

UNIVERSITY OF BAHRAIN

College of Engineering



Department of Mechanical

Theoretical Study of Natural Vacuum Desalination Unit in Bahrain

A Thesis Submitted in Partial Fulfillment of the Requirement for the Master's Degree
in Mechanical Engineering

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DECLARATION

I declare that this work is the result of my own investigation and that it has not already been accepted in substance for any degree, nor is being currently submitted for any degree.

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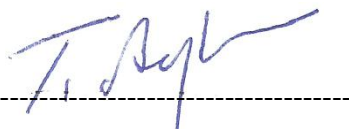
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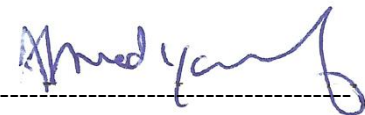


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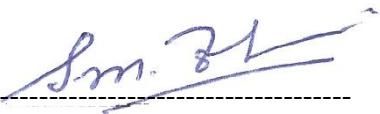


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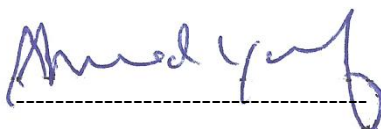
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To my father and mother, who dedicated their life to see mine grows

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ABSTRACT (ENGLISH)

A new and innovative concept was used to design and study an inverse-U shaped ($\cap$) desalination unit, the system utilizes the low pressure (near vacuum) generated naturally by pushing water more than 10.33 meters using the atmospheric pressure as the main pumping force. By introducing low pressure on top of the water to be distilled, evaporation of water can be carried at lower energy levels compared to conventional types of water desalination units. The unit is a $\cap$ shaped pipe that consists of saline water chamber at one end and a fresh water chamber at the other end of the pipe, the saline water chamber is under solar irradiance (which is the main heat source) and the fresh water chamber is enclosed by a cylindrical heat exchanger that passes water to keep the chamber cold. The saline and fresh water chambers are at more than 10 meters height and connected to saline water inlet and fresh water outlet pipes, additionally, a pipe is connected to the saline water chamber to release the brine. Saline water evaporates and the vapor travels to the fresh water chamber to be condensed.

A theoretical study was carried out on the natural vacuum desalination unit under the operating conditions of Bahrain. A mathematical model was developed consisting of the suitable thermo-dynamical and heat transfer relations that closely describes the process of desalination. The natural vacuum desalination model was solved numerically using a customized built MATLAB code coupled with number of readymade functions. Two main cases were studied; hot and cold weather operating conditions, additionally, sensitivity analysis was carried out on a group of specific parameters.

The original configuration or design of the system (with 0.05 m^2 surface area of evaporation) was able to produce up to 0.54 kg/day of fresh for hot weather operating conditions and 0.149 kg/day of fresh water for cold weather operating conditions. The thermal efficiency and exergy efficiency were 44.58 and 5.44% for hot conditions and 9.98 and 0.375 % for cold conditions, respectively. For an evaporation area of 1 m^2 , the output of the system was 3.60 kg/day, generally increasing the area of evaporation increased the system's fresh water production, but stopped changing after 2 m^2 .

The theoretical results of this study configuration have been compared to previous studies. For 1 m² area of evaporation surface, the NVD system achieved lower water production affected by the low efficiency of the current design.

Decreasing the depth of the saline water showed an increase in thermal efficiency (from 44.58 to 79.85%), but the fresh water production decreased considerably (from 0.54 to 0.313 kg). Additionally, the salts concentration increased when the depth was decreased (from 3.521 to 3.724%). The temperature of the cooling water was studied; decreasing the temperature 4 °C (from 30 to 26 °C) increased the output of the system from 0.54 to 0.710 kg. Various withdrawal rates were studied, it was found that using withdrawal rate beyond 0.001 m³/hr stabilizes the salts concentration, but significantly decreases the fresh water production (from 0.313 to 0.228 kg for 0.1 m depth of saline water). Finally, the economic aspect was taken into consideration, the minimum cost of 1 kg of fresh water produced was found to be 0.166 BD for a unit with 1 m² of evaporation surface.

ABSTRACT (ARABIC)

ملخص البحث

عنوان الأطروحة : دراسة نظرية لوحدة تحلية المياه باستخدام ضغط منخفض مولد طبيعيا في البحرين
اسم الطالب : يوسف ابراهيم حسن العزي
التخصص : الهندسة الميكانيكية
السنة : يونيو 2013م

تم استخدام مفهوم جديد ومبتكر لدراسة وتصميم وحدة على شكل حرف يو معكوس (∩) لتحلية المياه، يستغل النظام الضغط المنخفض (شبه فراغي) المولد عن طريق دفع الماء 10.33 متر باستخدام الضغط الجوي كمصدر للقوة الرئيسي. عن طريق توليد ضغط مخفض فوق سطح الماء المراد تحليته، فإن عملية التبخير تتم بطاقة أقل مقارنة بوحدات التنقية التقليدية. الوحدة عبارة عن (∩) انبوبة الشكل تضم حجرة للماء المالح في جهة وحجرة أخرى للماء النقي في جهة أخرى من الانبوب، حجرة الماء المالح معرضة للطاقة الشمسية (والتي تعتبر المصدر الرئيسي للطاقة) وحجرة الماء النقي محاطة بمبادل حراري اسطواني الشكل للإبقاء على الحجرة باردة. حجرتا الماء المالح والنقي تقعان على ارتفاع أكثر من 10 امتار ومرتبطتان بانبوب لإدخال الماء المالح وانبوب لإخراج الماء النقي، بالإضافة الى ذلك، يوجد انبوب مرتبط بحجرة الماء المالح لإخراج الماء المالح. الماء المالح يتبخّر والبخار ينتقل الى حجرة الماء النقي ليتكثف.

تم انجاز دراسة نظرية لوحدة التحلية باستخدام الضغط المنخفض المولد طبيعيا تحت ظروف التشغيل في البحرين، تم تطوير نموذج رياضي يتكون من علاقات الديناميكا الحرارية وطرق انتقال الحرارة المناسبة التي تصف عملية التحلية. تم حل النموذج الرياضي الذي يصف التحلية باستخدام الضغط المنخفض المولد طبيعيا بالطرق العددية عن طريق استخدام برنامج اعد خصيصا بلغة البرمجة MATLAB الى جانب عدد من الاوامر الجاهزة. حالتان رئيسيتان قد درستا؛ ظروف جوية حارة وباردة، بالإضافة الى ذلك، تمت عملية دراسة حساسية تغيير عدد من المتغيرات.

الشكل او التصميم الاصلي (مع مساحة سطح التبخر قيمته 0.05 متر مربع) استطاع ان ينتج 0.54 كغ/يوم تحت ظروف تشغيلية حارة و 0.149 كغ/يوم تحت ظروف تشغيلية باردة. الكفاءة الحرارية وكفاءة الشغل بلغتا 44.58 و 5.44% تحت ظروف تشغيلية حارة و 9.98 و 0.375% تحت ظروف تشغيلية باردة، بالترتيب. لمساحة سطح تبخر تبلغ قيمته 1 متر مربع، بلغ انتاج الماء النقي 3.60 كغ/يوم، بشكل عام، زيادة مساحة سطح التبخر زاد من انتاج الماء النقي، ولكن هذه الزيادة توقفت عند سطح تبخر مساحته 2 متر مربع.

تمت مقارنة النتائج النظرية لهذا التصميم مع دراسات سابقة. لمساحة سطح تبخر تبلغ قيمته 1 متر مربع، حققت وحدة التحلية بإستخدام الضغط المنخفض المولد طبيعيا انتاجية واطنة متأثرة بالكفاءة الواطنة للتصميم الحالي لوحدة التحلية بإستخدام الضغط المنخفض المولد طبيعيا.

خفض عمق الماء المالح اظهر زيادة في الكفاءة الحرارية (من 44.58 الى 79.85%)، ولكن انتاج الماء النقي انخفض بشكل ملحوظ (من 0.54 الى 0.313 كغ)، اضافة الى ذلك، ازدادت نسبة الملوحة عندما انخفض عمق الماء المالح (من 3.521 الى 3.724%). تم دراسة درجة حرارة ماء التبريد؛ خفض الحرارة 4 درجات مئوية ادى الى ارتفاع انتاج الماء النقي من 0.54 الى 0.710 كغ. تم دراسة عدد من معدلات سحب الماء المالح؛ وجد ان زيادة معدل سحب الماء المالح اكثر من 0.001 متر مكعب/ساعة يثبت نسبة الملوحة، ولكن يخفض من انتاجية الماء النقي بشكل ملموس (من 0.313 الى 0.228 كغ لعمق ماء مالح قيمته 0.1 متر). اخيرا؛ اخذ الجانب الاقتصادي بعين الاعتبار، اقل كلفة لإنتاج كغ من الماء النقي لوحدة بمساحة سطح تبخر تبلغ قيمته 1 متر مربع هو 0.166 د.ب.

