STUDY OF THE PERFORMANCE AND PRODUCTIVITY OF HYBRID (TVC/DCMD) DESALINATION SYSTEM

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ABSTRACT

This study presents a state-of-the art hybrid desalination system which consists of thermal vapor compression (TVC) and direct contact membrane distillation system (DCMD). Characteristics of this hybrid desalination system has been investigated. The proposed hybrid system aims to recover the heat of the rejected brine from TVC system in order to obtain the highest fresh water productivity and performance ratio. The theoretical simulation of all the systems were developed and solved by Engineering equation solver (EES). The study concluded that the best operating conditions to run the system is at motive steam pressure of 3000 kPa and boiling temperature of 70 ^{o}C. The results showed also that both of the performance ratio and water productivity were enhanced by 7% by adding the DCMD as a secondary desalination unit.

Keywords: Desalination, Water, Memberane, TVC, DCMD, Hybrid System

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1 INTRODUCTION

The Middle East and North Africa (MENA) region is considered as the most water-scarce region of the world. The need for alternative and improved water resources options is a must. Therefore, desalination of sea water is a very important issue. Nowadays, some methods of desalination need more studies and research like thermal vapor compression (TVC) and membrane distillation (MD). These two types are expected to be more efficient but need further investigations considering their integrity in a hybrid desalination system.

Literature studies of the TVC desalination system are found by many workers. A1-Juwayhel et al. (1997) performed a comparison for four types of single-effect evaporator systems. The systems were thermal vapor compression (TVC), mechanical vapor compression (MVC), absorption vapor compression (ABVC) and adsorption vapor compression (ADVC). The results showed that for TVC the performance ratio increased at high motive steam pressure.

Darwish and El-Dessouky (1996) made a comparison of the specific available energy, performance ratio and specific heat transfer area for Multi-Effects Evaporation (MEE), Multi Effect-Thermal Vapor Compression (ME-TVC) and Multi Stage Flash distillation (MSF) systems. Their result showed that the MEE is more efficient from a heat transfer viewpoint than MSF. Also, the ME-TVC system uses less heat transfer surface area compared to MSF and MEE systems for the same energy consumption. Hamed et al. (1996) compared the exergy losses due to irreversibility of the TVC system with multi-effect boiling (MEB) and the mechanical vapor compression (MVC) systems. Their result of this comparison was that the TVC system has the least exergy destruction between the three systems. Han et al. (2014) developed a new method to improve the entrainment performance of the thermal vapor compressors (TVCs) that was used in multi effect distillation (MED) desalination systems by preheating the entrained vapor by using the heating water from solar system and using steam from an electric boiler as heating source of the entrained vapor preheating.

On the other hand, many literatures studied membrane distillation systems. Alkhudhiri et al. (2012) reviewed all membrane distillation configurations, characteristics, its applications and its mathematical models. Schofield et al. (1990) presented a model of the DCMD. The effects of heat transfer coefficient, membrane permeability and partial pressure of air within the pores were studied. The results of their study showed that the permeate flux could be improved by deaeration. Termpiyakul et al. (2005) studied the heat and mass transfer on an experimental unit using flat sheet Polyvinylidene Difluoride (PVDF) membrane and concluded that the permeate flux was increased with feed temperature and velocity. Khayet et al. ((2004) presented a theoretical model of direct contact membrane distillation taking into account the pore size distribution together with the gas transport mechanisms through the membrane pores. It was concluded that the predicted water vapor flux increases with the temperature.

Furthermore, many researchers developed several studies about the hybrid desalination systems. Drioli et al. (1999) presented experimental (membrane distillation and reverse osmosis) hybrid system (MD/RO) for water desalination. The MD was proposed to treat the rejected brine from RO with concentration of 75 g/L and temperature of 35^{o}C because of the MD is less sensitive to the salt concentration. It was found that the productivity of the hybrid system increased twice as much as that produced only by RO. Hamed(2005) presented an overview of the existing hybrid desalination systems, which considered a good economic systems. One of these systems is Hybrid (membrane/thermal/power) configuration which has the advantages of flexibility in operation and less specific energy consumption.

In the present work, a hybrid system consisting of TVC unit and DCMD system is proposed, simulated and analyzed. The rejected heat from the TVC unit is recovered in the DCMD system. The performance of the proposed hybrid system is estimated theoretically.

2 HYBRID (TVC-DCMD) DESALINATION SYSTEM DESCRIPTION

The proposed hybrid desalination system is a combination between the TVC and DCMD systems. The hot brine from the TVC's evaporator and the heated saline water from the condenser are used one more time as a feed solution of the DCMD system, this system is driven by a heat source as shown in "Fig. 1".

The TVC unit consists of evaporator, condenser, steam ejector and heat source. The motive steam (1) is generated in the TVC loop using energy from the heat source and directed at a relatively high pressure into the steam jet ejector then it entered the evaporator (3). then condenses and exits from the evaporator at points (12,13).

The intake seawater (6) is entered the condenser where it is preheated by using a portion of vapor (5) formed by the boiling through the evaporator. A part of heated seawater is used as feed water to the evaporator of the TVC (9) where it is sprayed at the top of the evaporator falling in the form of a thin film down the evaporator tubes. The vapor formed in the evaporator (4) splits into two portions: The first part (5) condenses outside the tubes of the condenser, while the rest (2) is entrained by the steam jet ejector. The entrained vapor (2) is compressed in the steam jet ejector along with the motive steam. Then, the compressed vapor from the steam jet ejector (3) flows through the tubes of the evaporator to heat the feed water. The temperature of boiling inside the evaporator is controlled by the feed water temperature, the available heat transfer area and the overall heat transfer coefficient. The condensed steam flowing out the evaporator (12) pumped to (15) raising its pressure back to motive steam pressure (P_m). Then the pumped water (15) is heated by the heat source. The water is heated to a temperature equal to the saturated temperature of the motive steam pressure that drives the steam jet ejector.

