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Modeling and Simulation of Multi-Effect Membrane Distillation Systems

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Abstract

Membrane distillation is a thermal and pressure-driven process through hydrophobic microporous membranes, it is a promising technology for water desalination. In this article, a modeling and simulation approach of Multi-Effect Vacuum Membrane Distillation (MEVMD), was implemented and verified using the experimental results of small scale locally designed and manufactured system, using an early prepared hydrophobic microporous membrane. The energy economization of the system is enhanced through latent heat recycling. Theoretical analysis of this system was achieved through the development of a lumped parameter model to describe the MEVMD performance. The developed model was solved numerically for different design and operating conditions using MATLAB Simulink software. The model was verified and validated using the experimental results to achieve a reliable tool for design, replication, scaling-up, and optimization.

Keywords: Vacuum Membrane Distillation, Multi-effect membrane distillation, Model, Simulation

Introduction

Water covers 72% of the earth's surface, making it the most abundant substance on our planet earth, yet most of this resource is inaccessible or non-drinkable. The water available for human use is diminishing rapidly due to global industrialization and the gradual rising of environmental pollution. Thus, the big annoying worldwide problem, which sufferings principally from the remote and arid zones, is a freshwater deficiency due to the fast development of population, 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 to 30% above the current level of water use [5].

Desalination is acknowledged as the most distinct method to decrease water deficiency in the world through the production of freshwater from seawater and brackish water [4]. Nevertheless, the established desalination technologies are heavy energy consumers, and relatively expensive, besides they generate an enormous amount of concentrated brine as a by-product [6,7]. These issues lead to looking for an alternative method for desalination [7,8].

Membrane distillation (MD) is a novel technology, that includes the transport of water vapor molecules from a hot aqueous solution through a microporous hydrophobic membrane. MD can be defined as a thermally driven separation process where only water vapor can pass through the pores of the hydrophobic microporous membranes. Also, it can effectively remove volatile organic compounds from feed solutions. Therefore, it can be applied for water treatment. The driving force is the partial vapor pressure difference across the membrane created by the temperature difference between the two sides of the membrane. This technology is an attractive

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method, for water desalination, it creates high water quality, operates at low temperatures, and is suitable for feed with highly concentrated feed [9]. Moreover, the capability of utilizing solar energy or waste heat from power stations and chemical plants can make this process efficient, cost-effective, and environmentally friendly [10,11].

MD can be classified based on the condensation and the vapor recovery and the application of the driving force into four different configurations [12]: (i) the direct contact membrane distillation (DCMD), (ii) the air gap membrane distillation (AGMD), (iii) the sweep gas membrane distillation (SGMD), and (iv) the vacuum membrane distillation (VMD). Although DCMD is the simplest configuration VMD process exhibits higher permeate flux and negligible conductive heat loss.

Vacuum Membrane Distillation (VMD) is a new promising desalination approach, and it is a reliable competitor for Reverse Osmosis (RO) technology. It is a thermally driven process, compared with earlier developed distillation processes, such as Multi-Stage Flash (MSF), and Multiple Effect Evaporators (MEE). The advantages of the VMD method are the low requirement of plant space, low operating temperature, and pressure. It is not affected by feedwater concentration and has low mass transfer resistance and low heat loss [8]. VMD process is applied in various industrial operations, 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 [13].

The recovery of the latent heat of condensation contributes to enhancing the design of the MD systems, and improves their performance [14], additionally, the unit comprises multi-stages, has lower thermal energy demand, and offers high water productivity and economy [15]. MEMSYS, is a German company, that has successfully commercialized the vacuum-multi-effect membrane distillation (V-MEMD) module [16]. This new compact module combines the vacuum membrane distillation (VMD) and the Multi-Effect Distillation (MED) concept, achieving a highly efficient heat recovery [17].

The following article develops a mathematical model describing the MEVMD system implemented in the early stage, based on experimental results verifying and validating the such model.

Development of a mathematical model describing the MEVMD system.