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NOMENCLATURE

A_{con}	Internal area of the fresh water chamber (m ²)
A_{eva}	Internal area of the saline water chamber (m ²)
A_s	Surface area of the saline water chamber (m ²)
C	Salt concentration (%)
C_o	Salt concentration in saline water feed (%)
$C_{p,f}$	Specific heat capacity of fresh water (J/kg. °C)
$C_{p,s}$	Specific heat capacity of saline water (J/kg. °C)
$C_{p,wall,fresh}$	Specific heat capacity of the fresh water chamber wall (J/kg. °C)
$C_{p,wall,saline}$	Specific heat capacity of the saline water chamber wall (J/kg. °C)
D_h	Hydraulic diameter (m)
$\frac{dX_f}{dt}$	The rate of exergy change of fresh water (Watt)
$\frac{dX_s}{dt}$	The rate of exergy change of saline water (Watts)
$\frac{dX_{wall,fresh}}{dt}$	The rate of exergy change of fresh water chamber wall (Watts)
$\frac{dX_{wall,saline}}{dt}$	The rate of exergy change of saline water chamber wall (Watts)
d_c	Depth of fresh water (m)
d_e	Depth of saline water (m)

e	Exergy per unit mass (J/kg)
f_c	Solute concentration factor (%)
Gr	Grashof number (dimensionless)
g	Gravitational acceleration (m/s^2)
h	Specific enthalpy (J/kg)
h_{air}	Convection coefficient of air ($\text{Watt/m}^2 \cdot ^\circ\text{C}$)
h_b	Enthalpy of brine water leaving the saline water chamber (kJ/kg)
$h_{cooling}$	Convection coefficient of cooling water ($\text{Watt/m}^2 \cdot ^\circ\text{C}$).
h_f	Enthalpy of fresh water leaving the fresh water chamber (kg/hr)
h_{fg}	Latent heat of evaporation (J/kg).
h_{fresh}	The convection coefficient between the fresh water and the internal surface of the fresh water chamber ($\text{Watt/m}^2 \cdot ^\circ\text{C}$).
h_o	Specific enthalpy at dead state temperature (J/kg)
h_s	Enthalpy of saline water feed (kJ/kg)
h_{saline}	The convection coefficient between the saline water and the internal surface of the saline water chamber ($\text{Watt/m}^2 \cdot ^\circ\text{C}$)
I	The solar irradiance per unit area as a function of time (Watts/m^2).
i	Annual interest rate (%).
k_{air}	Thermal conductivity of air ($\text{Watt/m} \cdot ^\circ\text{C}$)
$k_{cooling}$	Thermal conductivity of cooling water ($\text{Watt/m} \cdot ^\circ\text{C}$)
k_{saline}	Thermal conductivity of saline water ($\text{Watt/m} \cdot ^\circ\text{C}$)

M_f	The fresh water mass inside the fresh water chamber (kg)
M_s	The saline water mass inside the saline water chamber (kg)
$M_{wall,fresh}$	Mass of the fresh water chamber wall (kg)
$M_{wall,saline}$	Mass of the saline water chamber wall (kg)
$\dot{m}_{cooling}$	Mass flow rate of cooling water (kg/s)
$\dot{m}_b$ (kg/hr)	Mass flow rate of brine water leaving the saline water chamber
$\dot{m}_e$ (kg/s)	Mass flow rate of vapor produced by the saline water chamber
$\dot{m}_f$ (kg/hr)	Mass flow rate of fresh water leaving the fresh water chamber
$\dot{m}_{in}$	Mass flow rate of saline water feed (kg/hr)
$\overline{Nu}$	Average nusselt number (dimensionless)
n	Desalination unit life time (years).
P_f	Fresh water saturation vapor pressure (Pa)
Pr_{air}	Prandtl number of air (dimensionless)
$Pr_{cooling}$	Prandtl number of the cooling water (dimensionless)
Pr_{saline}	Prandtl number of saline water (dimensionless)
$Pr_{wall-air}$	Prandtl number of air at saline water chamber wall-air interface temperature (dimensionless)
P_s	Saline water saturation vapor pressure (Pa)
Q_{Air}	Heat losses to the environment (kJ/hr)

Q_c	Evaporation heat lost (kJ/kg)
$Q_{cooling}$	Heat transferred from the fresh water chamber wall to the cooling water (Watt)
Q_e	Evaporation losses from the saline water chamber (Watt)
$Q_{fresh-wall}$	Heat transferred from the fresh water to its wall (Watt).
Q_{in}	Heat input (kJ/hr)
Q_{solar}	Heat supplied as solar irradiance (Watt)
Ra	Raleigh number (dimensionless)
Re	Reynolds number (dimensionless)
$r_{c,in}$	Inside radius of the fresh water chamber (m)
$r_{c,out}$	Outside radius of the fresh water chamber (m)
$r_{cooling}$	Internal radius of the condenser (m)
$r_{e,in}$	Inside radius of the saline water chamber (m)
$r_{e,out}$	Outside radius of the saline water chamber (m)
S	Salinity (g/kg)
s	Specific entropy (J/kg. K)
s_b	Specific entropy of brine (J/kg. K)
s_f	Specific entropy of fresh water leaving the system (J/kg. K)
s_{in}	Specific entropy of saline water feed (J/kg. K)
s_o	Specific entropy at dead state temperature (J/kg. K)
$T_{cooling}$	Cooling water temperature ($^{\circ}\text{C}$)

T_f	Fresh water temperature ($^{\circ}\text{C}$)
$T_{fresh-wall}$	Fresh water-wall interface temperature ($^{\circ}\text{C}$)
T_o	Dead state temperature (K)
T_s	Saline water temperature ($^{\circ}\text{C}$)
$T_{saline-wall}$	Saline water-wall interface temperature ($^{\circ}\text{C}$)
T_{sun}	Temperature of the sun (K)
$T_{wall,fresh}$	The temperature of the fresh water chamber wall ($^{\circ}\text{C}$)
$T_{wall,saline}$	The temperature of the saline water chamber wall ($^{\circ}\text{C}$)
$T_{wall-air}$	Wall-air interface temperature ($^{\circ}\text{C}$)
$T_{wall-cooling}$	Wall-coolant interface temperature ($^{\circ}\text{C}$)
U	Overall heat transfer coefficient ($\text{kJ/ hr. }^{\circ}\text{C.m}^2$)
V_{air}	Speed of air (m/s)
ν_{air}	Kinematic viscosity of air (m^2/s)
$\dot{v}_e$	Volumetric evaporation rate from the saline water chamber ($\text{m}^3 /$ s)
$\dot{v}_{in}$	Volumetric flow rate of saline water feed (m^3/s)
ν_{saline}	Kinematic viscosity of saline water (m^2/s)
w	Constant (dimensionless)
$\dot{X}_{air}$	Exergy of surrounding air (Watt)
$\dot{X}_b$	Exergy of brine (Watt)
$\dot{X}_{cooling}$	Exergy of heat transferred from the fresh water wall to the cooling water (Watt)

$\dot{X}_{destroyed,fresh}$	Exergy destruction of fresh water (Watt)
$\dot{X}_{destroyed,saline}$	Exergy destruction of saline water (Watt)
$\dot{X}_{destroyed,wall,fresh}$	Exergy destruction of fresh water chamber wall (Watt)
$\dot{X}_{destroyed,wall,saline}$	Exergy destruction of saline water chamber wall (Watt)
$\dot{X}_{fresh,out}$	Exergy of fresh water leaving the fresh water chamber (Watt)
$\dot{X}_{fresh-wall}$	Exergy of heat transferred from the fresh water to its wall (Watt)
$\dot{X}_{saline,in}$	Exergy of saline water feed (Watt)
$\dot{X}_{solar}$	Exergy of solar irradiance (Watt)
$\dot{X}_{vapor}$	Exergy of vapor (Watt)
$\dot{X}_{wall-saline}$	Exergy of heat transferred from the saline chamber wall to the saline water (Watt)
Z	Constant (dimensionless)

Greek Letters

α_c	Empirical coefficient factor (dimensionless)
α_m	Experimental coefficient 10^{-7} to 10^{-6} (kg. K ^{0.5} / m ² . Pa. s)
α_{steel}	Absorptivity of steel (Dimensionless)
β	Thermal expansion coefficient of saline water (K ⁻¹)
μ	Viscosity of cooling water (N/m ²)
ρ_f	Pure water density (kg/m ³)
$\rho_{s,in}$	Saline water feed density (kg/m ³)

ABBREVIATIONS

ARS	Absorption Refrigeration System
ED	Electro Dialysis
EWA	Electricity and Water Authority
GCC	Gulf Cooperation Council countries
MEE	Multi Effect Evaporation
MENA	Middle East and North Africa
MGD	Million Gallons per Day
MSF	Multi Stage Flash
MVC	Mechanical Vapor Compression
NVD	Natural Vacuum Desalination
OM	Organic Matters
PPM	Part per Million
RO	Reverse Osmosis
TDS	Total Dissolved Solids
TVC	Thermal Vapor Compression

CHAPTER 1

INTRODUCTION

1.1 Introduction

It is well known that water covers more than two thirds of the earth surface (around 70%) (CIA, 2008), which is about 1.4 billion km³, although the abundance of this vital substance in our life, no more than 3% (35 million km³) (Barlow & Clarke, 2002) is fresh water and from this small percentage only 0.77% (11 million km³) of all the earth water (Shiklomanov, 1993) which basically comes from rivers, lakes, and underwater reservoirs is not accessible due to the fact that most of it comes in the form of ice caps and glaciers. The previous numbers are not considered enough and demand satisfying, the reduction in fresh water can be very dangerous and health hazardous. It is found that 88 developing countries, approximately half of the world population, are affected by such scarcity of fresh water, more than 80% of all diseases and 30% of all deaths are results from poor water quality (Leitner, 1998). 0.77% of overall earth water is fresh and suitable for hygienic, and this amount is considered to be nonrenewable similar to fossil fuel, which accumulated slowly throughout time and will be depleted one day; the renewable amount from the fresh water is only 0.3% (110,000 km³), this very small amount is acquired through a global water cycle.