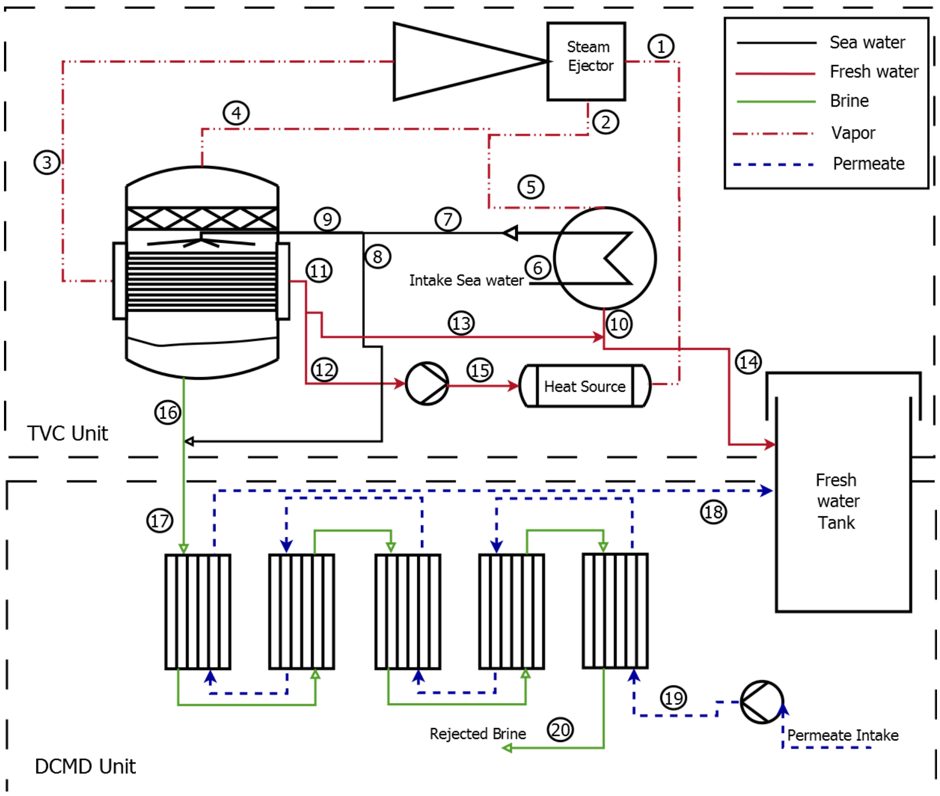

Figure 1. Hybrid (TVC-DCMD) desalination system.

A second part of the heated sea water from the condenser (8) is added to the hot brine (16) flowing out of the evaporator and fed to the DCMD unit (17). Membrane Distillation process is a thermally driven desalination process, which depends on the temperature difference between the two, sides of the membrane (Feed/ Permeate). The present DCMD unit consists of five in-series stages. In each stage, a five flat sheet PVDF hydrophobic are arranged in-parallel, forming a number of flow channels for the feed and the permeate to flow counter-currently at the two sides of the membrane. The total direct contact membrane area is 11.25 m^2. In the DCMD system the hot feed solution (17) and the permeate stream (19) become in a direct contact with the hydrophobic membrane. The hot feed solution and the cold permeate solution are circulated tangentially using circulating pump. Due to the temperature difference between the two sides of the membrane, a pressure difference is established resulting in the water vapor molecules migration through the membrane pores from the saline feed side to the other fresh side comprising the permeate flux.

The total distilled water productivity (14,18) is related to the operating conditions of both TVC and DCMD units while the exhausted brine (20) is finally rejected.

3 MATHEMATICAL FORMULATIONS AND MODELS VALIDATIONS

3.1 Mathematical formulation of TVC system:

The mathematical model of the TVC unit includes energy and mass balance equations for the evaporator, condenser, and steam ejector.

By applying a mass balance of the system:

$$\dot{m}_f = \dot{m}_b + \dot{m}_d \tag{1}$$

$$\frac{\dot{m}_d}{\dot{m}_f} = \frac{x_b - x_f}{x_b} \tag{2}$$

Then, by applying a heat balance on the evaporator:

$$\dot{Q}_e = \dot{m}_s \lambda_s \tag{3}$$

$$\dot{Q}_e = \dot{m}_f \, c_{pb}(T_b - T_f) + \dot{m}_d \lambda_d \tag{4}$$

$$\dot{m}_s = \dot{m}_m + \dot{m}_{ev} \tag{5}$$

Both of the specific heat, c_{pb},and the latent heat,λ_d,can be obtained from empirical correlations of El-Dessouky and Ettouney (2010)as a function of saturation temperature and water salinity. The generated vapor is at the saturation temperature T_v, which corresponds to the pressure in the evaporator vapor space. This temperature is less than the boiling temperature T_b by the boiling-point elevation BPE.

$$T_v = T_b - BPE \tag{6}$$

Boiling Point Elevation (BPE) is calculated from an empirical formula as a function of boiling temperature. Then the evaporator heat transfer surface area,A_e, can be obtained from:

$$A_e = \frac{\dot{Q}_e}{U_e(T_s - T_b)} \tag{7}$$

The condensation temperature of vapor in the condenser(T_c) is less than the boiling temperature in the evaporator (T_b) by the boiling point elevation (BPE) and the saturation temperature decreased according to the pressure losses in demister the (ΔT_p).