2.1 Model Assumptions

Figure (1) depicts the schematic representation of the Multi-Effect Vacuum Membrane Distillation (MEVMD) a system. Such system includes four effects. The following simplifying assumptions have been applied:

1. The MEVMD is considered an adiabatic system of negligible heat losses (the system is perfectly insulated).
2. The system is operated under steady-state conditions.
3. The membrane can reject all the salts (100% rejection), and only water molecules are allowed to pass.
4. The properties of water and vapor are assumed to be uniform in each effect and they are calculated based on the bulk average pressure, temperature, and salt concentration in the corresponding effects.

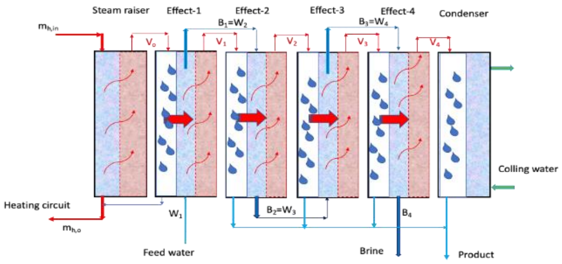

Fig. 1. Schematic diagram of the ME-VMD system

2.2 Model Equations

1- Steam Raiser

a- Mass balance on steam raiser:

$$m_{h,in} = m_{h,o} + m_{V_0} \tag{1}$$

where $m_{h,in}$ and $m_{h,o}$ are the hot water inlet and outlet flowrates (kg/h), respectively. V_o is the evaporation rate across the membrane (L/h).

b- The Heat balance on steam raiser:

$$m_{h,in}Q_{h,in} = m_{h,o}Q_{h,o} + V_oQ_v \tag{2}$$

where $Q_{h,in}$ and $Q_{h,o}$ are the specific enthalpy of the hot water at the inlet and outlet, respectively; Q_v is the enthalpy of the vapor.

2- Each effect

Similarly, the mass and heat balances on each effect are:

Mass balance on each effect

$$m_{f,in\,,eff} = m_{f,out,eff} + V_{eff} \qquad (3)$$

Heat balance on each effect:

$$Q_{foil,eff}A_{eff} = m_{f,out}C_{p,sw}T_{f,out} - m_{f,in}C_{p,sw}T_{f,in} + Q_{evap,eff}A_{eff} \qquad (4)$$

Salt mass balance:

$$m_{fin}.\ C_{fin} = m_{fout}C_{fout}. \qquad (5)$$

$$C_{f,out} = \frac{m_{fin}.\,C_{fin}}{m_{fout}} \qquad (6)$$

Where $m_{h,in}$ and $m_{h,o}$ are the hot water (of the Steam Raiser Circuit) inlet and outlet flowrates (kg/h); $m_{f,in\,,eff}$ and $m_{f,out,eff}$ are the flow rate in and out each effect, kg/s; C_{fin} *and* C_{fout} are the Concentration of feed water in and out of each effect; kg/m^3

2.3 Model Verification

The model was verified, throughout four consecutive experiments, these experiments were conducted on each effect separately and sequentially under the operating conditions of:

1. Feed of steam coming from Steam Raiser =0.018 kg/s
2. Temperature of feed steam = 70-95°C
3. Saline feed water flow rate = 0.004 L/s
4. Temperature of feed water = 45-65°C
5. Temperature of cooling water at condenser = 25°C
6. Feed water TDS 40 kg/m^3

The first experiment was conducted, using the mentioned operating conditions on a single Effect (ef1) (Figure 2). The Second experiment was performed on the two connected effects; the output saline water is the feed of the second effect with its properties (Figure 3). The third and fourth experiments are conducted with Three and Four Effects respectively, with above same concept (Figures 4, 5). The generated distillate water, from the four Effects, is collected and gets out through a non-return valve to keep the vacuum, through all the system.