The global water cycle is a process of precipitation of water occurring over land, most of the water recycled is due to evaporation and transpiration from plants which accounts for 69,600 km³/year, 26% of this amount (18,200 km³ /year) is used mainly in agriculture, the remaining 74% is available for direct use which is 47,700 km³ /year, this amount infiltrate soil and replenish ground water; and only 12,500 km³

/year is available due to the remoteness and other seasonal events, which is a scarce quantity (Postel, et al., 1996)

The distribution of fresh water across the world is uneven, the quantities of water varies according to regions and countries, also the seasonal changes clearly influence the distribution discrepancies. Most of the renewable resources come from lakes, rivers, and aquifers, etc (Roudi-Fahimi, et al., 2002). This uneven distribution of fresh water amounts affects some areas in an unfortunate way. For instance, consider MENA (Middle East and North Africa) countries, those are the most water scarce regions of the world, their population is 6.3 % of the overall world populations, and they have only 1.4% of the worlds renewable fresh water. Additionally, the population rapid growth complicates the problem even more. Unlike the MENA countries, the U.S. have a relatively abundance of fresh water, although, fresh water amounts are not distributed evenly especially in the western states.

Another important and a clear factor that leads to the scarcity of fresh water is the size and rate of increase of population (Viessman Jr & Hammer, 1998). The high growth rate of the world population and industry has resulted in large demands for fresh water which eventually leads to acute shortage. One cannot neglect the effect of community type wither it is agricultural, residential, or industrial; for each of these community type, the consumption of fresh water is different. The wealth and economical statues of the community have a significant influence; it can affect the level of technology available to produce fresh water to maintain a high level of living. Cultural values and ethics have a degree of impact regarding the production and conservation of fresh water, for example, the laws and policies of a certain state or nation government may favor agricultural orientation which increases the need for usable and fresh water.

Experts measure water availability in terms of the amount of annual renewable fresh water per person, when a person's renewable fresh water amount per year lies between 1,000 cubic meters and 1,700 cubic meters (Falkenmark & Widstrand, 1992), that person's country is in a 'water-stressed' condition, usually water stressed countries are those which have less than 1,000 cubic meters of renewable fresh water per person per year, a number that is found in MENA countries, TABLE 1 shows fresh water in the middle east and north Africa per capita, MENA population has nearly doubled rising from 173 million to 386 people from 1975 to 2001, this increase in population has decreased the fresh water amount per person per year more than half reaching 1,640 cubic meters per person per year. Another problem with MENA countries is the uneven distribution of the resources; this is because almost 75% of available fresh water is located in Iran, Iraq, Syria and Turkey, while the remaining countries of Bahrain, Jordan, Kuwait, Libya, Qatar, Saudi Arabia, the United Arab Emirates, and Yemen have fresh water amount below 250 cubic meters per person per year. What stresses the matter more is the rapid and continuous increase in the population of MENA, at a rate of 2 % growth (Roudi, 2001) (which is about 7 million people per year) despite of decrease in the birth rate of women in 1960 from 7 births to 3.6 births in 2001. In spite of lower women birth rate, MENA's population will continue to rise, resulting in dropping the amount of fresh water below 1,100 cubic meters per person per year. The fastest growing populations are the ones with less developed technological and economical statues such as Yemen.

TABLE 1 Fresh water in the Middle East and North Africa per capita, adapted from (Roudi-Fahimi, et al., 2002)

	Per Capita Annual Renewable Fresh Water (m ³)			% of Freshwater Use, by Sector	
	1970	2001	2025	Domestic	Industrial
MENA	3,645	1,640	1,113	8	5
Algeria	1,040	462	331	25	15
Bahrain	455	140	97	39	4
Egypt	2,460	1,243	903	6	8
Iran	4,770	2,079	1,555	6	2
Iraq	10,304	4,087	2,392	3	5
Israel	740	342	247	16	5
Jordan	555	174	103	22	3
Kuwait	27	9	5	37	2
Lebanon	1,944	1,120	896	28	4
Libya	302	114	72	11	2
Morocco	1,960	1,027	741	5	3
Oman	416	206	5	2	94
Qatar	901	170	129	23	3
Saudi Arabia	418	114	59	9	1
Syria	7,367	2,700	1,701	4	2
Tunisia	800	422	327	9	3
Turkey	5,682	3,029	2,356	16	11
United Arab Emirates	897	60	44	24	9
Yemen	648	228	103	7	1

Gulf Cooperation Council countries (GCC) have a great interest in producing fresh water due to their low renewable fresh water amounts, generally those countries have the same economical statues due to the massive oil and gas discovered in the last decades, their economy is highly driven by oil exportation which is 90 % of their revenues (Al-Rasheed & Sherif, 2000). Their natural water resources are being depleted and the demand is increasing due to the growth of their population, which led them to acquire approximately 50% of the overall world desalination plants, most of them are driven by natural gas; it's safer, and cost effective, but they produce high amounts of CO₂.

1.2 Fresh water in Bahrain

Because this research is conducted in the Kingdom of Bahrain, which has the lowest population and area among the GCC countries, it is important to point out the current capability regarding fresh water production and where does it stand. In Bahrain the source of the natural fresh water comes from the underground which is constantly being depleted, and the general view from the society towards the water availability is

not helping because they don't consider the scarcity of the fresh water resources a real problem. With the decrease of the fresh water amounts, one solution is to come up with better demand management programs to control the usage and to be able to satisfy the increasing demand. In 1975 Bahrain's demand for fresh water was 16 mgd (million gallon per day), increasing to 48 mgd in 1985 (Al-Maskati, 2001); such a high percentage of increase induced the Kingdom to take steps to control the extraction of fresh water from its resources within safety limits; Bahrain's electricity and water authority (EWA) succeeded in dropping the increase in demand of fresh water rate from 11.8% to 1.19% between 1985 and 1999. Moreover, the authority assigned a maximum supply ceiling of 70 mgd to maintain the annual percentage within affordable limits.

The ground water resources in Bahrain consists of three main aquifers; alat, khobar belonging to the dammam formation, and Rus-Umm ErRadhuma carbonate (Al-Zubari & Al-Ansari, 1999). See appendix (A) for a schematic illustration of the aquifers system. Alat aquifer contains the best quality of ground water with TDS (Total Dissolved Solids) of about 2,000 PPM (Part per Million) but has a low productivity of 2-6 m³/day. On the other hand, khobar unit provide a relatively high yield of about 15-200 m³/day with TDS of 2,000-5,000 PPM which most of the ground water is extracted from. The third source is the Rus-Umm ErRadhuma which has salinity more than 8,000 PPM. Thus, it is considered unsuitable for conventional use. The khobar unit is the main source of the ground water due to the high yield and low salinity.

To broaden the choices and options for fresh water production, AEW went to use the treated sewage effluent for the agricultural purposes. The first sewage treatment station was constructed in 1983 in tubli. Its supply was originally 22 Mm³/year, currently it produces more than 70 Mm³/year, but only 20% of the produced amount is used and the rest is flushed to the sea. This is done because it is not accepted socially based on religious and psychological reasons to reuse treated waste water, not to mention some other health concerns. Although of that behavior, the Sewage and Drainage Directorate constructed many sub-stations for sewage treatment across the country, see appendix (A) for complete list of treatment stations in Bahrain.

To cover and compensate the shortages for fresh water and to ease the demand from the aquifers, a small number of desalination plants were constructed. The first plant was built in 1975 with a capacity of 8 Mm³/year (Khater, 1999). Currently the country's capacity is 73 Mm³/year, TABLE 2 shows the desalinations stations with their production capabilities. The distilled water is mixed with a low quality groundwater for domestic uses. Officially, the first desalination plant was built in sitra, it consisted of two unit Multistage Flash (MSF) seawater desalination units, and each one has a capacity of 11,500m³/day. In 1984, sitra station faced a second phase of expansion, by installing a 25 MW gas turbine with a waste heat recovery boiler and a 5 MGD (million gallons per day) MSF evaporator. A third phase was commissioned in 1985 consisting of three MSF evaporators, each with 5 MGD and can increase up to 6.8 MGD at high temperature operation.

In 1997, a contract to build the first phase of Al-Hidd plant, it is a dual-purpose plant (generating electrical power and fresh water) consisting of a 280 MW gas turbine and 30 MGD MSF plant for desalinating water (4 units x 7.5 MGD).