$$T_c = T_b - (BPE + \Delta T_p) \tag{8}$$

Where ΔT_p is the saturation temperature corresponding to the pressure drop in the demister pad. The pressure loss in the demister pad can be obtained from a correlation given by El-Dessouky and Ettouney (2002). Then by applying a heat balance on the condenser:

$$\dot{Q}_c = \dot{m}_c \lambda_c \tag{9}$$

$$\dot{Q}_c = (\dot{m}_{cw} + \dot{m}_f) c_{pf} (T_f - T_{cw}) \tag{10}$$

Then the condenser heat transfer surface area,A_c, can be obtained from:

$$A_c = \frac{\dot{Q}_c}{U_c (LMTD)_c} \tag{11}$$

$$\dot{m}_c = \dot{m}_d - \dot{m}_{ev} \tag{12}$$

The logarithmic mean temperature difference $(LMTD)_c$(°C)and can be calculated from:

$$(LMTD)_c = \frac{T_f - T_{cw}}{ln(T_c - T_{cw})/(T_c - T_f)} \tag{13}$$

Both of the overall heat transfer coefficient of the evaporator and condenser, $(U_e \; and \; U_c)$ can be calculated by El-Dessouky and Ettouney (2010) empirical correlations.

The compression ratio of the steam ejector is defined as the ratio of the heating steam pressure, P_s, to the entrained vapor pressure, P_{ev}.:

$$CR = \frac{P_s}{P_{ev}} \tag{14}$$

While, the entrainment ratio is defined as the motive steam, $\dot{m}_m$,to the entrained vapor mass flow rate, $\dot{m}_{ev}$:

$$Ra = 0.915 * \frac{(P_s)^{1.091}}{(P_{ev})^{0.887}} * \left(\frac{P_m}{P_{ev}}\right)^{-0.2496} \tag{15}$$

In the present study, with steam is the motive fluid , for pressure range of $500 \geq P_m \geq 1500\,(kPa)$, the equation used to calculate the entrainment ratio is predicted by El-Dessouky and Ettouney (1999, 2002 and 2010). For the range of $1500 \geq P_m \geq 2000\ (kPa)$, the equation used to calculate the entrainment ratio is predicted using DataFit version 9. Silva et al. (2015) and Rashed et al. (2016).

$$Ra = 0.915 * \frac{(P_s)^{1.091}}{(P_{ev})^{0.887}} * \left(\frac{P_m}{P_{ev}}\right)^{-0.2496} \quad (16)$$

The results from this equation are compared with the power graphical method and give a good agreement for the given range of motive steam pressure. For the range of $2000 \geq P_m \geq 3000\ (kPa)$. The equation used to calculate the entrainment ratio is, predicted by Bin Amer (2009, 2011), as:

$$Ra = 0.235 * \frac{(P_s)^{1.19}}{(P_{ev})^{1.04}} * \left(\frac{P_m}{P_{ev}}\right)^{0.015} \quad (17)$$

The performance of the TVC system is measured by the following variables:

- The performance ratio is defined as the ratio of the distillate water, $\dot{m}_d$, mass flow rate to motive steam mass flow rate:

$$PR = \frac{\dot{m}_d}{\dot{m}_m} \quad (18)$$

- The specific heat transfer surface area is defined as the ratio of the total heat transfer area of the condenser and evaporator to the distillate water mass flow rate:
-

$$SA = \frac{A_e + A_c}{\dot{m}_d} \quad (19)$$

- The specific cooling water mass flow rate is defined as the ratio of the cooling water mass flow rate to the distillate water mass flow rate:

$$SM_{cw} = \frac{\dot{m}_{cw}}{\dot{m}_d} \quad (20)$$

The design data used in the TVC calculations are given in “Table 1”.

Table 1. Input data to the mathematical model of TVC

Data	Value	Unit
Boiling temperature, T_b	50 to 70	℃
Seawater temperature, T_{cw}	25	℃
Density of demister pad material, ρ_p	375	kg/m^3
Ejector compression ratio, CR	2 to 5	
Feed sea water temperature, T_f	$T_c - 5$	
Feed seawater salinity, x_f	42000	ppm
Distillate water, $\dot{m}_d$	1	kg/s
Maximum brine salinity, x_b	70000	ppm
Motive steam pressure, P_m	500 to 3000	kPa
Thickness of demister pad, L_p	0.1	m
Vapor velocity in demister pad, V_p	6	m/s
Wire diameter of demister pad, δ_w	0.28	mm

3.2 Mathematical formulation of DCMD system:

In DCMD process, both heat and mass transfer through porous hydrophobic membranes are involved simultaneously. The mass transfer occurs through the pores of the membrane whereas heat is transferred through both the membrane and its pores.At steady state, the heat transfer through the feed aqueous solution of the DCMD unit is a convective heat transfer rate and is equal to the rejected flow energy of the feed solution which can be expressed as:

$$\dot{Q}_f = h_f\ A_m\left(T_{bf} - T_{mf}\right) = \dot{m}_{fmd} cp_{bf}\left(T_{bfi} - T_{bfo}\right) \quad (21)$$

Where cp_{bf} is feed specific heat transfer and can be calculated from EES seawater library.