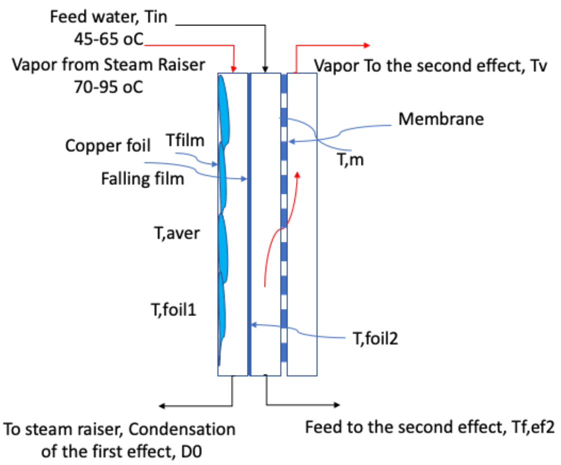

Fig. 2. First experiment (Single first effect)

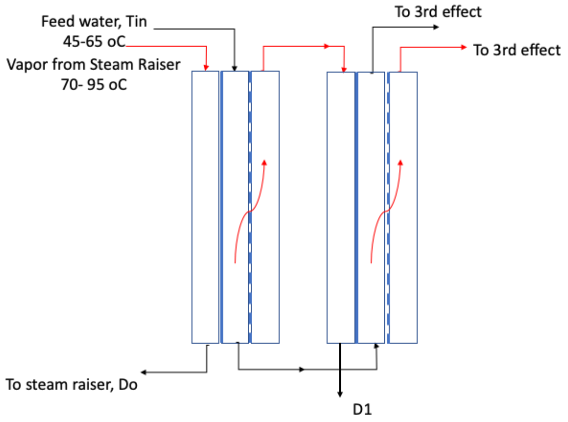

Fig. 3. Experiment of two effects

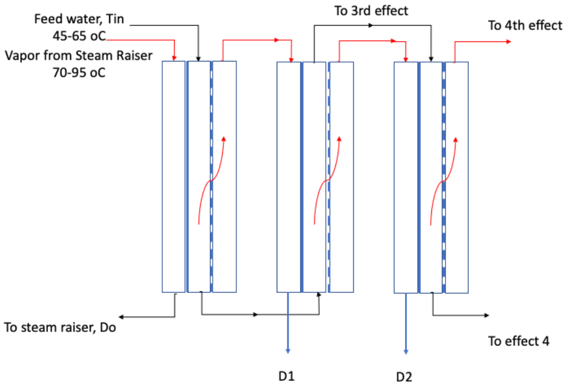

Fig. 4. Experiment of three effects

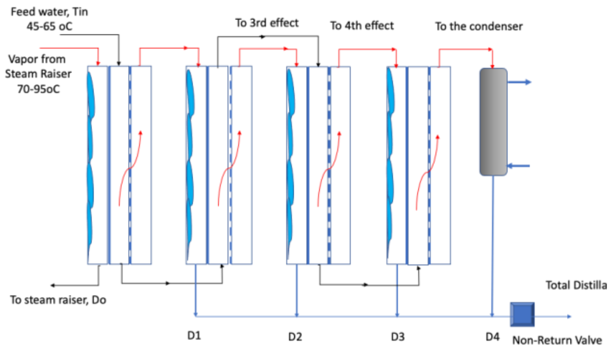

Fig. 5. Experiment of four effects

2.4 Modeling, simulation, and solution

The developed lumped parameter model of a Multi-Effect Vacuum Membrane Distillation system of four Effects (Figure 6) was solved using MATLAB (The Mathworks, Release 2014b), based on the Simulink block solution illustrated in Figure (7). The setting was fragmented into individual cells to determine the state variable change of the controlling parameters, such as the local vapor flux, local membrane surface temperature, local heat and mass transfer coefficients, and local fluid temperature.

The model was solved based on the following conditions:

- According to the energy balance (at the steady-state conditions), the amount of heat transferred through the steam raiser, each effect, and the condenser are equal.
- For simplicity, the feed temperature, in the feed channel, remained constant along the channel's length.
- The membrane properties and operating conditions are previously defined above.
- The thermophysical properties of the feed water are calculated at the correlations developed from the pieces of literatures.