TABLE 2 Desalination plants in Bahrain, adapted from (Khater, 1999)

Desalination Plants	Capacity in Mm ³ /yr	Remarks
Sitra combined power and water MSF plant	42	The oldest distiller and power plant are to be refurbished to extend their remnant life to 2010
Ras Abu Jarjur brackish water RO plant	17	An efficient operating plant and expected to continue to beyond 2005.
Ad-Dur seawater RO plant	17(Now 5 Mm3/y)	Under rehabilitation to bring it to designed production
Hidd Seawater MSF Phase 1	50 Mm ³ /year	available from 3/2000
Hidd Seawater MSF Phase 2	50 Mm ³ /year	Will be available from 2005
Hidd Seawater MSF Phase 3	50 Mm ³ /year	Will be available from 2010

The cost of water in the kingdom of Bahrain highly depends on the type and availability of the plant, for example, RAS Abu Jarjur brackish water RO (reverse osmosis) plant cubic meter water cost was 0.225 BD in 1998 and 0.248 BD in 1997, another issue to consider is the reverse osmosis plants nature which require new membranes, pretreatment chemicals and electrical power. While the MSF produced water at a cost of 0.198 BD/m³, the Ad-Dur plant suffered from technical setbacks

which resulted in a low production capacity of 5 Mm³/year which in turn increased the cost of the produced water.

1.3 Desalination processes

There are three main methods to desalinate raw water i.e. separating or extracting pure water from the salt; which are: thermally or phase change, physically, and chemically.

Thermal techniques implies the use of thermal energy to change the water to vapor or solid phase, separating the produced phase physically from the salt solution, and then recover the energy by condensing the vapor into liquid. One of the most famous processes that falls under this category is the "Multi Stage Flash" process (Spiegler & El-Sayed, 2001). The process uses thermal energy to evaporate the water from its salty feed, then condenses it to obtain fresh water. As the name indicates, the desalination process takes place in steps or number of stages. In this process the latent heat of evaporation of a stage is recovered and used to preheat the next stage. To maximize the yield of the whole system, each stage operates at relatively lower pressure, because as the stages advance, the water temperature decreases, thus needing a lower pressure to evaporate the water. One of the major advantages of the MSF process is the bulk liquid that is boiling, which reduces the problem of the undesired scale formation on heat transfer tubes.

MSF units are usually coupled with steam or gas turbines power plants to achieve higher thermal efficiencies (similar to Sitra and Hidd power stations in Bahrain). Steam at high temperature and pressure is used to generate electricity when entering the turbine, at the exit the steam has low temperature and pressure which is used to drive the desalination process. FIG. 1-1 shows a schematic illustration of the multi stage flash desalination process.

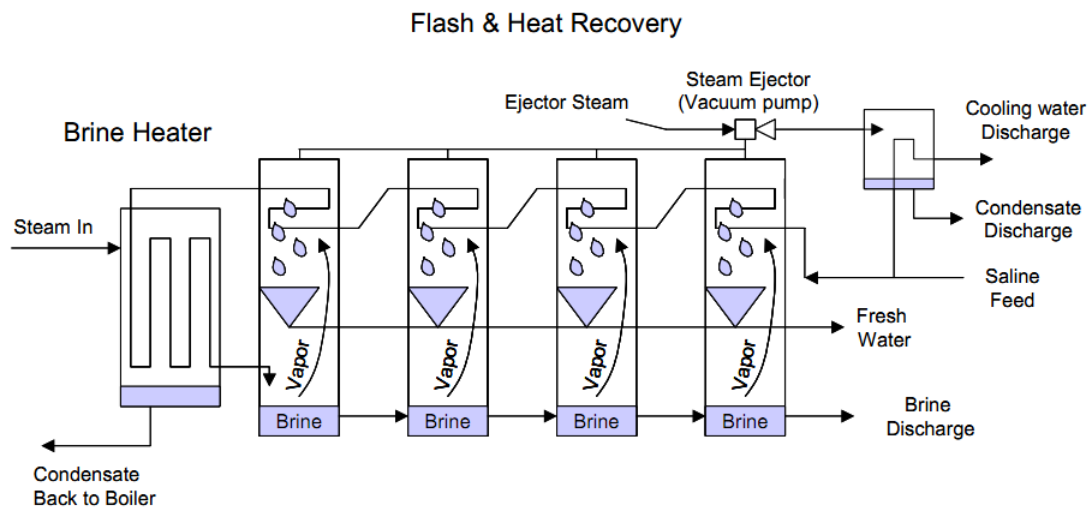


FIG. 1-1 Multi stage flash desalination process, adapted from (Miller, 2003)

Another desalination process called multi-effect evaporation (MEE) related to MSF process, it was first developed in 1950s (Al-Shammiri & Safar, 1999), however it did not have the same success as the MSF due to the scaling formation on the heat transfer tubes surfaces. So, it lost its ground to the MSF process. But even suffering from this disadvantage, it has a higher thermal performance than the MSF (i.e. consumes less thermal energy). The process runs in multiple stages, the vapor produced in each stage is condensed in the next consecutive stage allowing the latent heat produced to evaporate the newer stage. To increase the performance along the stages, the pressure is reduced to allow for many temperature ranges of operations whether the operating conditions are high (higher than 90 °C) or low (lower than 90 °C). As low as 55 °C boiling temperature can be achieved in this system, allowing for the use of low sources of heat (such as waste heat sources) and reduce the scaling and corrosion.

MEE process can have many different configurations depending on: (a) the type of heat transfer used, which can be a vertical climbing film tube, rising film vertical tube, or horizontal tube falling film. Or (b) according to the brine flow type wither it is forward, backward, or parallel. Just like MSF process when combined with other heat sources it can increase the thermal performance ratio. FIG. 1-2 shows a schematic illustration of a multi-effect evaporation desalination process.

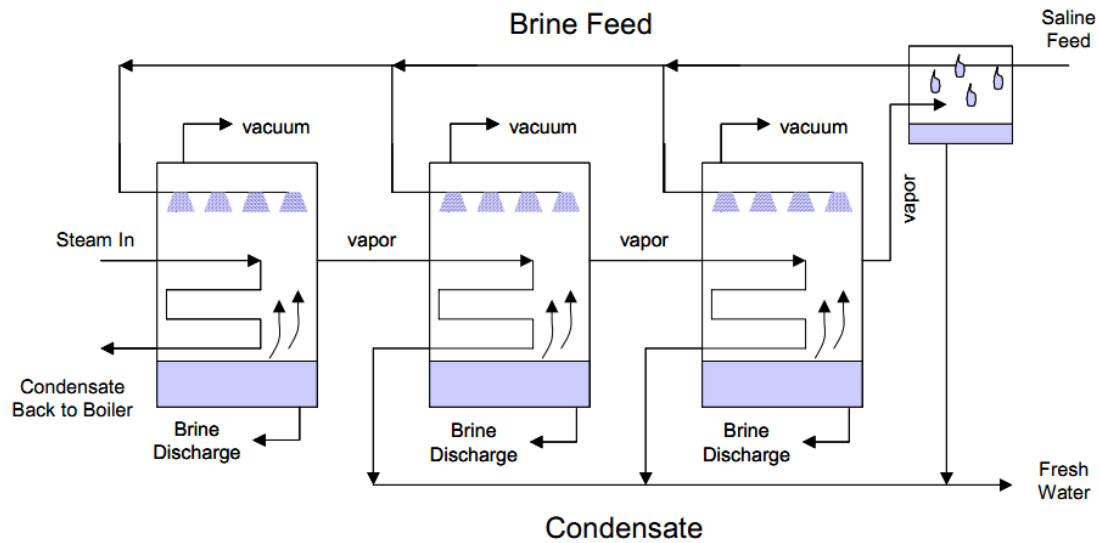


FIG. 1-2 Multi effect evaporation desalination process, adapted from (Miller, 2003)

A third desalination process is called the vapor compression process. It relies on the reduction of pressure to start and maintain the evaporation process. There are two methods for supplying the heat required for evaporation by compressing the vapor (Buros, 2000): (a) the usage of mechanical compressor to compress the vapor which in this case the process is called mechanical vapor compression (MVC), or (b) by the usage of steam ejector which the process is referred to as thermal vapor compression (TVC). There are several differences between the two processes. For instance the MVC is used with a system of small to medium capacities up to 3,000 m³/day. The TVC capacity can reach up to 20,000 m³/day. MVC process is usually only a single stage process while TVC has multiple stages, which increases and enhances the capacity of the system. FIG. 1-3 and FIG. 1-4 show a schematic illustration of a single stage mechanical vapor and thermal vapor compression systems, respectively.

