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Development of vacuum multi-effect membrane distillation system of pilot-scale for water desalination

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ABSTRACT

The main objectives of this article are to describe the design, manufacture of a pilot unit of multi-effect vacuum membrane distillation (ME-VMD). The designed system comprises four effects. A hydrophobic porous membrane is prepared for testing the developed unit. The integrated system included the development of supporting instruments and equipment such as the electrical control panel and the vapor condenser. The pilot unit was implemented, installed, operated, and evaluated. Test trials conducted using the synthetic solution of a concentration of 40,000 ppm. A preliminary economic evaluation of the system was carried out: at a capacity of (3.4 m^3/d) and temperature between 60°C and 65°C, the production cost was \$2.8/m^3, placing it in competition with conventional systems. The developed system is compared with the reverse osmosis systems. Findings reveal that the developed ME-VMD is a reliable water desalination system.

Keywords: Membrane distillation; Water desalination; Multi-effect; Pilot-scale; Economic evaluation

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1. Introduction

Freshwater deficiency is a problem that plagues various areas worldwide, principally remote and arid zones, due to rapid population increase, climate change, augmented industry development, and environmental pollution [1–4]. Water use has been increasing worldwide by about 1% per year since the 1980s, driven by a combination of population growth, socio-economic development, and changing consumption patterns. Global water demand is expected to continue increasing at a similar rate until 2050, accounting for an increase of 20%–30% above the current level of water use, mainly due to rising demand in the industrial and domestic sectors [5].

Desalination was acknowledged as the most talented method to decrease water deficiency in the world through the production of freshwater from seawater and brackish water [4]. Nevertheless, established desalination technologies are heavy energy consumers, relatively expensive, and they generate an enormous amount of concentrated brine as a by-product [6,7]. These issues lead to the need to look for an alternative method for desalination [7,8]. Membrane distillation (MD) is a promising, novel non-isothermal separation technology. It includes the transport of water vapor molecules from a hot aqueous solution through a microporous hydrophobic membrane [1]. The driving force is the partial water vapor pressure difference across the membrane created by the temperature difference between the two sides of the membrane [9]. This technology is a talented method for water desalination since it produces high water quality. It can operate at low temperatures and pressure, handle high concentrated feed water, or supersaturated solutions [9]. Moreover, the capability of utilizing solar energy or low-grade heat from power stations

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and chemical plants can make this process more efficient, cost-effective, and environmentally friendly [10,11]. The advantages of the vacuum membrane distillation (VMD) method are the low requirement of plant space, low operation temperature, low hydrostatic pressure, and low influence of NaCl concentration. In addition, it is distinguished by moderate heat transfer with the feed and permeate sides, lack of need for permeate side cooling, low mass transfer resistance, and low heat loss [12]. The advantages of this technology are (1) the water liquid state does not permeate across the hydrophobic membrane, (2) the salts in the feed water are entirely rejected, (3) this technology can be applied for any feed water characteristics, (4) it is simple and ease technology, and (5) it operates under small temperature gradients (ΔT at least 2°C). In addition to low energy consumption, MD can utilize solar energy, low-grade waste energy, and the recovery of latent heat can enhance energy utilization, and consequently, the operation costs. MD can be classified based on the condensation and the vapor recovery and the application of the driving force into four different configurations [9]: (i) the direct contact membrane distillation (DCMD), (ii) the air gap membrane distillation (AGMD), (iii) the sweep gas membrane distillation (SGMD), and (iv) the VMD. Although DCMD is the easiest configuration, the VMD process exhibits higher permeate flux under the same temperature gradient due to reduced mass transfer resistance under a vacuum condition, and negligible conductive heat loss [13,14].

VMD is a promising desalination approach, and it is a good competitor for reverse osmosis (RO) technology. It is a thermally driven process, compared with earlier developed distillation processes, such as multi-stage flash (MSF), multiple-effect evaporators (MEE), and RO. VMD processes can be applied in various parts of the industrial operation, such as concentrating aqueous solutions, removing volatile organic compounds from contaminated water, and treating wastewater. However, VMD processes have critical performance disadvantages, such as high energy consumption for heating brine water [15].

Multi-stage arrangements are an essential approach to economize the energy consumption to produce the desalted water throughout such technology. Therefore, the precise design of this system represents a great experience to overcome the challenging dynamic behavior, notably when the salt concentration is augmented, creating a significant decrease in vapor pressure (Raoult's Law), and decreasing the driving force.