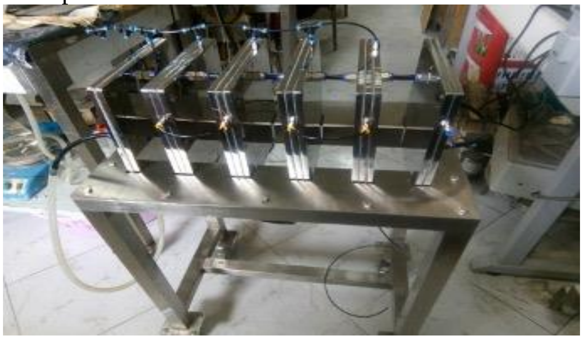

Fig. (6-a). The integrated system

Fig. (6-b). The integrated insulated system

Results and discussions

3.1 Model Validation and Verification

The model was solved at the following simulating conditions:

3.1.1 Design Parameters:

1. Membrane area of SR and each effect: 0.0625 m^2
2. No. of effects: 4
3. Copper foil thickness: 1.5 mm
4. Feed channel width: 2 mm

3.1.2 Membrane specifications:

1. Pore size: 1e-7 m
2. Porosity: 50%
3. Membrane thickness: 3E-4 m
4. Membrane polymer base: PVDF

3.1.3 Operating conditions:

1. Flow rate of hot water to steam riser (SR): 0.83 kg/s
2. Feed water flow rate: 0.022 kg/s
3. Feed input temperature: 65 °C
4. Salinity of feed water 40 kg/m^3
5. Vacuum pressure: 5000 Pa

The model was validated under the same operating conditions. Table (1), attached, illustrates that the model results matched fairly with the experimental ones, under the same operating conditions. It is clear that there is perfect matching between all values except the values of the temperature of generated vapor at each effect, which may be attributed to the heat losses in the vapor line as shown in Figure (6-b). Hence, the verified model can be used to investigate the all influencing parameters affecting the system performance.

3.2 Parametric study of ME-VMD system

To evaluate the performance of the predesigned and implemented MEVMD unit, the variation of some of the performance indicators at the operating parameters are analyzed, such as water productivity, Recovery Ratio (RR), Gained Output Ratio (GOR), and Specific Thermal Energy Consumption (STEC). Hence, a parametric study was conducted for namely the input hot water temperature of the steam riser (SR), the feed water temperature (fed to the first effect), the feed water flow rate, and also, study the impact of the mentioned parameters on the productivity of the unit and energy consumption. The study was carried out under the previously mentioned conditions.

3.2.1 Effect of hot water temperature on Multi-Effect VMD system performance:

- **Operating conditions:**

1. Hot water temperature range: 70-95 °C
2. Flow rate of hot water to SR: 0.83 kg/s
3. Feed water flow rate: 0.022 kg/s
4. Feed input temperature: 45-65 °C
5. Salinity of feed water 40 kg/m^3
6. Vacuum pressure: 5000 Pa

a. Distillate production

Figure (8) illustrates the dependence of the predicted distillate flux and the Recovery Ratio percent on the hot water temperature of the Steam Raiser. In this context, we used a water bath to feed the Steam Raiser with the hot water.

As expected, the total distillate (productivity of the unit) increases with increasing the hot feed water temperature to the Steam Raiser because the vapor pressure gradient between both sides of the membrane (i.e., the driving force) is increased. Therefore, the increasing T_{hw} (hot water to steam raiser), from 70 to 95 °C leads to a 1.5-fold increase in the production of pure water from 4.12 kg/h to 6.62 kg/h. As observed, the productivity increase is nearly linear. Also, the increased temperature increases, consequently, the Recovery Ratio.