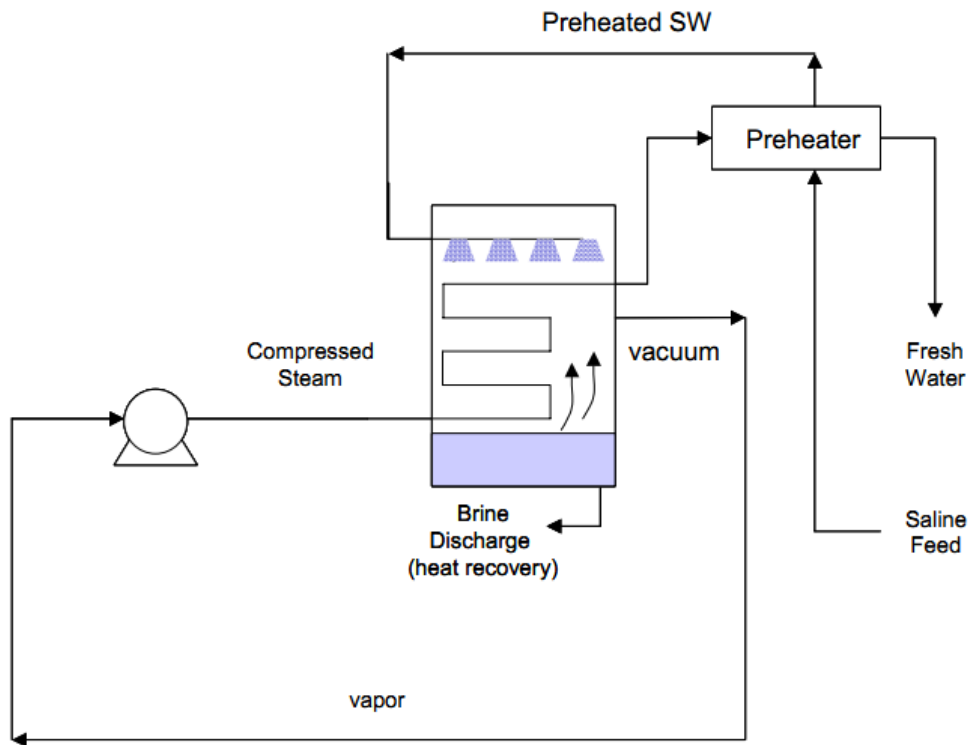


FIG. 1-3 Single stage mechanical vapor compression process, adapted from (Miller, 2003)

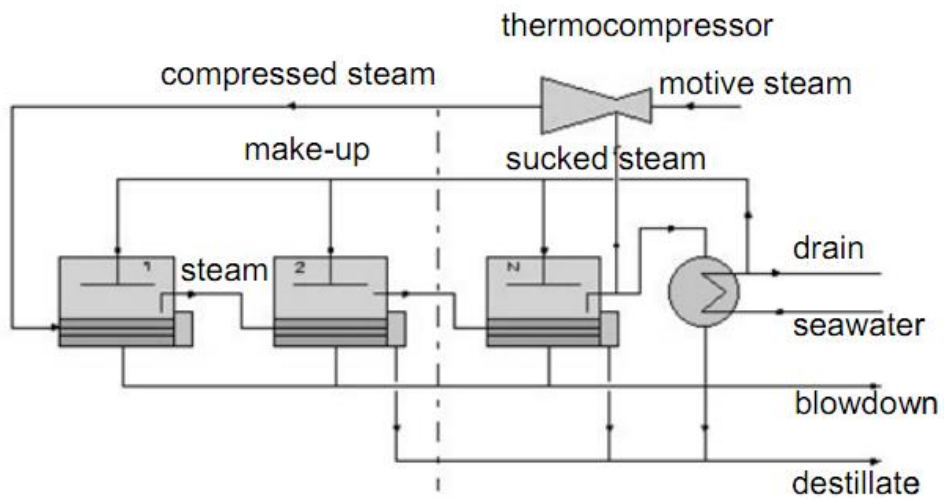


FIG. 1-4 Thermal vapor compression process, adapted from (Trieb, 2007)

Another phase change process is the freezing desalination technique, as the name implies the water is frozen to obtain ice, the technology dates back at least to the

1950s (Hendrickson & Moulton, 1956). The process can be direct or indirect, in the case of a direct freezing process, the water or brine is mixed with a refrigerant. In the case of an indirect process the refrigerant and the water are separated, the process is a conventional refrigerant compression cycle. Here the evaporator is the ice freezer, and the condenser is the ice melter. The ice is formed as small crystals of slush with brine in it. To separate the ice from the brine centrifugation is used, the slush is flown upward in a column and the brine is absorbed through peripheral discharge screens. Finally, to extract any residuals of brine from the ice a counter flow of fresh water is fed from the top of the column, then the ice goes to the melter to produce fresh water. A heat exchanger collects energy from freshwater and reject brine by precooling the feed. FIG. 1-5 shows a schematic illustration of an indirect freezing desalination process.

In the direct freezing desalination process the water is the refrigerant and it operates in vacuum conditions (Karnofsky & Steinhoff, 1960). The advantage of this is that the compressor operates at lower temperature range, hence, requiring less work per unit of fresh water produced. Butane can be used in this process as the refrigerant. One advantage is that the process does not have to be tightly under vacuum conditions.

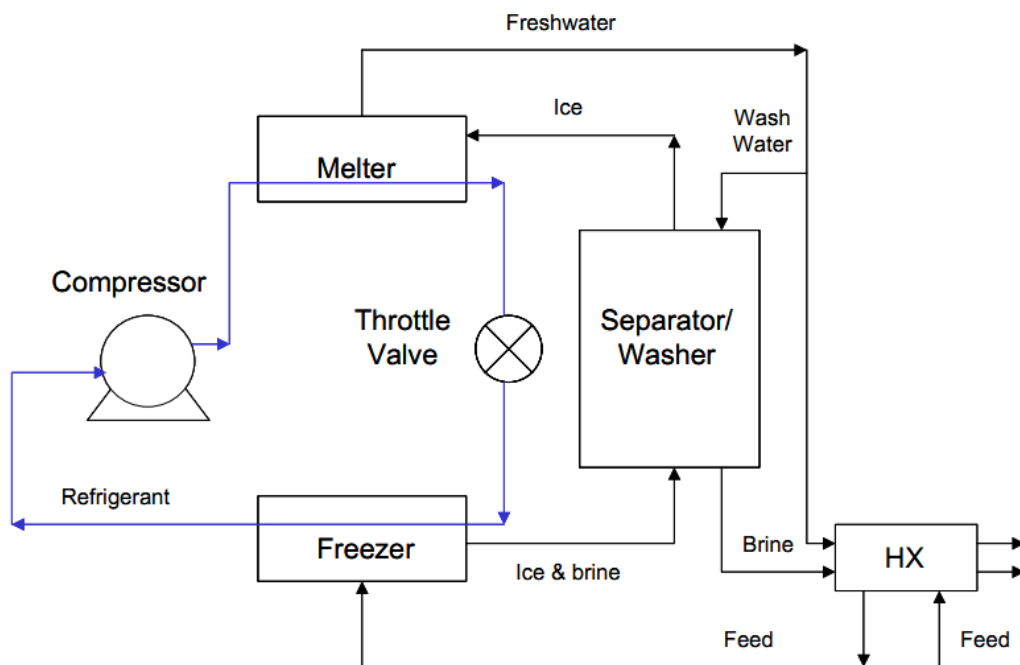


FIG. 1-5 Indirect freezing desalination process, adapted from (Miller, 2003)

The previous desalination processes were thermal or phase change based processes, the second category of desalination process is the physical type. In this methodology the separation of fresh water is due to the use of physical means such membranes. One famous and widely used method is the reverse osmosis (RO) process (Semiat, 2000). It separates the water from a pressurized saline solution to a point greater than the osmotic pressure; this method is greatly used in many countries like the United States and also Bahrain. Simply the process works by passing the pressurized solution through a special membrane which filters out the salt ions from the solution. Post treatments secondary operations are performed to extract the dissolved gases such as CO₂ and stabilizing the pH levels by the use of Ca or Na salts. Most of the power consumed by the RO process goes to pressurizing the salt solution. The pressure needed is proportionally related to the salt concentration, the more the salt percentage the more pressure needed to apply on the solution. This is why the RO process is usually used with brackish water due to the low and medium pressure values it requires to reach. A typical operating pressure for brackish water is 15-25 bars compared to 54-80 bars for sea water, this difference in pressures tend to get low yields of the seawater when using RO processes (Spielger & El-Sayed, 1994).

To increase the efficiency of the RO process (i.e. reduce the required energy), the released concentrated brine after filtration is used to recover some mechanical energy since this brine is still highly compressed. A problem arising within this process is the accumulated organics, algae, and bacteria on the membranes which leads to membrane fouling, not to mention that those filters are sensitive to pH levels and oxidizers, therefore is it essential to treat the water before entering the process to lower the cost by changing the membranes less frequently. FIG. 1-6 shows a block diagram for the reverse osmosis process.

