. Fig. 12a compares the heater power at different total feed flow rates of 5, 6, and 7 L/min for the three stages in parallel flow arrangement and equivalent stage feed flow rate of 1.67, 2, and 2.3 L/min for the series flow arrangement. It is clear that the MS-DCMD parallel flow system consumes less heating power compared to the series flow system, and it is even less sensitive to changes in the feed flow rate. Approximately 65% increase in heating power when connecting stages in series compared to parallel for the same inlet conditions reported in Fig. 12a. For the power consumed by the chiller to cool permeate stream, a series flow connection between stages still showing higher power consumption compared to parallel connections. However, the percentage increase is between 6% and 22% for the tested values of permeate flow rates. It is noted that the cooling power is higher than the heating power for the same flow rate of circulation of feed and permeate streams, for example, check the flow rate of 2 L/min of both feed stream (Fig. 12a) and permeate stream (Fig. 12b).

As energy utilization indicators, specific energy consumption (SEC) and GOR are calculated. Higher GOR values and lower SEC are targeted in the design of MS-DCMD system. SEC is defined as the amount of energy consumed to produce one cubic meter of freshwater KWh/m$^3$. GOR represents the ratio between the energy used to produce the permeate (evaporation) to the energy consumed by the MS-DCMD system. GOR is defined as:

$$\text{GOR} = \left(\frac{J_w \Delta H_v}{Q_{\text{in}}}\right) \times A_m \tag{3}$$

where $J_w$ is the permeate flux, $\Delta H_v$ is the enthalpy of vaporization of water, $A_m$ is the effective membrane area, and $Q_{\text{in}}$ is the total heat supply to the MS-DCMD system.

Fig. 13 compares the SEC and GOR values of parallel and series flow arrangements at different inlet feed temperatures of the MS-DCMD system. The SEC increases with the increase of feed temperature, with a higher slope of increase at higher temperatures as shown in Fig. 13a. The increase of system SCE with feed temperature is not linear, it is closer to exponential variation in reality. Parallel flow MS-DCMD system provides less SEC when compared to the series system, due to higher temperature drop through the stages in series connections. At feed temperature of 90°C and compared to parallel stages connection, about 55% increase in SEC when the three stages are connected in series; and this percentage increases as the feed temperature is decreased and reaching 125% at feed temperature of 50°C.

From Fig. 13b, GOR values of the parallel flow MS-DCMD are always higher than the series flow stage connections.

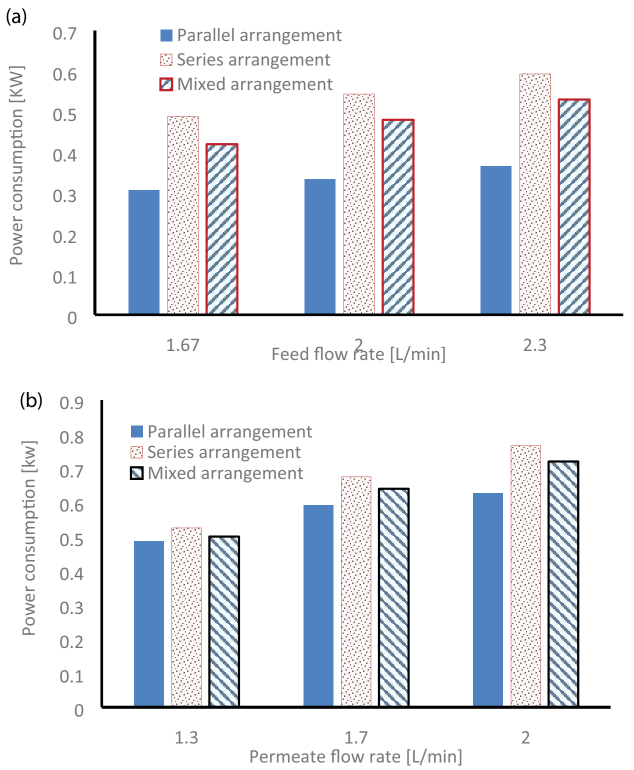



Fig. 12. Power consumption of the MS-DCMD system—effect of flow rates. Conditions: feed temperature 50°C, permeate temperature 25°C. (a) Heater power consumption and (b) chiller power consumption.

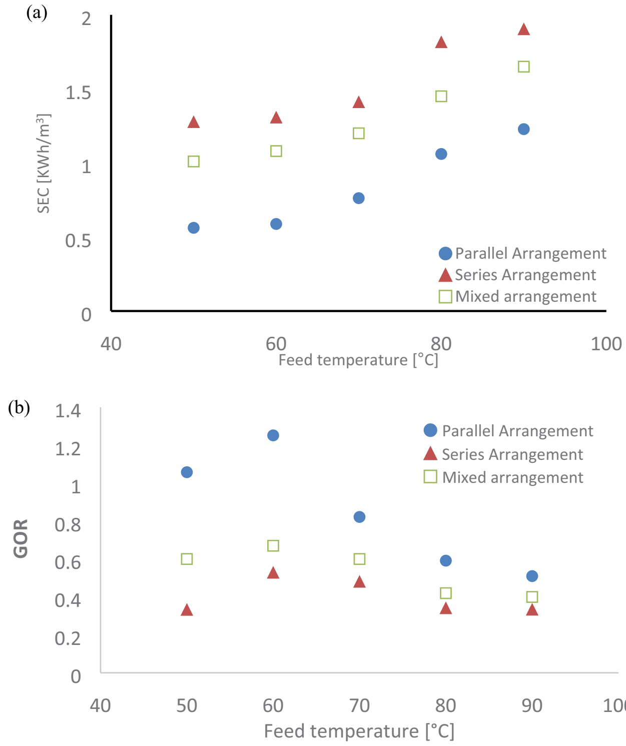



Fig. 13. Variation of a system (a) SEC and (b) GOR with feed temperatures. Conditions: permeate temperature 25°C, feed and permeate flow rates of 2 L/min for each stage.

However, it is noted that the differences between parallel and series flow arrangements are getting smaller at higher feed temperature. GOR values increased with feed temperature up to 60°C then started to continuously decrease for feed temperatures above 60°C. Similar behavior was reported for single stage DCMD system in [22,23]. It may be concluded from the energy analysis that it is recommended to operate the MS-DCMD system in parallel flow stage connection and at a low operating temperature of 60°C.

## 4. Conclusions

Experimental investigations on the performance of MS-DCMD have been conducted. Parallel, series, and mixed flow connections between three stages of the multistage system were compared for a wide range of operating conditions. Moreover, the power consumption and energy efficiency indicators of the MS-DCMD system had been studied and analyzed. The performance of the system depends on the combination of operating feed temperature, feed flow rate, permeate temperature, and permeate flow rate. The temperature and flow ratios between hot feed and cold permeate streams can be used to maximize the system output. The parallel flow connection between the three stages of the system proved superior performance as compared to series and mixed flow connections. The percentage increase in flux due to the change of stages flow connection from series to mixed is around 20% and from series to parallel flow arrangement is about 33% at feed temperature 90°C. In addition, Parallel flow arrangement showed better energy utilization compared to the series flow arrangement as indicated by the SEC and GOR.

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