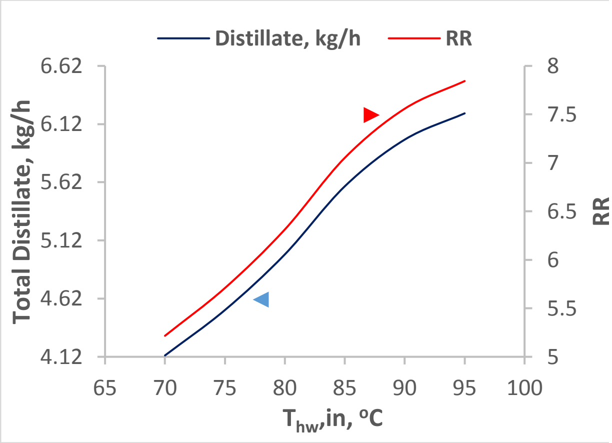

Fig. 8. Change of the Total Distillate and Recovery Ratio (RR) with the temperature of the hot water (water fed to the Steam Raiser)

b. Heat consumption

The influence of the mentioned operating parameters on the water productivity and the energy efficiency indicators; gained output ratio (GOR) and the specific thermal energy consumption (STEC) is studied. The GOR is a dimensionless ratio, calculated by equation (7):

$$GOR = \frac{\sum_i^n Q_{evap,ef,i}}{Q_{hw}} \qquad (7)$$

Where;

$$Q_{evap,ef,i} = J_{v,eff,i} A_{eff,i}\, \Delta H_v$$

The specific thermal energy consumption (STEC) is calculated by equation (8):

$$STEC\ (kWh/m^3) = \frac{Q_{hw}}{F_{dist}\times 10^6} \qquad (8)$$

Which is the thermal energy required to produce 1 m^3 of distillate pure water.

Figure (9) illustrates the values of the GOR and STEC obtained as a function of hot water temperature fed to the Steam Raiser. As observed, GOR increased with increasing the inlet hot water temperature, which is attributed to the increase of steam formation, which is consequently, used to heat the feed water with its latent heat of vaporization, thus, the corresponding specific thermal energy consumption (STEC) is decreased. For the conventional VMD unit, the value of GOR is typically < 1, whereas for the MEVMD systems the GOR value ranges from 2 to 20 [13], in our case, the GOR ranged from 2.8-2.96, which is considered a good achievement for the very small developed unit. Therefore, on the contrary, the STEC decreases approximately from 230.0 to 145 kWh/m^3, this can be explained by the increase of the distillate flow rate concerning the contribution of the heat input to the system.

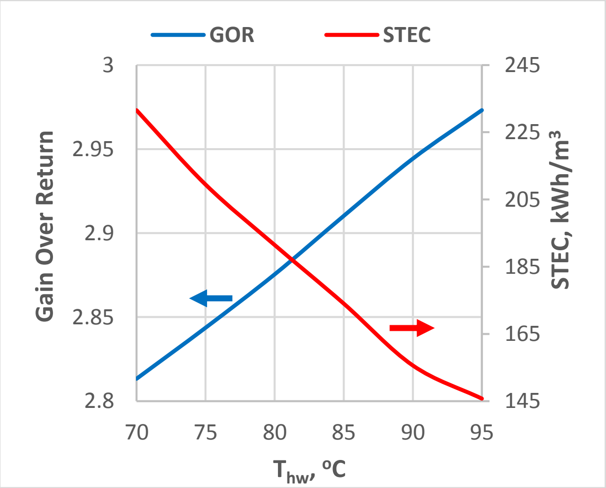

Fig. 9. Change of the Gain over return and Specific Thermal Energy consumption with the temperature of the hot water (water fed to the Steam Raiser)

The Multi-Effect design permits reprocessing energy as latent heat in the successive effects, producing more distillate with less thermal energy consumption and thus, increasing the heat efficiency and performance.