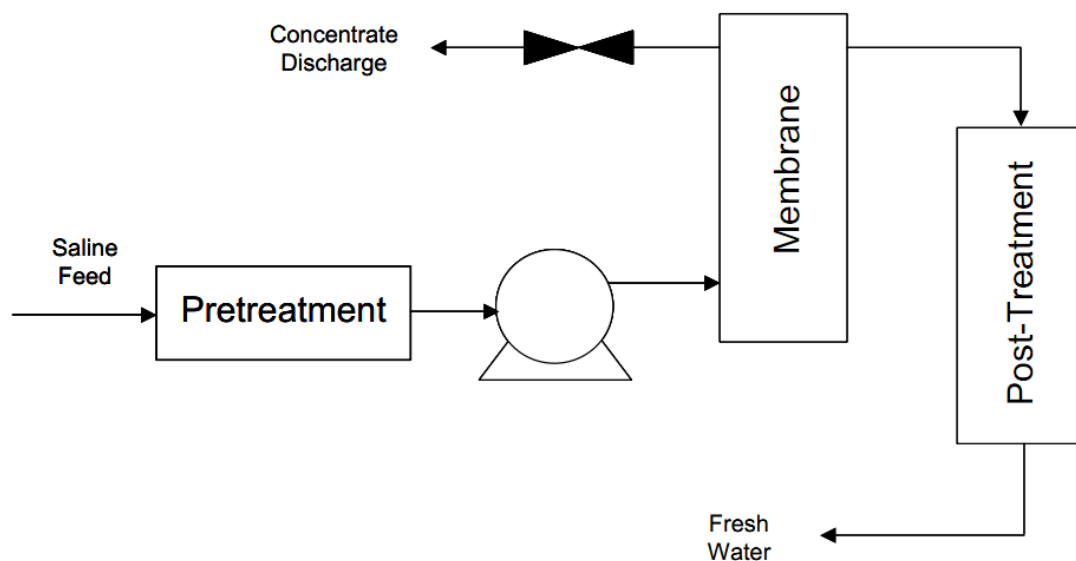


FIG. 1-6 Reverse osmosis process, adapted from (Miller, 2003)

Electrodialysis (ED) is another desalination process that depends on certain types of membranes to achieve the separation (Mandani, et al., 2000). The main principle is the use of direct current sources to drive the process with number of channels for the water to flow, and these channels are made of anion and cation membranes. A major drawback of this method is its inability to distil other than ionic substances. The process works by a water flow fed parallel to the separation channels, while applying a voltage, anions and cation migrate to the opposite direction, and since the membranes have selective characteristics the ion concentration increases and decreases in alternating channels in the process. Usually hundreds of alternating channels are packed into a single stack allowing the process to be carried out slowly, this is because the resistance changes from up to bottom. This gradual separation process makes the desalination more economical and easier to control. The process requires more power to separate the salt as its percentage increases (similar to RO process) thus it is usually limited to brackish water containing a few thousands of ppm of dissolved solids.

Since ED membrane does not allow any flux of water through it, the process can treat higher level of suspended solids than RO process, but still the membranes are

prone to fouling that will considerably lower their performance. Thus the process of Electrodialysis Reversal is used to eliminate such fouling affecting the membranes, the process switches the polarity of the membrane multiple times per hour which changes the flow of brine water to fresh water channels and vice versa which will break up the fouling and deposits of the membrane walls. FIG. 1-7 shows a schematic diagram of the Electrodialysis desalination process.

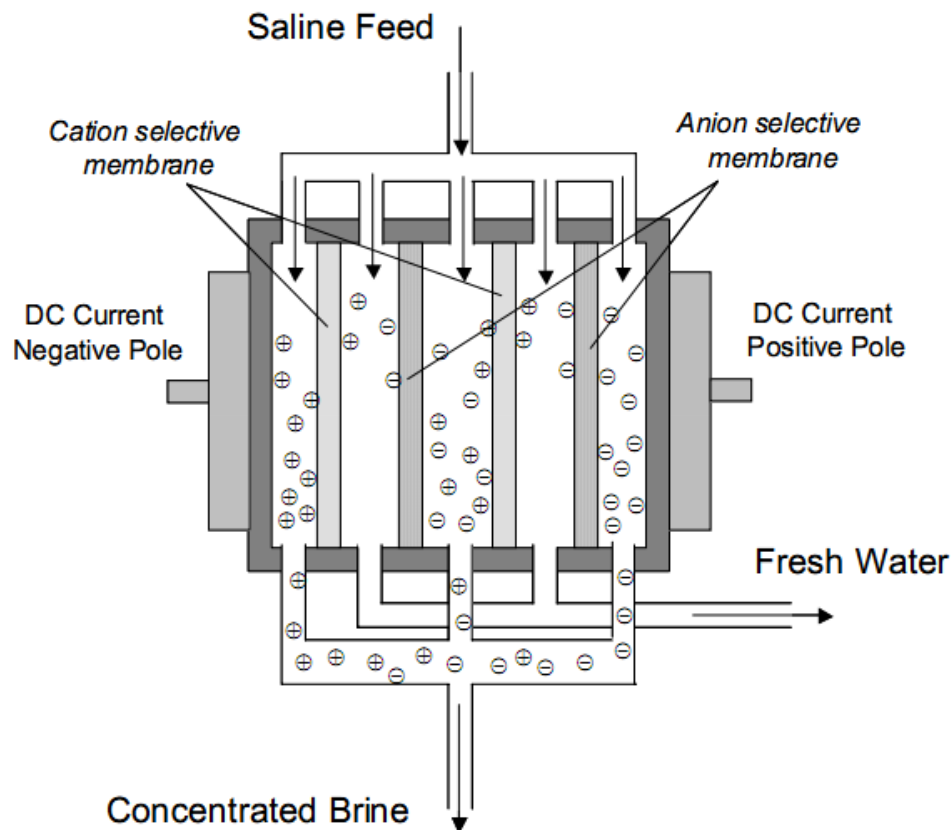


FIG. 1-7 Electrodialysis desalination process, adapted from (Miller, 2003)

The third category of desalination is of chemical nature, such as the ion exchange method (Harland, 1994). It is essentially an organic or inorganic solid capable of exchanging a cation or anion with another type of cation or anion in a solution surrounding the ion exchanger. For example to purify sodium chloride solution, a cation exchanger would replace the Na^+ with H^+ and an anion exchanger would replace the Cl^- with OH^- resulting in a demineralization of the solution. To regenerate and

rebuild a cation exchanger the process is reversed using an acid substance and the anion exchanger is rebuilt using a base substance.

Although the ion exchange process seems attractive, due to its ability to deal with impurities such as salt rather than the water to achieve its purpose, the process falls short when it comes to the cost side of the process, it is known that for generation 1000 gallon of water from a solution with an initial NaCl concentration of 3500 ppm, the cost needed is 4 dollars which is more than the RO process, and this is the cost of regeneration only, in reality the process is not 100% efficient, meaning that it would cost more than previously estimated.

To solve the high cost of the ion exchange process, an alternative process called Sirotherm process to produce fresh water from brackish water (Bolto & Weiss, 1977). This process involves the use of weak and less developed acidic and basic ion exchangers that can be regenerated by ordinary hot water (90 °C). The high temperature of water enables it to dissociate to H^+ and OH^- 30 times more than if the water was at ambient temperature. In spite of this improvement, the batch operation was deemed uneconomical and the continuous process was too complex for large scale operations. FIG. 1-8 shows a schematic illustration of ion exchange desalination unit.

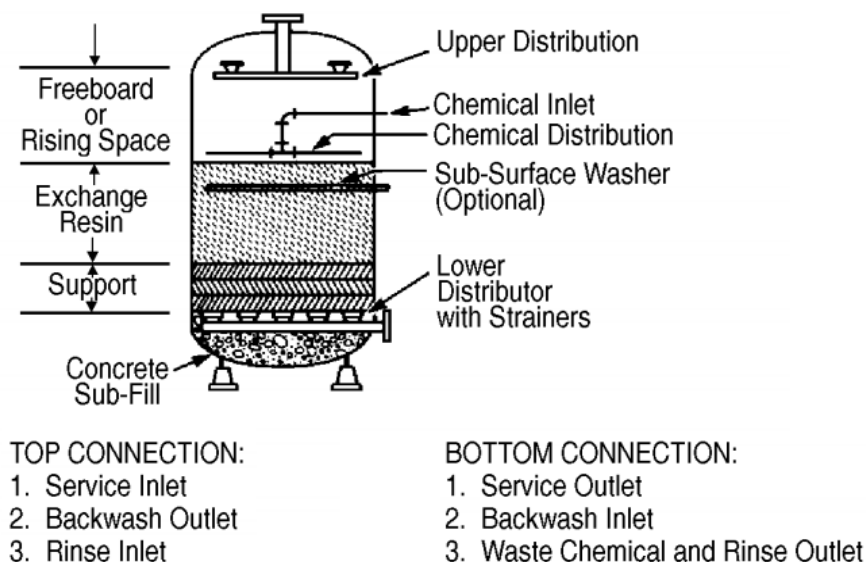


FIG. 1-8 Ion exchange desalination unit, adapted from (NALCO CHEMICAL COMPANY, 1998)

1.4 Solar desalination

Solar desalination uses the solar energy to desalinate salt water. It is considered fairly suitable especially in rural areas and in countries with abundance of solar power such as MENA countries. It can be used directly as thermal power or indirectly by converting it to electricity to drive conventional desalination processes such as reverse osmosis (Al-Hallaj, et al., 1998). Solar energy can be collected directly in solar stills, ponds, or collectors, while electricity can be generated from solar energy using photovoltaic cells or from solar thermal power plants.

Solar still (Goosen, et al., 2000) is one of the most basic and widely used to desalinate water; it has been in use for several decades due to its simple design, virtually maintenance free nature, and its low cost. The typical yield of a solar still is 2-5 kg/day which is considered low; the problem with solar stills is that they have only 50% efficiency, this is due to the loss of the energy from the brine water to the cover and ground. FIG. 1-9 shows a simple solar still. Basically the still absorb the solar radiation through the glass cover resulting in an increase in water temperature and hence increase in the vapor pressure, this vapor rises via natural convection to the cover, there it condensates and the condensed water flow down under the effect of gravity to the collection tank.