The total heat flux through the membrane, $\dot{Q}_m$, is due to the latent heat associated with the vaporized molecules, $\dot{Q}_v$. And the conduction across the membrane, $\dot{Q}_c$. The heat transfer due to the latent heat of vapor molecules can be calculated as:

$$\dot{Q}_v = J_w \, \Delta H_v A_m \quad (22)$$

Where J_w is the permeate flux through the membrane pores $(kg/m^2.s)$ and can be calculated by "Eq. (26)" and ΔH_v is the latent heat of evaporation associated with the migration of the water vapor molecules through the membrane pores and can be calculated at the mean membrane temperature, $T_m = T_{mf} + T_{mp}/2$, Bahmanyar et al. (2012).

The heat transfer rate of conduction through the membrane is:

$$\dot{Q}_c = \frac{K_m}{\delta_m} (T_{mf} - T_{mp}) A_m \quad (23)$$

At steady state, the convective heat transferin the permeate side is equal to flow energy of the permeate side. This can be expressed as follows:

$$\dot{Q}_p = \dot{m}_{pmd} cp_{bp}(T_{bpo} - T_{bpi}) = h_p \, A_m(T_{mp} - T_{bp}) \quad (24)$$

So, the total heat flow through the membrane can be expressed as:

$$\dot{Q} = U_m A_m \Delta T \quad (25)$$

Where U_m is the total heat transfer coefficient through the membrane module.

In the DCMD process, the mass transport is usually described by assuming a linear relationship between the mass flux (J_w) and the water vapour pressure difference through the membrane (Δp_w), Khayet et al. (2004, 2005 and 2011) and Qtaishat et al. (2008), can be expressed as follow:

$$J_w = B_m(P_{mf} - P_{mp}) \quad (26)$$

Where B_m is the permeability of the membrane while P_{mf} and P_{mp} are the partial pressure of water vapor at the feed side and permeate side of the membrane, respectively. The partial pressures of water at the feed and permeate sides evaluated at the temperatures T_{mf} and T_{mp}, respectively, such as the following Darwish& El-Dessouky (1996) and Hamed et al.(1996):

$$P^v = exp\left(23.328 - \frac{3841}{T-45}\right) \quad (27)$$

The performance of the DCMD system is measured by the following variables:

- Temperature Polarization Coefficient (TPC) is generally used to quantify the magnitude of the boundary layer resistances over the total heat transfer resistance:

$$TPC = \frac{T_{mf} - T_{mp}}{T_{bf} - T_{bp}} \quad (28)$$

- DCMD efficiency is defined as the heat of evaporation divided to the total heat input to the system:

$$\eta = \frac{J_w \, \Delta H_V A_m}{\dot{Q}} \quad (29)$$

The present DCMD module consists five stages are arranged in series each stage consists of a number of flat sheet PVDF membranes that are assembled in parallel, forming a number of flow channels for the feed and permeate to flow at two sides of the membranes. Each flow stream within the channels is in direct contact with one side of five membranes with total membrane area of $11.25 \, m^2$. The design data used in the DCMD calculations are given in "Table 2". Where The superscript m is 0.4 for heating and 0.3 for cooling.

Table 2.Input Data to the DCMD model

Data	Value	Unit
Thickness of the membrane, δ_m	126	μm
Thermal conductivity of the membrane, k_m	0.041	$W/m. K$
Porosity, ε	0.75	
Pore diameter, d_p	0.22	μm
Inlet bulk feed temperature, T_{bfin}	50 to 70	℃
Inlet bulk permeate temperature, T_{bpin}	25	℃
Salinity of the feed solution, x_f	70,000	ppm
Velocity of the permeate, V_{pmd}	1.5	m/s
Hydraulic diameter of the membrane, D_h	0.004	m
Tortuosity of the membrane, τ	1	
Width of the channel, w	0.3	m
Length of the membrane, L	1.5	m
Total membrane area, $A_m = L * w * 5 * 5$	11.25mm	m^2

3.3 Mathematical formulation of hybrid desalination system:

The mathematical model of the hybrid system is obtained by integrating the previously discussed mathematical models of TVC and DCMD systems. The performance of the Hybrid desalination system is measured by:

- Performance ratio of the Hybrid desalination system, which is the ratio of the total distillate water flow rate, $\dot{m}_{dt}$, to the motive steam flow rate, $\dot{m}_m$.

$$PR_{hy} = \frac{\dot{m}_{dt}}{\dot{m}_m} \qquad (30)$$

The solution of the system was accomplished using Engineering Equation Solver (EES). EES is a powerful tool for solving simultaneous equations iteratively**.** Also, it’s particularly useful in solving thermodynamic and heat transfer problems since it offers several built-in libraries comprising of thermodynamic and thermo physical properties.

3.4 Model Validation:

To validate the TVC model, the TVC code was run at the operating conditions of previous theoretical results of Al-Juwayhel et al. (1997). The conditions of the comparative runs were that: boiling temperature ranging from 50 to 100 ℃ , motive steam pressure ranging from 250 to 1500 KPa, the distillate flow rate was 1 Kg/s and the intake seawater temperature was 25°C. “Fig.2” presents a good agreement for the comparison between the present model results and Al-Juwayhel et al. (1997) results of the performance ratio as a function of the boiling temperature and the motive steam pressure