Therefore, M-VMD is necessary to improve productivity and reduce water production costs. Accordingly, the proposed MVMD system with a short module attached to each stage is required to minimize the membrane maintenance problem.

The recovery of the latent heat of condensation and the incorporation of additional stages in a single-stage module contributed to the optimal design of the MD systems, improving their performance [16]. Moreover, the multi-stages lead to lower thermal energy demand for the process, for example, the system (20 stages) has high water productivity and low water product cost [16]. Memsys has successfully commercialized the vacuum-multi-effect membrane distillation (V-MEMD) module [17]. This new compact module combines the VMD and the multi-effect distillation (MED) concept, achieving a highly efficient heat recovery. It integrates a high concentration photovoltaic thermal (HCPVT) system with a six-effect Memsys module to produce electricity and portable water [18].

Therefore, in the current article, a study, design, and implementation of a multi-effect vacuum membrane distillation (ME-VMD) system are attempted, and preparation of a large scale hydrophobic porous membrane is also achieved. The system performance is tested and economically evaluated.

2. Design approach

The ME-VMD system consists of two major parts: the membrane holders and the supporting auxiliary parts. The ME-VMD contains the earlier prepared hydrophobic microporous membranes, which are the principal player in the separation process and the condenser to obtain the distilled water. The ME-VMD system comprises four effects. For the membrane to achieve this process, many supporting steps are designed and tested.

2.1. Design of the ME-VMD

The ME-VMD unit is designed with four effects and a condensation system.

2.2. Design basis

- Design capacity: ~3 m^3/d.
- Feed flow rate: 4–5 L/min.
- Feed temperature 65°C.
- Feed water concentration: 40,000 ppm.
- The membrane flux is about 20–25 L/m^2 h
- The content of each effect is conveyed to the subsequent effect with the equal flow rate. The recycling of the reject water will enable to approach too near zero-liquid-discharge.
- The unit is working under about – 1 bar (gauge) or near 0 bar (absolute).
- The water vapor is condensed in an external condenser, using cold water as a coolant.

2.3. Design of membrane holder

In the new case of the ME-VMD, it combines the advantages of multi-effects evaporators and VMD to achieve high effectiveness and performance. The design approach depends on the obtained results and the earlier developed mathematical model [18,19]. It aims to increase the production rate by increasing the membrane area concerning keeping a small fingerprint for the unit. This suggestion was accomplished by a unique design of the module that consists of four elements, each comprised of a frame, with a membrane on each side supported with stainless steel screens. In this design, the brine of each effect is directed to the following effect to improve the gained output ratio (GOR) and enhance the production rate. The membrane element consists of a polypropylene frame, fixed on both sides of the two supports, and two plastic meshes on both sides of the frame as a spacer. The membranes are fixed as the final effective layer in this design; the three frames are fixed with 16 stainless steel 316 L nails and nuts with a stainless-steel frame, and a rubber gasket is used on each side to achieve the best sealing and cut off. The integrated element is equipped with two openings on the top and the bottom of the intermediate frame. Fig. 1 shows the detailed membrane element.

In the VMD system, a vacuum is applied at the permeate side of the membrane to maintain the pressure below the equilibrium vapor pressure and to enhance the vapor transport to the membrane.

The integrated elements operate excellently. The four elements for each stage are placed in the basin provided with an electrical heater which has hot water at the desired temperature. All elements are joined in parallel to the vacuum pump through the upper hole of each element. Under the pressure gradient on both sides of the membrane created by the difference between the vapor pressure corresponding to the operating temperature and vacuum pressure, the water is transferred through the hydrophobic porous membrane in the form of steam. These vapors are withdrawn by the vacuum pump where they are condensed by the condenser to obtain distilled water; during this process, some steam droplets condense inside the inner chamber of the membrane holder, where the condensate falls and collects from the bottom hole of the holder, and is then addressed to the product tank.

2.3.1. Mechanical design

Fig. 2 demonstrates the mechanical design of the membrane holder. It has an area of 50 × 50 cm^2 and 6 cm thickness. Fig. 3 depicts the non-assembled membrane element.