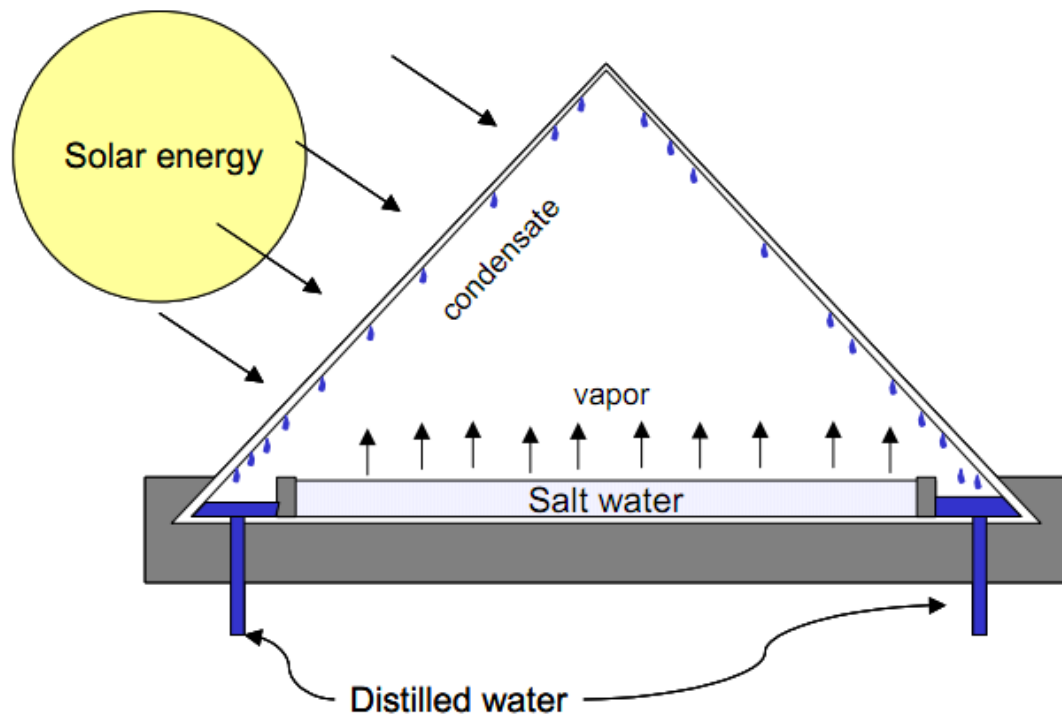


FIG. 1-9 Solar still, adapted from (Miller, 2003)

Studies have been carried out to increase the productivity of a conventional solar still by coupling it with a solar collector to absorb more solar energy (Lawrence & Tiwari, 1990), the system performance indeed was enhanced but with increased cost to add the collectors, the yield of such combination in some cases roughly doubled from 4 kg/day to 8 kg/day, FIG. 1-10 shows a solar still coupled with a solar collector.

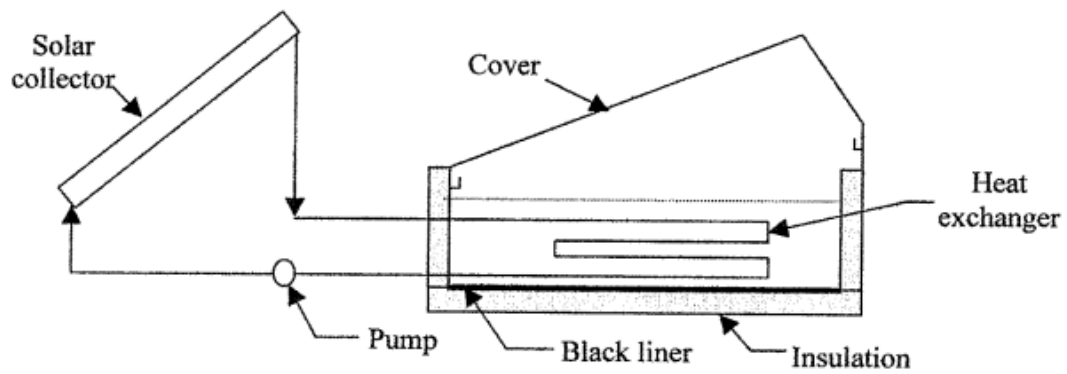


FIG. 1-10 Solar still coupled with a solar collector, adapted from (Al-Kharabsheh, 2003)

Another way to increase and enhance the performance of the solar still is to use an external condenser and solar reflectors to increase the heat sink capacity, thus, increasing the temperature difference between the saline water temperature and the glass cover (El-Bahi & Inan, 1999). FIG. 1-11 shows a solar still coupled with a reflector and external condenser.

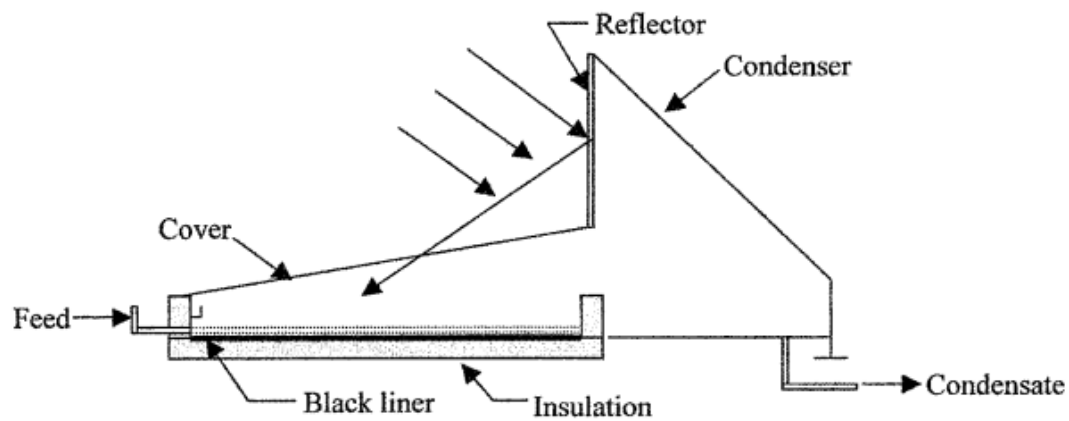


FIG. 1-11 Solar still coupled with a reflector and external condenser, adapted from (Al-Kharabsheh, 2003)

Using solar collectors to absorb additional amounts of solar energy is not effective if those collectors were of a low temperature capacity type (Fahrenbruch & Bube, 1983), thus, they are designed to maximize their heat carrying capacity, they may

include glazed flat plate collectors or vacuum tube collectors with air or liquid as the heat transfer medium, and then providing heat indirectly to other desalination processes (Kalogirou, 2005). One example of high temperature collectors are parabolic troughs or central receivers, typically the radiation gained is concentrated on a focal point in which a certain fluid gathers the radiation via a heat exchanger, either this hot fluid can be used to generate steam to operate turbines for electricity generation or they can be used to heat up water in other desalination processes.

A drawback of such system is its inability to deal with the constantly change of sun position daily and yearly, this requires it to use a sun tracking device to assure an optimum position for solar rays to be in focus with the reflector to improve its efficiency and productivity, which adds extra cost specially if desalination plants are of a large scale. FIG. 1-12 shows a parabolic solar collector.

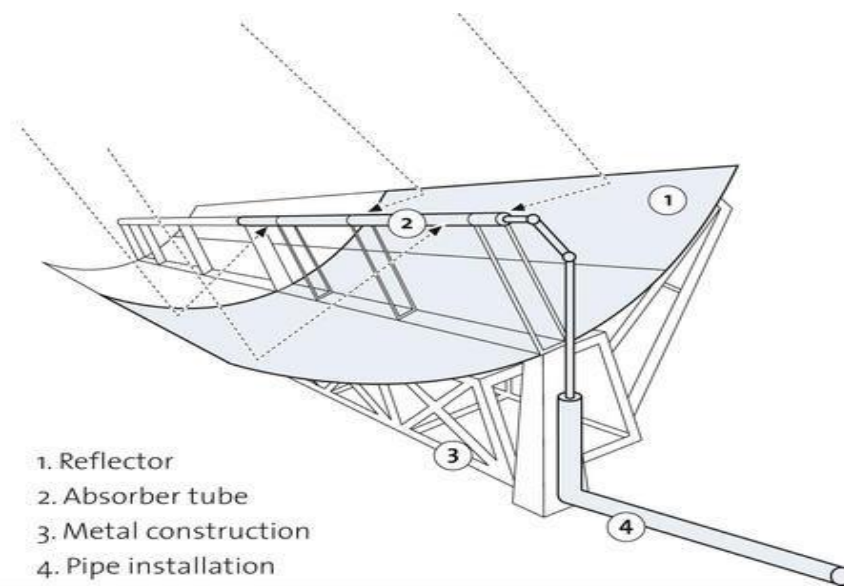


FIG. 1-12 Parabolic solar collector, adapted from (Solar Millenium , 2010)

To utilize the latent heat produced by the condensation of vapor in solar stills, multiple chambers are used to distill water in many successive steps called effects (Fernandez & Chargoy, 1990), the main or first effect gets its energy from a solar source (directly or indirectly), the hot water evaporates producing a vapor that travels upward to condense on the bottom of the consecutive effect, while the condensate is

stored in a chamber for extraction, the latent heat rejected in the condensation process heats the second or the next effect to evaporate the water, the process is repeated again in upcoming effects.