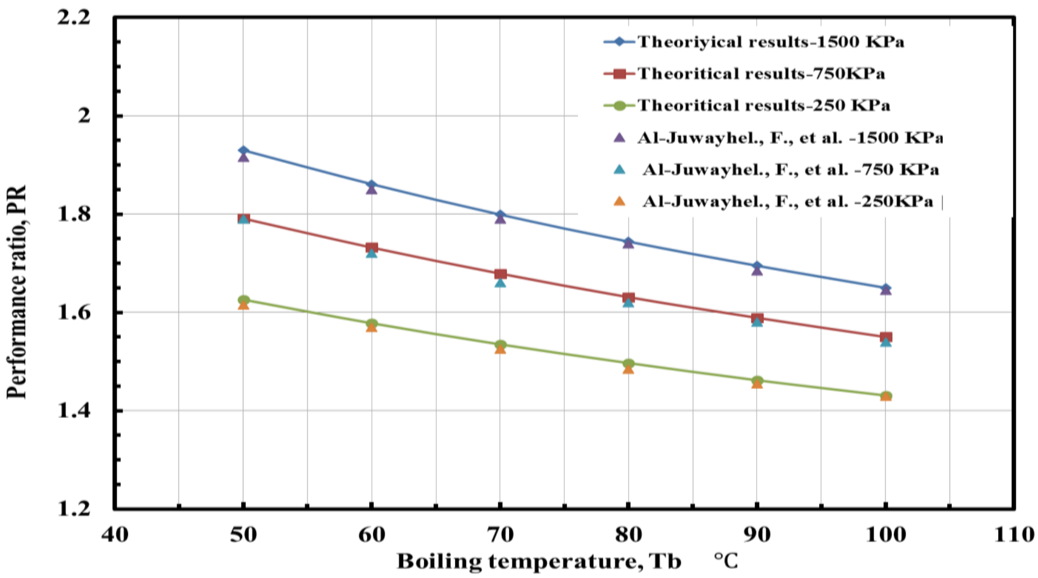

Figure 2. Comparison between the present model results and Al-Juwayhel et al. (1997) results of the performance ratio as a function of the boiling temperature and the motive steam pressure.

The DCMD model was validated against previous experimental results of Termpiyakul et al. (2005)The module used in the experiments was PVDF with rectangular channel and the same membrane area. The feed velocity was 3.7 m/s and the permeate velocity was 2.92 m/s. The feed temperature was varied from 40 to 70 ℃, the feed solution was pure water and the permeate solution was at 25 ℃.

"Fig. 3" describes the comparison between the present model results of the DCMD and results obtained by Termpiyakul et al. (2005) for permeate flux as a function of the feed solution temperature while a comparison of the temperature polarization coefficient as a function of the feed temperature is presented in "Fig.4".

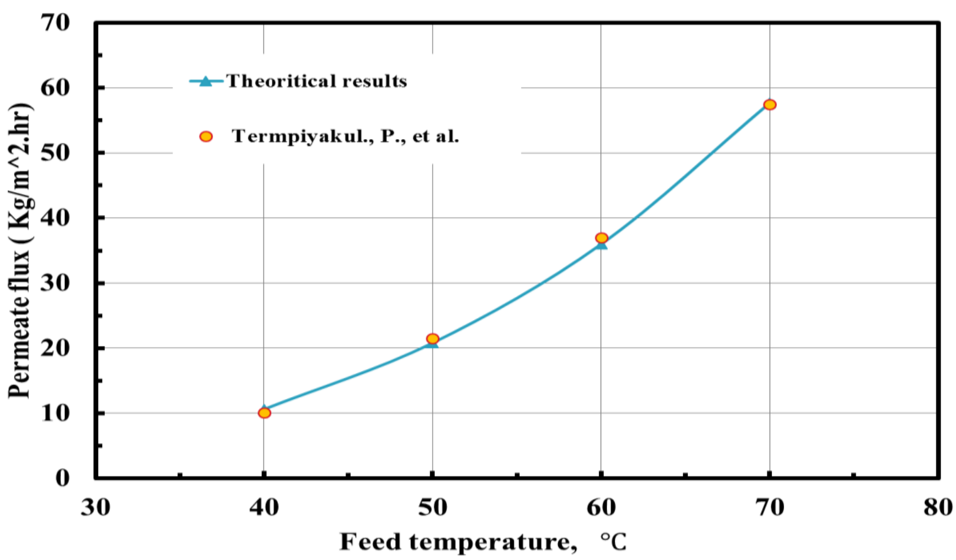

Figure 3. Comparison between the present model results and Termpiyakul et al. (2005) results of the permeate flux as a function of the feed temperature

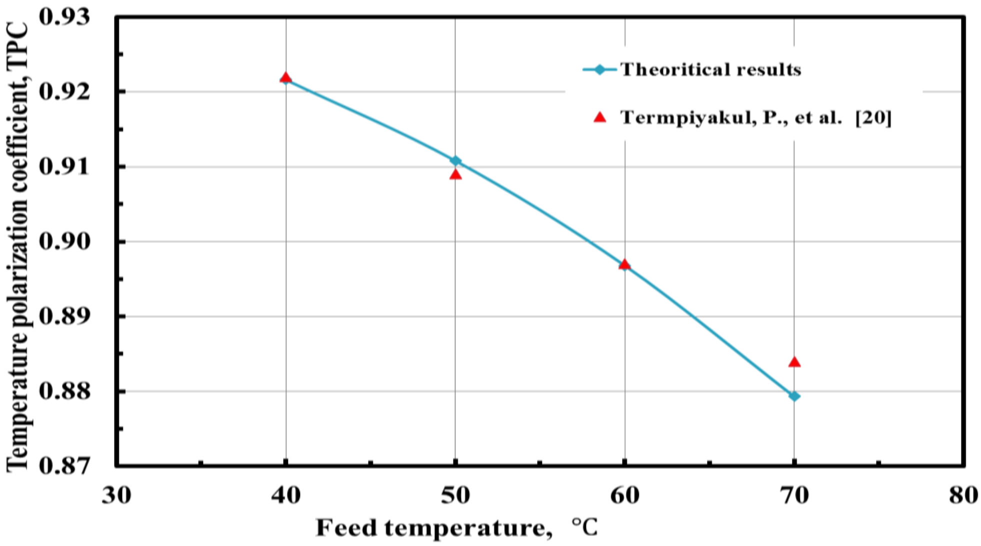

Figure 4. Comparison between the present model results and Termpiyakul et al. (2005) results of the temperature polarization coefficient as a function of the feed temperature.