2.4. Design of the integrated system of ME-VMD

2.4.1. Design of a single effect

The single effect of the ME-VMD system consists of the basin of the feed water and an electric heater placed at the bottom, used to heat the feed water to the desired temperature. The four membrane elements are connected from the top opening to a steam collection pipeline, and they are also joined from the bottom to the condensate pipeline, as shown in Fig. 4. Each effect is fed through a side opening from

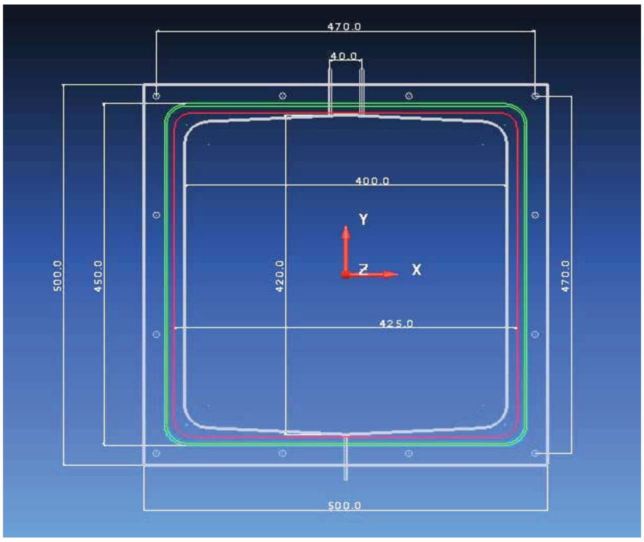


Fig. 2. Mechanical design of the membrane element.

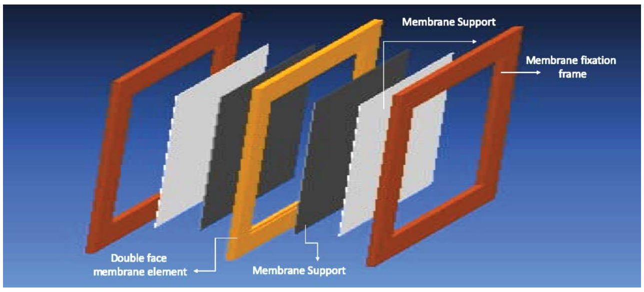


Fig. 3. Non-assembled frame element.

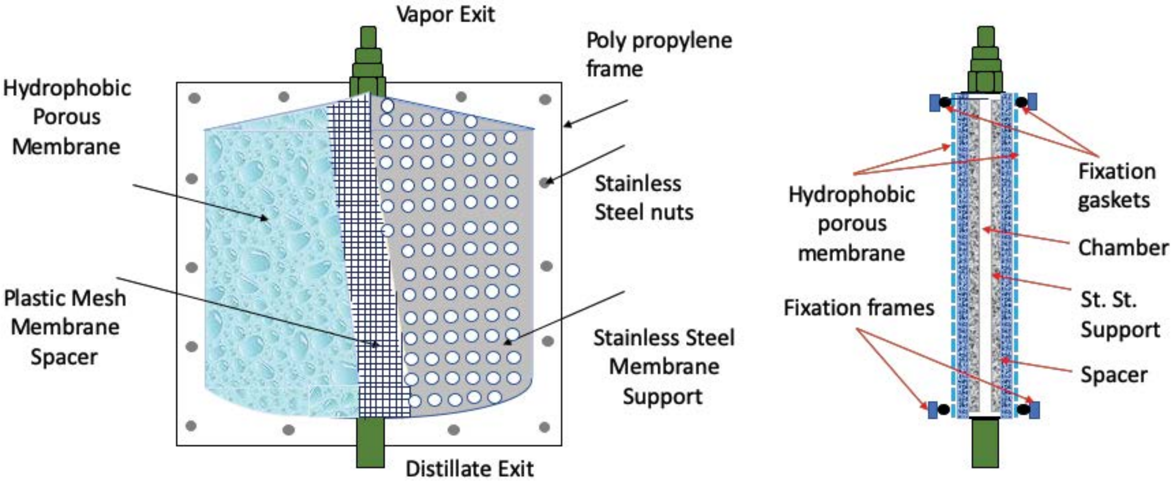


Fig. 1. Membrane element.

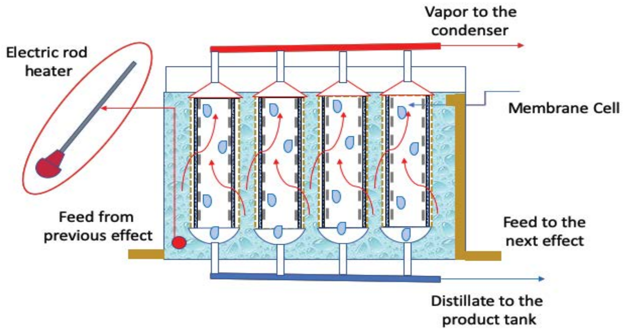


Fig. 4. Single stage of ME-VMD.

the bottom. There is a pipe at a certain height that allows the transfer of a constant overflow to the next effect at the steady-state condition.