3.2.2 Effect of feed water temperature on MEVMD system performance.

- **Operating conditions:**

1. Inlet feed water temperature range: 45-65 °C,
2. Flow rate of hot water to SR: 0.83 kg/s
3. Temperature of hot water: 90 °C
4. Feed water flow rate: 0.022 L/s
5. Salinity of feed water 40 kg/m^3
6. Vacuum pressure: 5000 Pa

a. Distillate production

The feed inlet temperature has a positive influence on the water productivity and the Recovery Ratio (RR) over the studied temperature range, as shown in Figure (10). This is probably due to an increase of vapor pressure at the inner side of the membrane with increasing in feed water temperature, while the pressure on the other membrane side is constant (vacuum pressure), hence the driving force is increased, and the generating water vapor flux is, also, increased, and consequently augmented the distillate production.

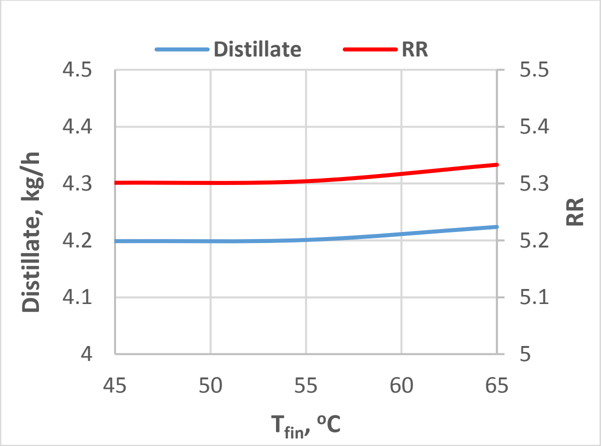

Fig. 10. Change of the total distillate and Recovery Ratio with the temperature of the feed water

b. Heat consumption

The same trend of GOR and STEC was observed as the productivity increased by increasing the feed temperature, as illustrated in Figure (11). The explanation of this situation is as previously explained in the previous Section (3.2.1-b).

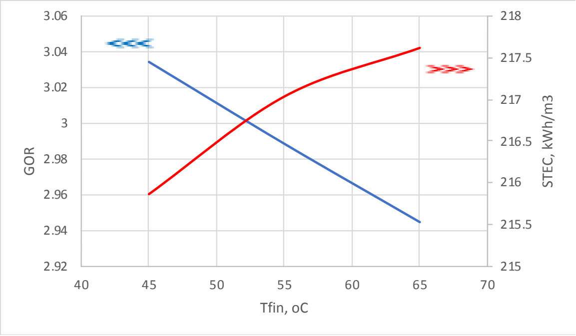

Fig. 11. Change of the Gain over return and Specific Thermal Energy consumption with the temperature of the feed water

3.2.3 Effect of feed water flow rate on MEVMD system performance.

- **Operating conditions:**

1. Feed flow rate range: 0.022-0.035 kg/s
2. Flow rate of hot water to SR: 0.83 kg/s
3. Temperature of hot water: 90 °C
4. Temperature of the feed water: 65 °C
5. Salinity of feed water 40 kg/m^3
6. Vacuum pressure: 5000 Pa

a. Distillate production

To assess the effect of the feed flow rate on the performance of the MEVMD unit as a function of water productivity and RR. Figure (12) illustrates this influence. The water productivity increases with increasing the $m_{f,in}$. This behavior of productivity is owed to the increase of the mass and heat transfer coefficients at the feed side and the consequent reduction of the feed boundary layer thickness due to the turbulence in the flow, enhancing the driving force of the process.

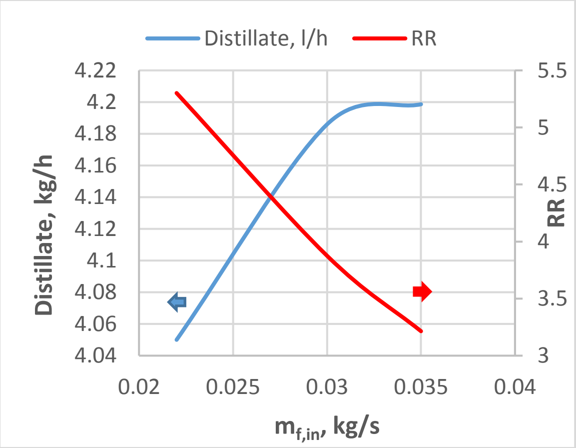

Fig. 12. Change of the total distillate and Recovery Ratio with the flow rate of the feed water