From these comparative figures "Figs. 3 and 4", a good agreement between the present results and the old ones can be depicted.

4 RESULTS AND DISCUSSION

This section presents the theoretical results of studying the characteristics of the TVC system and the (TVC-DCMD) hybrid system.

Firstly, The stand alone TVC system is studied for fresh water productivity of 1 kg/s considering the change of operating conditions: boiling temperature $T_b(50 \text{ to } 70\ °C)$; motive steam pressure $P_m(500 \text{ to } 3000 \text{ kPa})$ and compression ratio $Cr(2 \text{ to } 5)$. The performance ratio, the specific heat transfer area and specific cooling water flow rate are investigated under different operating conditions. The input data for the TVC system listed in Table.1. On the main objective to obtain high performance ratio, high productivity and low energy consumption the highest motive steam pressure, moderate boiling temperature and lowest compression ratio are selected. Hence, the condenser and evaporator heat transfer areas are selected to be 43.52 m^2 and 68.59 m^2, respectively.

The effect of the variation of the motive steam pressure on the performance ratio of TVC system selected design at different values of boiling temperature can be depicted from Fig. 5.

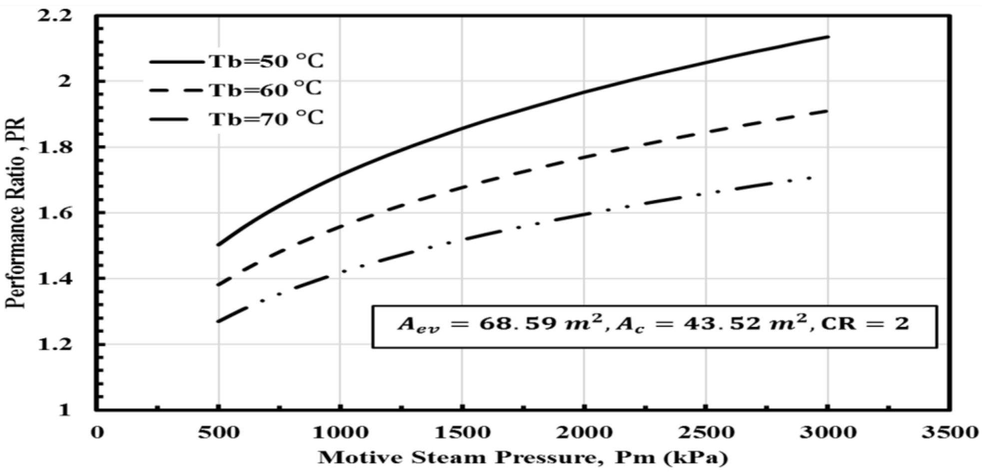

Figure 5. Effect of the motive steam pressure on the performance ratio at different values of boiling temperature for the selected TVC design conditions.

Increasing the motive steam pressure causing an increase in water productivity as shown in "Fig. 6" that presents the effect of the motive steam pressure on the water productivity at different values of boiling temperature.

Secondly, on the basis of the selected design of the TVC system , the two systems; TVC and (TVC-DCMD) hybrid system are compared under operating conditions of different boiling temperatures T_b and motive steam pressures P_m.

The mathematical model of the DCMD is solved for the conditions presented in "Table 2" under the constrain that all the heat rejected from the TVC unit are totally consumed. So, the rejected feed temperature from the DCMD system equals to nearly 35 ℃. The feed temperature of the DCMD module depends on the boiling temperature of the TVC evaporator where the feed solution to the DCMD unit is the sum of rejected brine and the remainder of condenser cooling water emerging out from the TVC unit

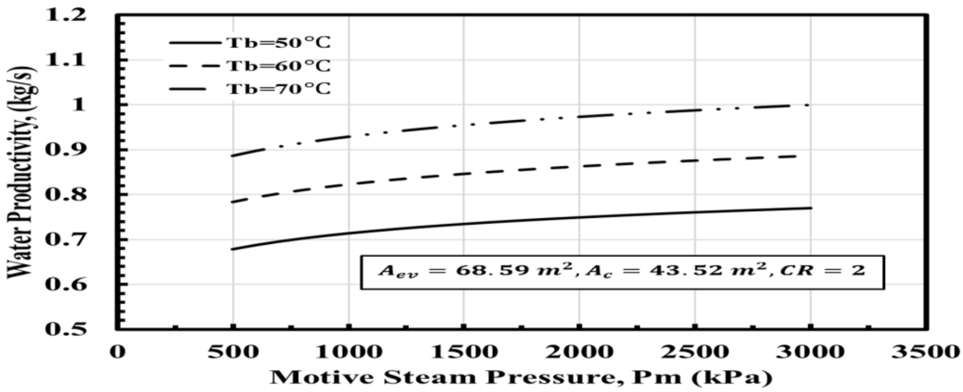

Figure 6. Effect of the motive steam pressure on the water productivity at different boiling temperatures for the selected TVC design conditions.