The first effect is supplied by the feed water that is heated electrically by a heater (3 kWh), which is located in a metal pocket. Under the driving force of the pressure difference between both sides of the membranes, the vapors permeate through the membranes, then collect, and exit from the upper opening of the elements, and are directed to the condenser. The content of the feed water is transferred to the next stage continuously through the over weir side tube.

2.4.2. Design of multi-effects

The distillate inside the effects is transported automatically to the product tank, with the condensate coming from the condenser. At the steady-state conditions, the concentrate of the first effect is moved to the following one with a flow rate similar to the feeding flow rate of the first effect. Fig. 5 displays an integrated unit of four effects.

2.4.3. Integrated unit with all accessories

The integrated system consists of four effects, condenser, steam trap, chiller, vacuum pump, feeding pump, product pump, non-return valve, control panel, and three tanks (feed, product, and brine tank), as shown in Fig. 6.

The unit operates as follows in steady-state conditions:

- Initially, the unit is fed using the feed pump.
- All heaters work to reach the desired temperature.
- The vacuum pump is working, and due to the pressure difference on the two sides of the membrane, the vapors form, and pass through the membranes.
- Under steady-state conditions, the feed pump operates continuously at a rate higher than the vapor formed from the unit.
- The feeding water is transferred from the first to the second effect, and so on. Thus, the recycled water is concentrated as it moves from one effect to another, with a slight decrease in its temperature.
- The recycling of feed water increases the water recovery percentage.
- The transport of feed water from an effect to another reduces energy consumption.

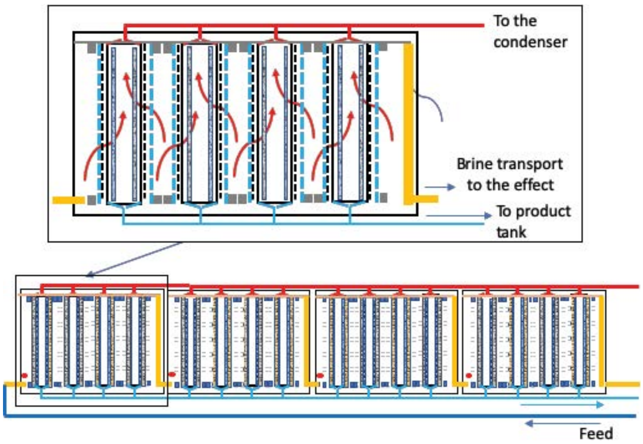


Fig. 5. Four effects (stages) of ME-VMD unit.

- The formed vapors are drawn to the condenser by the vacuum pump, where they are condensed and collected in a surge tank equipped with a non-return valve to maintain the vacuum inside the whole system; the product is withdrawn from this tank by the product pump.
- The vapor condensed by cold water comes from a small chiller attached to the unit.
- The temperature is monitored and controlled by a thermostat for each effect.
- The flow rate of the feed water and the formed product recorded.
- The pressure on the permeate side is measured and recorded.
- The conductivity of the product and the concentrate are recorded and monitored.
- The unit is monitored, managed, and controlled by a power panel.

The mechanical design is illustrated in Fig. 7.

2.4.4. Design of the condenser

In case the unit is placed on the shore, the seawater will be used for condensation, but since it operates at the National Research Center laboratories, the cooling water is recycled after it cools with an external chiller. The design calculations of the condenser calculations were carried out as follows:

- Steam enters the condenser at 60°C–65°C and leaves at 45°C.
- The steam is condensed using cooling water at 10°C.
- The heat transfer area is calculated; 0.6 m^2. The condenser is designed as a shell and tube heat exchanger, of 9 U tubes of stainless steel, with a diameter of 1″ (0.0254 m) and a length of 0.7 m. The performance of the condenser increases through-out passing the vapor outside the tube (shell side).

3. System implementation

3.1. Membrane preparation

Thirty-two sheets of PVDF membranes were prepared according to the steps shown in Fig. 8. The composition of the dope solution is depicted in Table 1.