The recovery ratio (RR) is decreased with increasing the flow rate as illustrated in Figure (12), which is attributed to the increase of feed water in the system, will decrease apparently the ratio.

b. Heat consumption

On the contrary, GOR presents a rapid decrease with the increase of the feed flow rate, m_f, of saline feed water. At high values of m_f, in, a large amount of the latent heat of condensation will need to preheat the feed to its boiling point for constant heat input. The energy of evaporation will be reduced and consequently, the GOR will drop (Figure 13). However, for a constant heat input, at high values of feed flow rate, a large amount of the latent heat of condensation, will be used to preheat the feed to its boiling point. The available energy for evaporation, will be reduced, and as a consequence, the flux will drop, Figure (13). At low feed flow rates, the STCE exhibits a similar trend with productivity, and with a further increase in the feed flow rate, it increases because more thermal energy is required to preheat the feed at high rates. The STEC increases from 218 kWh/m^3 to 229 kWh/m^3 as the $m_{f,in}$ increases.

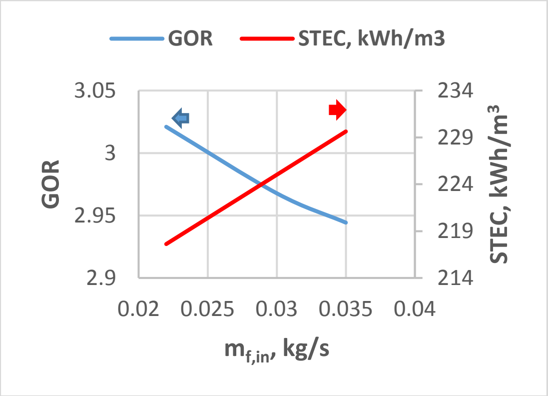

Fig. 13. Change of the Gain over return and Specific Thermal Energy consumption with the flow rate of the feed water

Conclusion

The MEVMD system, as explained before, is designed to recover the latent heat of evaporation in a series of effects. The previously developed model, based on mass and energy balances, was utilized to carry out an extensive analysis of the performance of the multi-effect MD system, in terms of distillate productivity, recovery ratio, and thermal indicators (in terms of GOR and STEC) for different performance indicators, namely the hot water temperature (fed to the steam raiser) which represents the heat input to the system, the initial feed water temperature, and the feed water flow rate.

Acknowledgement

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Nomenclatures

A_{eff}: Area of each effect, m^2

$C_{p,sw}$: Specific heat of saline water, kJ/kg.^{o}k

C_{fin}, C_{fout}: Concentration of feed water in and out of each effect; kg/m^3

Eff: Effect

F_{dist}: Flow rate of produced distillate, kg/s

GOR: Gain output ratio, dimensionless

hw: Hot water (at Steam Raiser Circuit)

ΔH_v : Latent heat of evaporation, kJ/kg

i : any effect

$J_{v,eff,i}$: Vapor flux for each effect i

MEVMD: Multi-Effect Vacuum Membrane Distillation

$m_{h,in}$ and $m_{h,o}$: The hot water (of the Steam Raiser Circuit) inlet and outlet flowrates (kg/h).

$m_{f,in\,,eff}$, $m_{f,out,eff}$: Flow rate in and out each effect, kg/s

n: Number of effects

$Q_{h,in}$ and $Q_{h,o}$: The enthalpy of the hot water at the inlet and outlet, respectively (kJ/s).

Q_v: Enthalpy of the vapor, (kJ/s).