The DCMD unit is analyzed for the TVC's evaporator boiling temperature ranging from (50 to 70℃) and variation of the motive steam pressure of (500 to 3000 kPa). Figure 7 shows the effect of the variation of the boiling temperature on the permeate flux produced by the DCMD system at different values of motive steam pressures. It is clear that, by increasing the boiling temperature, the permeate flux increases. This is due to the increase in the DCMD inlet feed temperature that grows the temperature difference across the membrane and enhances the heat and mass transfer through the DCMD module.

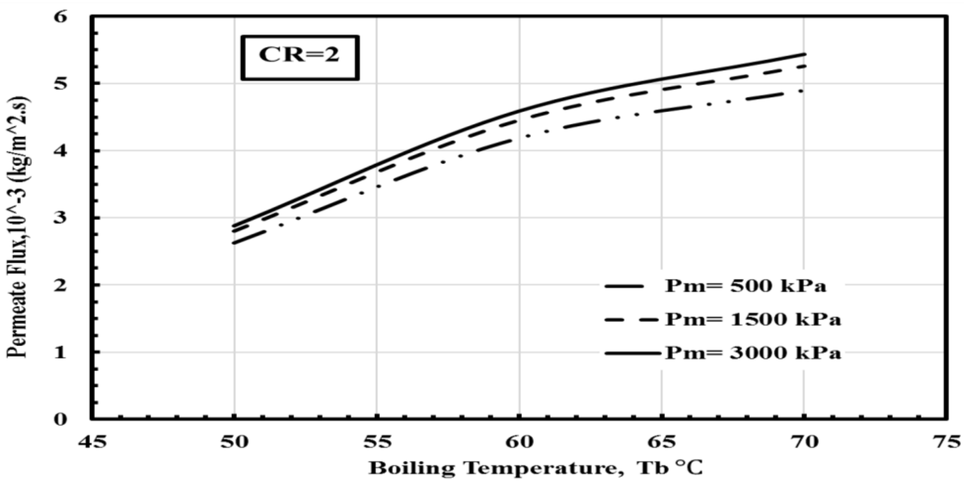

Figure 7. Effect of the boiling temperature on the permeate flux at different values of motive steam pressure.

On the other hand, increasing the motive steam pressure increases the permeate flux due to the increase of the total emerging feed flow rate from TVC.Figure 8 presents the effect of variation of the boiling temperature on the DCMD efficiency at different values of motive steam pressure. It can be observed that increasing both the motive steam pressure and boiling temperature increase the efficiency of the system due to the increase in the permeate flux produced.

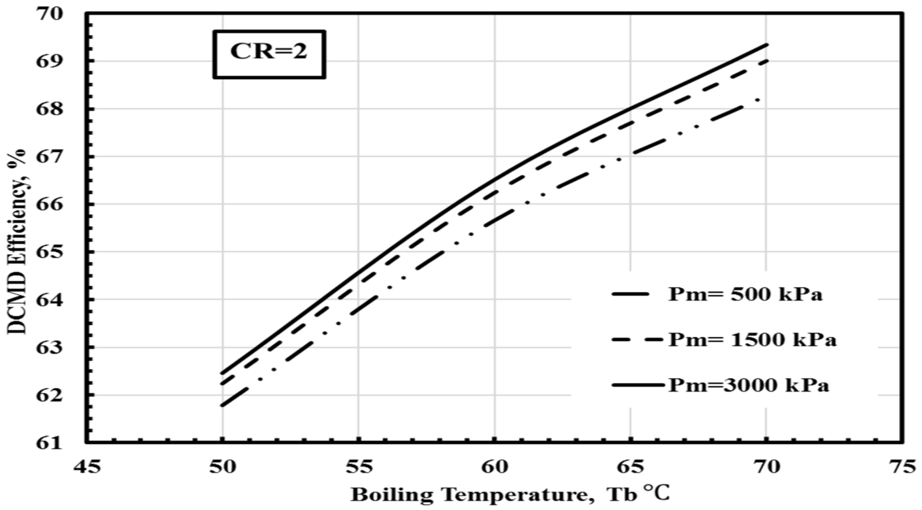

Figure 8. Effect of the boiling temperature on DCMD efficiency at different values of motive steam pressure.

Figure 9 demonstrates the effect of variation of the motive steam pressure on the water productivity of the (TVC-DCMD) hybrid system at different values of boiling temperature compared to the stand alone TVC system. It could be noticed that, the water productivity from the hybrid system is higher than the water productivity from the TVC system at the same operating conditions. And hence, the performance ratio of the hybrid system is improved as shown in, Fig. 10, which presents the effect of the motive steam pressure on the performance ratio of the hybrid system at different values of boiling temperatures compared to the TVC system.