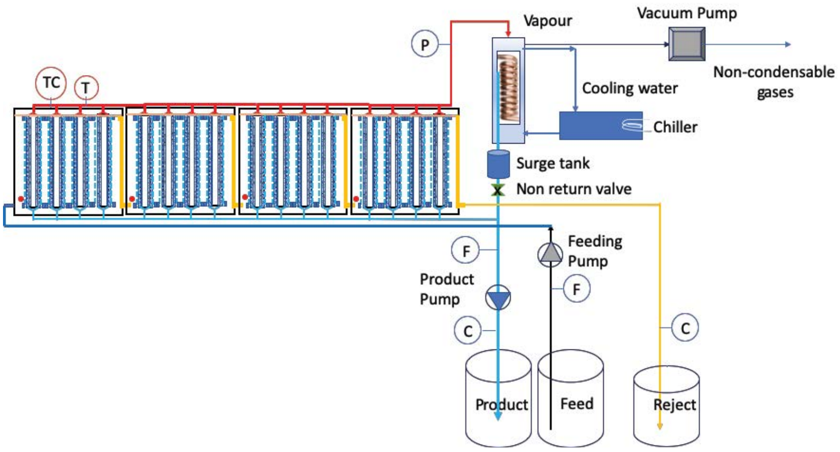


Fig. 6. Flow diagram of ME-VMD unit.

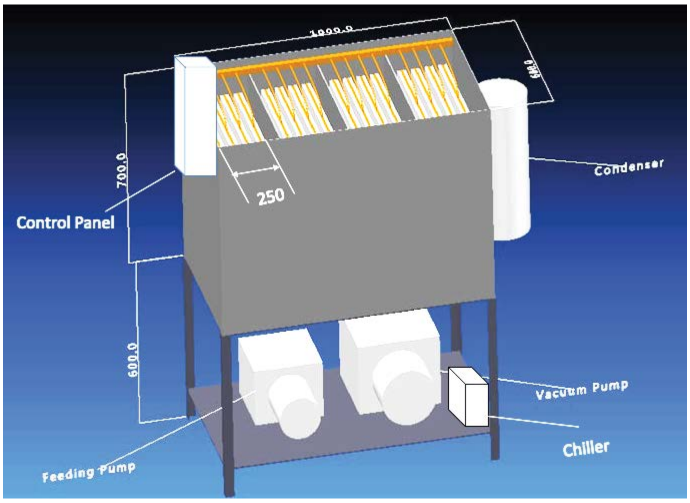


Fig. 7. Mechanical design of integrated ME-VMD system (all dimensions in mm).

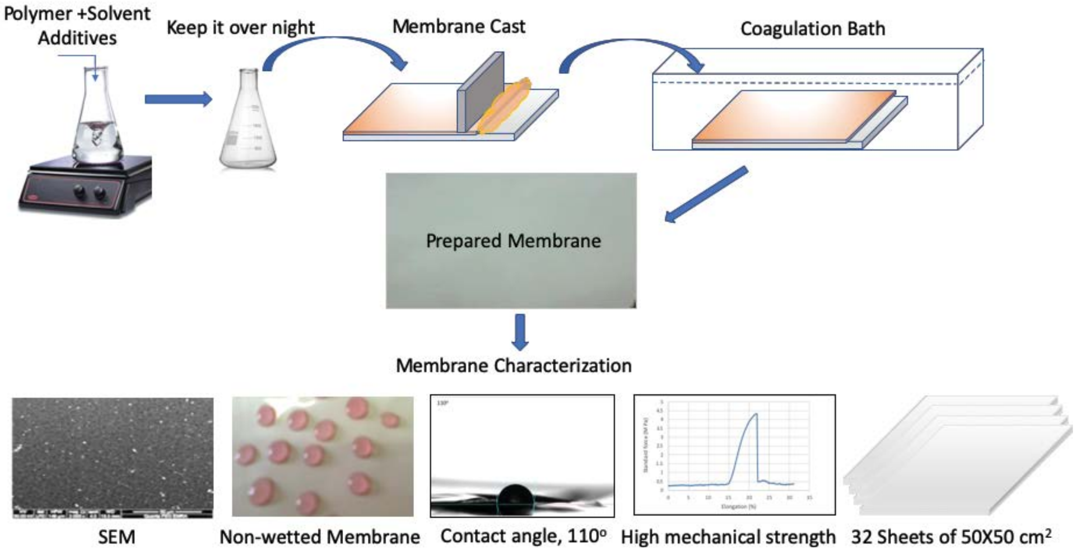


Fig. 8. Membrane preparation.