$Q_{foil,eff}$: Conductive heat through copper foil surface, kJ/s

$Q_{evap,eff}$: Heat of evaporation, kJ/s

Qhw: Enthalpy of hot water (at Steam Raiser), kJ/s

RR: Recovery Ratio

SR: Steam Raiser

$STEC$: Specific Thermal Energy Consumption, $(kWh\ m^3)$

$T_{f,in}, T_{f,out}$, Temperature in and out of each effect ^{o}K

T: Temperature, ^{o}K

V_o: The evaporation rate across the membrane at SR (kg/h).

V_{eff}: Generated vapor from every effect, kg/s

Table 1: The Experimental and predicted results

Parameter	Effect 1		Effect 2		Effect 3		Effect 4	
	Exper.	**Predict**	Exper.	**Predict**	Exper.	**Predict**	Exper.	**Predict**
m_f, in, kg/s	0.004	**0.004**	0.003714	**0.00369**	0.0034	**0.00341**	0.0031	**0.00314**
$T_{f,}$ in, °K	373	**373**	369.9	**369.6**	367	**368.1**	364.2	**366.9**
$T_{f,}$ out, °K	369.4	**365.7**	367.2	**364.6**	363.5	**365.7**	361.5	**364**
T_v, °K	340.4	**369.5**	339.7	**368.1**	365	**365.7**	336.8	**364.8**
Flux, kg/m^2.h	16.48	**17.7804**	17.92	**15.9336**	17.32	**15.7104**	17.472	**14.9832**
Distillate, kg/s	0.000286	**0.000309**	0.00031	**0.000277**	0.0003	**0.00027**	0.000303	**0.00026**

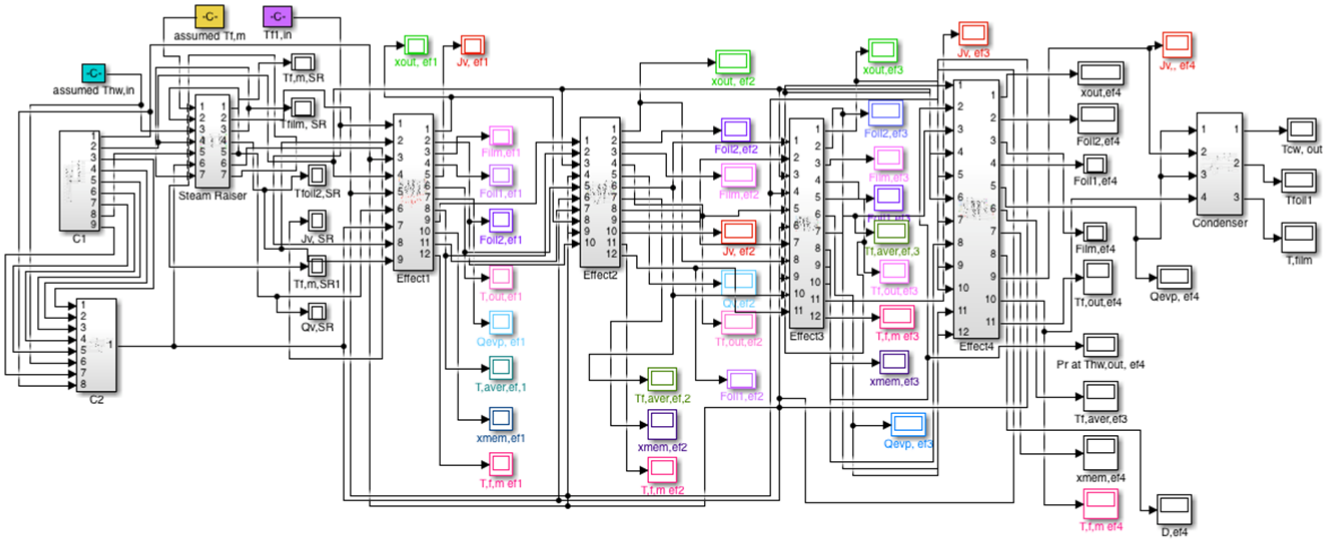

Figure (7) Model Solution, Using the MATLAB Simulink

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