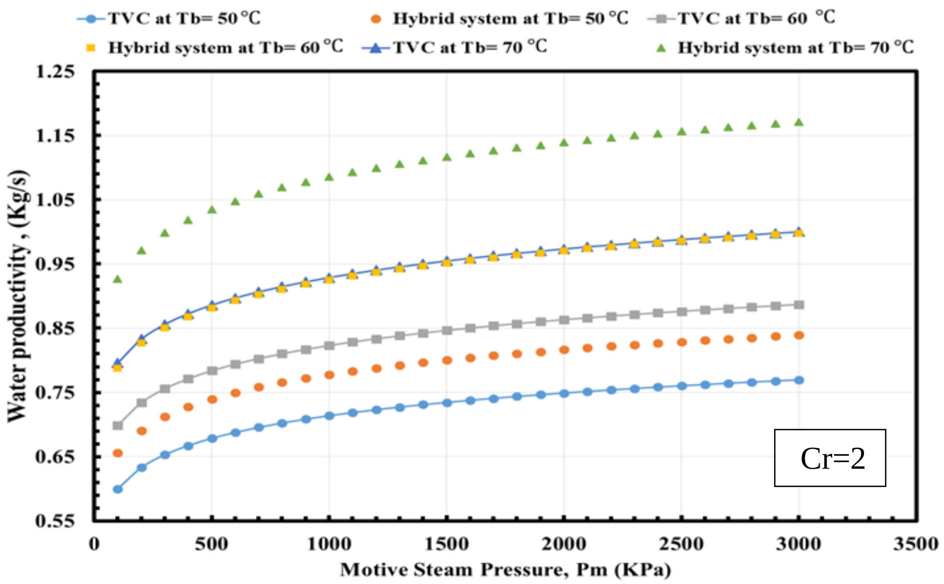

Figure 9. Effect of the motive steam pressure on the water productivity at different values of boiling temperatures for Hybrid(TVC-DCMD) and TVC systems.

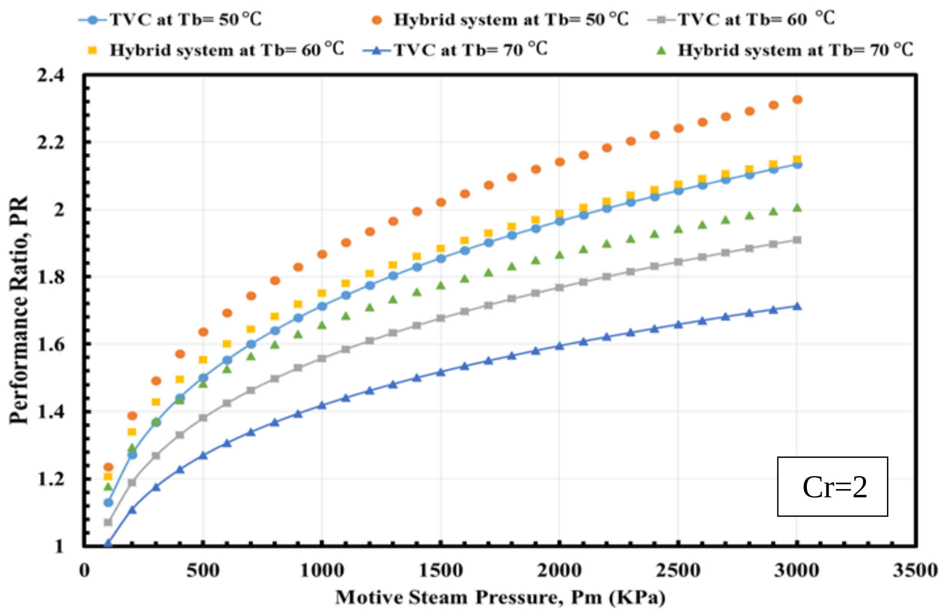

Figure 10. Effect of the motive steam pressure on the performance ratio at different values of boiling temperatures for Hybrid(TVC-DCMD) and TVC systems.

CONCLUSION

It's an interesting to find out the membrane technology role in the hybrid desalination system because of its flexibility and modular design.

A proposed (TVC-DCMD) hybrid desalination system was analyzed theoretically by integrating the DCMD as a secondary desalination unit to the TVC unit that has a pre-specified design. The main objectives of this system are to make the whole system to have higher efficiency or performance ratio, higher productivity, lower energy consumption and lower environmental damages.

The theoretical analysis that both of the performance ratio and water productivity are enhanced by around 3, 4.2, 7 % at boiling temperatures of 50, 60, 70 °C, respectively at 3000 kPa motive steam pressure.

NOMENCLATURE

B	Permeability,	$kg/m^2.s.Pa$
BPE	Boiling point elevation,	°C
c_p	Specific heat at constant pressure,	$kJ/kg.K$
h	Heat transfer coefficient, Enthalpy,	$kW/m^2.°C$, kJ/kg
J	Permeate flux,	$kg/m^2.s$
k	Thermal conductivity,	$kW/m.°C$
M	Molecular weight,	$kg/kmole$
$\dot{m}$	Mass flow rate,	kg/s
PCF	Pressure correction factor,	kPa
PD	Diffusivity of water vapor,	m^2/s
$\dot{Q}$	Heat transfer rate,	kW
R	Universal Gas constant,	$kJ/kmole.K$
S	Salinity	g/kg
TCF	Temperature correction factor,	°C
U	Overall heat transfer coefficient	$kW/m^2.°C$
V	Velocity,	m/s
w	Width,	m
x	Salinity,	ppm
ΔH	Latent heat of vaporization,	kJ/kg
δ	Membrane thickness,	m
λ	Latent heat	kJ/kg
τ	Tortuosity,	---
ε	Porosity,	---
σ	Stefan Boltzmann constant,	$W/m^2.K^4$

Subscripts

a	ambient
b	Brine or boiling
bf	Bulk feed
bp	Bulk permeate
c	Condenser, condensate or conduction
cw	Cooling water
d	Distillate
e	Evaporator

ev	Entrained vapor
f	Feed, fluid
H.ex	Heat exchanger
hy	Hybrid system
i	Inlet, inner
m	Motive steam or membrane or mean
md	Membrane distillation
o	Outlet
p	Pore or permeate
s	Heating steam
v	Vapor
w	Water vapor

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