Table 1
Dope composition and performance

Dope blend	Thick, μm	Flux, L/m^2 h	Rejection %
PVDF/EG/LiCl/NMP/AL_2SiO_5	300	28	98.3

3.2. Implemented unit

The detailed design of the ME-VMD unit is implemented through a tendering process, the bid-offer, was a local factory that belongs to the private sector (Hasco Co., Egypt), Figs. 9–12 demonstrate the integrated and detailed executed system.

Fig. 9. Integrated ME-VMD unit.

3.2.1. Membrane holder

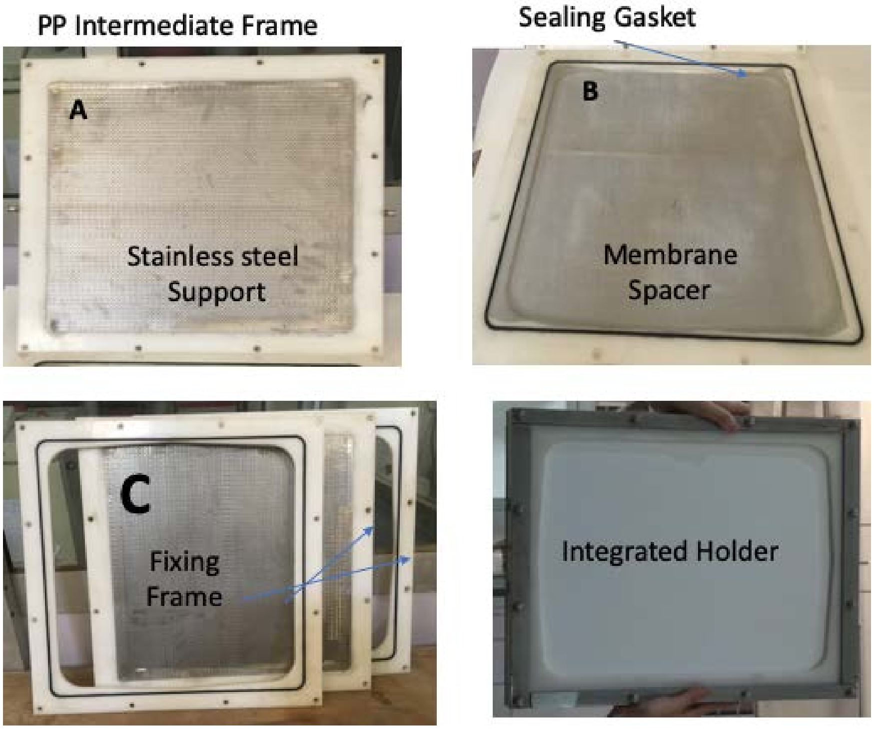
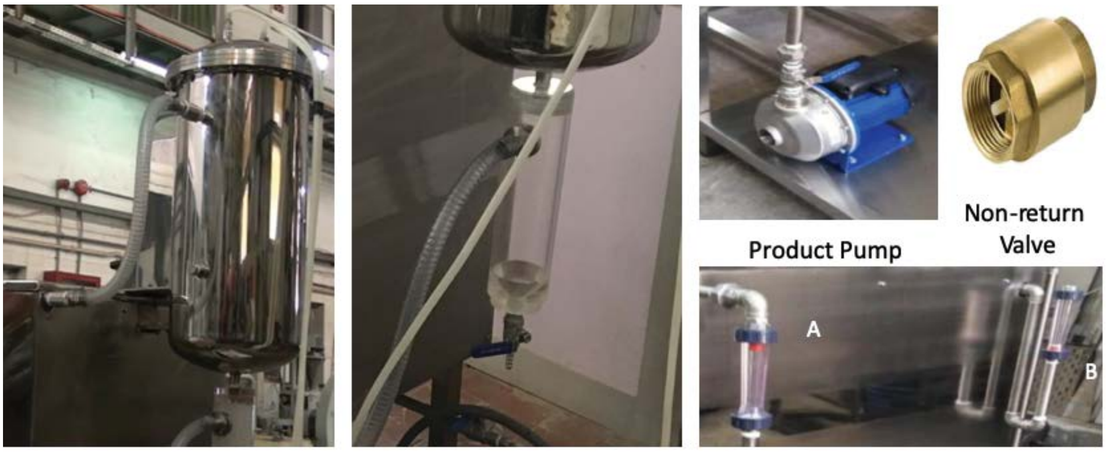


Fig. 10. Membrane holder.

3.2.2. Condenser and allied parts



Shell and Tube Condenser Intermediate product tank Rotameters (A- Feed), (B-Product)

Fig. 11. Condenser and allied parts.

3.2.3. Feeding and vacuum pumps and other parts

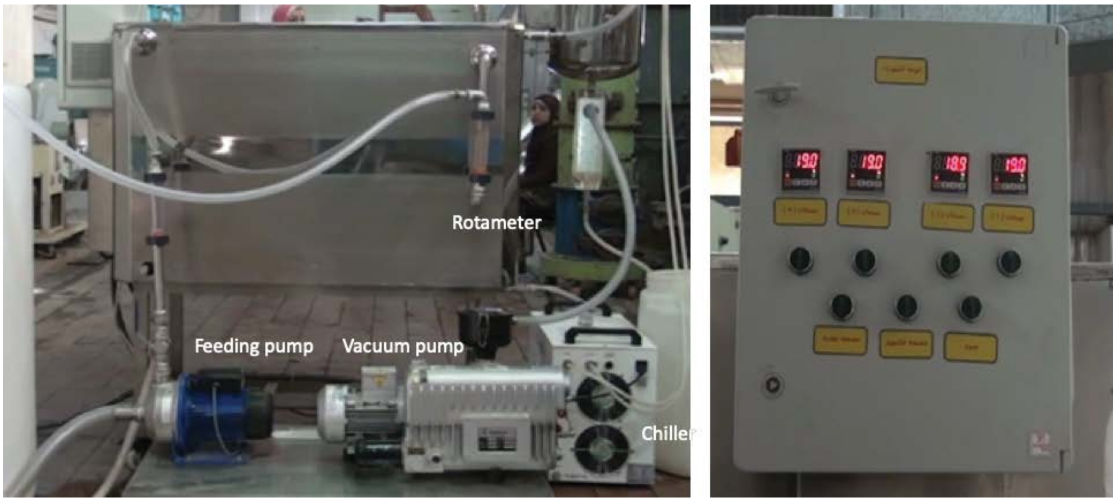


Fig. 12. Feeding and vacuum pumps and control panel.

3.2.4. Control panel

The control panel for the membrane distillation system comprises PLC, which controls the temperature of each stage, and the operating and stopping of the heaters by a manner keeping the system operating automatically at the set temperature (65°C).

The controlling variable is TDS of the product water stream of the unit; the conductivity sensor measures the conductivity of water when it reaches the set point of an alarm, then the unit will shut entirely down.

4. Techno-economic evaluation

4.1. Design technical evaluation

The ME-VMD system performance is evaluated as a function of the permeate flux and salt rejection. Three experiments were conducted using this system that was manufactured. In each experiment, the unit worked continuously for 6 h at 65°C. Under the conditions of the feed water was a synthetic solution that simulated the seawater of 40,000 ppm. The flux and salt rejection were recorded. The four-stages worked with their full capacity and a whole membrane area of 5.12 m^2. The results of these experiments are displayed in Table 2. Figs. 13 and 14 illustrate the performance of the unit. Each reading on this figure represents the average of the three mentioned experiments, the gross average flux, and salt rejection are calculated; about 27.69 L/m^2 h and 97.59%, respectively; the total production rate is 3.440 m^3/d. Fig. 13 clarifies that the design of the first prototype of ME-VMD is good and has a distinguished performance, and it may be considered as a step toward paving the road to promising new technology.

Table 2
Performance of the ME-VMD system

Time, h	Experiment 1		Experiment 2		Experiment 3	
	Flux, L/m^2 h	Salt rejection%	Flux, L/m^2 h	Salt rejection%	Flux, L/m^{2}h	Salt rejection%
0	–	–	–	–	–	–
1	28	97.7	29	97	27	98
2	29	97	27	98	28	97
3	27	98	28	97	28.5	99
4	27	98.5	27	98	27	98
5	29	97	28	99	29	98
6	27	96.4	27	96	26	97
Average	27.83	97.43	27.67	97.50	27.58	97.83

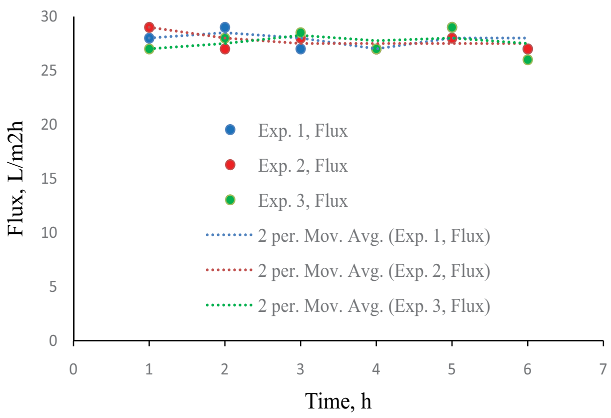


Fig. 13. ME-VMD performance, flux vs. time.

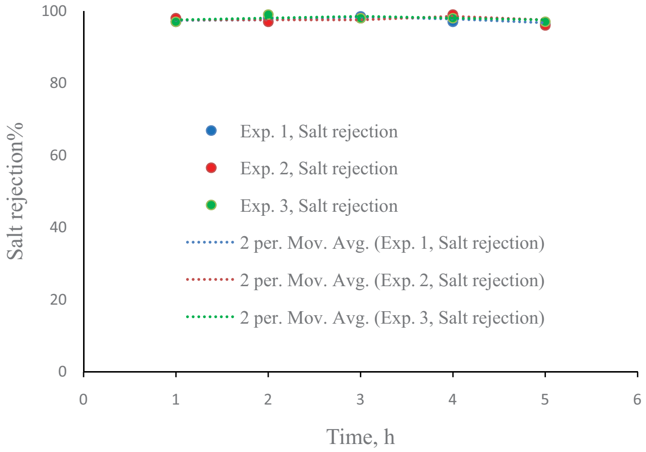


Fig. 14. ME-VMD performance, salt rejection time.

4.2. Economical evaluation

The flow diagram of the ME-VMD unit illustrated in Fig. 6 is used for equipment sizing and cost estimation.

4.2.1. Fixed cost of the ME-VMD unit

The total cost of the integrated system was based on the real cost of implementing the system on the local market, which was LE317,000. Also, the cost of fabricated membranes at the laboratories of the National Research Center was about LE 5000, therefore, the total fixed cost is LE 322000.

4.2.2. Annual investment cost

Table 3 depicts the operating cost estimation.

4.2.3. Product cost

Product cost (1 m^3 of produced water of almost salinity of 0 ppm); is the total annual cost divided by ((A) × (C) × 365), where the capacity (C) is 3.44 m^3/d, and the unit availability/y (A) is 95%; therefore, the cost is (LE 41 ~$2.5). The unit product cost (UPC) of seawater desalination using RO and different conventional technologies ranges between $0.8 and 3 [20] for large capacities. Hence, the production cost of the small unit's prototype of the pilot-scale is reliable.

Table 3
Total annual cost, LE

Item	Price, LE
Membrane	1,000
Depreciation cost	21,133
Maintenance	22,190
Energy	5,000
Total cost	49,323

The cost may be improved by several approaches:

- Apply the concept of latent heat recycling.
- Increase the production rate by enhancing membrane performance.
- Provide a commercial source of heat as solar energy or low-grade surplus heat from the power stations.
- Select material of construction rather than the stainless steel and cheaper.
- Use spiral wound or hollow fiber membranes.
- Use the multi bore hollow fibers membrane configuration.

5. Conclusions

The ME-VMD is designed and implemented in the framework of a project of ID 21802 funded by the Science and Technology Development Fund, which aims to indigenize water desalination in Egypt. Additionally, the hydrophobic porous membrane applied in this technology was prepared and optimized, giving about 27.69 L/m^2 h and 97.59% flux and salt rejection, respectively. The designed system (prototype) produces 3.44 m^3/d. The main results of the developed ME-VMD system may be concluded as follows:

- It combines the advantages of multi-effects evaporators and VMD to achieve high effectiveness and performance.
- The design approach depends on the obtained results and the earlier developed mathematical model [18].
- This design is characterized by having a large membrane area concerning keeping a small fingerprint for the unit; this approach was achieved by a special design of the module.
- The conceptual design of the prototype of ME-VMD pilot unit is based on the addressing of the brine of each stage to the next stage to increase the gained output ratio (GOR) and increase the production rate.
- This system operates at a relatively low temperature (60°C–65°C).
- The produced vapor is condensed using an external condenser.
- As this system is the first prototype, the feed water is heated by an electrical heater equipped in each stage. A team is currently working to develop this system with a heating system of renewable solar energy.
- The system was evaluated; it was operating, for a continuous period.
- The system is also evaluated by the development of techno-economic feasibility, which is revealed that the production cost is about $2.8, which can be considered a reliable competitor for RO.

Acknowledgments

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