Usually the first effect or chamber gets its evaporation energy indirectly from a solar collector to increase the productivity of the system (Franco & Saravia, 1994) leaving the last stage covered by glass; this allows the last effect to get the benefit of the heat produced from the previous effect in addition to the solar energy gained through the glass cover. FIG. 1-13 shows a multiple effect solar still.

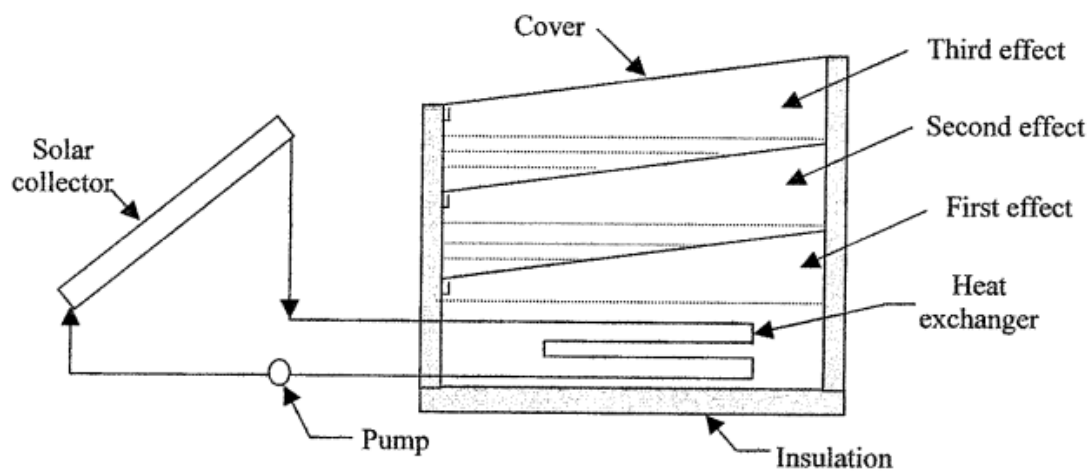


FIG. 1-13 Multiple effect solar still, adapted from (Al-Kharabsheh, 2003)

CHAPTER 2

LITERATURE REVIEW

In this section a number of previous studies regarding the application of vacuum principle in water desalination are reviewed.

Using vacuum technique for distillation of water (sea water or brackish) is not a new subject, although not many studies have been carried out to investigate the usage of this method combined with the solar energy as a main source of energy. Al-Hussaini (Al-Hussaini & Smith, 1995) studied the effect of vacuum in a simple solar distillation pond; with absence of air inside the still, no heat losses due to convection occurred, so the heat loss from the water in an insulated still is only via evaporation and radiation. Hence the mass flow rate that diffuses using air as a convection environment is not included in the calculations; another advantage of the absence of air inside the system is increasing the condensation rate, because non-condensable gases will decrease the condensation rate by impeding the vapor molecules. Depending on solar energy as the main source of heat, their experiment showed approximately 100% increase in the productivity, and efficiency. The maximum water production was 8.07 kg/day under vacuum condition.

Bemporad (Bemporad, 1995) conducted numerical analysis of the hydrodynamic aspects of solar energy distillation utilizing natural vacuum produced by the rise of the water column 10.33 meters above sea level; the design included two chambers connected via a pipe, one chamber for the evaporation and the other for fresh or distilled water, both chambers were under vacuum (although not absolute). The main driving force was the difference in vapor pressure between the two chambers; the evaporator was kept at considerably higher temperature than the distilled water chamber. This study was purely theoretical.

Al-Kharabsha (Al-Kharabsha & Goswami, 2003) studied distillation of water under natural vacuum conditions, his system utilized the solar energy indirectly, the condenser used was a horizontal tube with external fins, vacuum was produced using the atmospheric pressure to raise the level of water 10.33 meters, also, he used auxiliary heat exchanger to harness the heat of the brine water leaving the evaporator. The temperature of heat source varied between 40-100 °C depending whether it was solar powered or constant heat produced by the grid, he achieved 4.7 kPa absolute pressure inside the system. His simulation results achieved 6.5 kg/day of distilled water for 1 m² evaporator area; he also studied the effect of the withdrawal rate of the brine on the performance of the system and concluded that 1 kg/hr would noticeably lower the performance. He also investigated the effect of depth of water in the evaporator and thermal resistance. Based on his economic analysis the cost of 1 kg of fresh water produced under the climate conditions of Florida State, United States of America was reported to be \$ 0.135.

A theoretical study was investigated by Midilli (Midilli & Ayhan, 2004) of a natural vacuum distillation system which include balance design and selection of distillation method, natural vacuum formation, balancing and feeding processes are introduced and discussed in details. Additionally, P-v and T-s diagrams including the processes flow of each model were obtained by depending on thermodynamic behavior of the system. They also conducted an experimental analysis (Midilli & Ayhan, 2004) using solar power to distillate seawater, the concept of the vacuum evaporation is the same as in the previous studies, they studied the feasibility of such system in the Arabian Gulf region, specifically, the kingdom of Bahrain. Their design was a simple reversed U-shape pipe containing the evaporator on one side and the condenser on the other side. The system was installed at 10.33 high to benefit from the natural vacuum produced. The evaporator was a simple pipe shape painted black made of stainless steel, while the condenser was a cylindrical tank wrapped around the fresh water side, this tank works as a heat exchanger where cold water enters from the top and leaves from the bottom carrying the latent heat produced from the condensation of the vapor. About 7 Kpa of internal vapor pressure was achieved and the fresh water production

was 0.13 m³/day, the cost of the 1 m³ was found to be about \$0.702 compared to the water production cost in Bahrain which is about 1.05 \$/m³.

Another similar study of natural vacuum distillation was carried out by Veeragnaneswar (Veeragnaneswar & Nermalakhandan, 2007), their design used the solar intensity directly through the use of a glass sheet covering the evaporator and a cold plate for condensing the vapor, different types of heat sources were used to raise the water temperature including solar collectors, photovoltaic thermal collectors, constant heat produced from the grid, waste heat from ARS (absorption refrigeration systems), and geothermal energy sources, in spite of the many sources mentioned, their experiment concentrated mainly on the solar power as a heat source. Their experiment utilizing only solar collector resulted in a production of 4.9 kg/day of fresh water for an evaporator area of 1 m² with 61% average daily efficiency, using solar collectors aided by solar reflectors the output increased to 7.5 kg/day with an average daily efficiency of 80%, and using solar collectors and photovoltaic panels increased the fresh water distilled up to 12 kg/day with 6 m² photovoltaic area.

The concept of vacuum distillation was further studied by Moore (Moore, et al., 2008), in their experimental study, they used two water pumps to recycle the salt and distilled water inside the system, to compensate the heat loss and gain of the system. When evaporation occurs the water losses heat due to the phase change of the water bringing down the salt water temperature, to compensate the heat loss, a pump feeds the saline water chamber with hot saline water, the amount of saline water fed to the chamber is equal to the amount of vapor transferred to the fresh water chamber. The same principle is applied on the fresh water side, as the vapor comes with contact with the cold water it condenses raising the fresh water temperature, to keep the fresh water cold, a second pump feeds the fresh water chamber with cold fresh water. Their experiment produced 4.4 kg per 3000 minutes run time with 1.98 kW h/m³ energy cost, which is 40% more efficient than reverse osmosis.

Vacuum distillation using multiple stages was studied by Ahmed (Ahmed, et al., 2009) their design is different from the previously mentioned studies, although it utilized the advantage of vacuum to increase the evaporation rate. Their design

incorporated three vertical stages in a tank, the vacuum was created by the use of pumps, each chamber uses the vapor of the previous chamber to evaporate the water in the next chamber, the idea was that the vapor produced would act as a heat source and the heated water in the next chamber would act as a condenser. They used solar collectors as the main heat source of the first or base chamber; photovoltaic panels were also used to produce electricity to operate the vacuum pumps and other auxiliary equipment. The design was able to produce 0.5 bar operational pressure and 14.2 kg/m²/day, 1000 gallons of fresh water produced by this system was calculated to be \$25.44, based on a design of a large scale production plant.

Al Madani (Al Madani & Ayhan, 2010) performed an illustrative study showing the analytical relations that describe the phenomenon and according to their calculations and their assumptions their reported that the system is thermodynamically feasible, after some enhancements the system can become economically feasible. Al Madani (Al Madani & Ayhan, 2012) studied applications of natural vacuum desalination for hot and cold climatic conditions using waste heat and renewable resources.

From the previous mentioned studies, the fresh water production amount and efficiency increased desalination process worked under vacuum conditions, also the use of natural barometric head to establish vacuum above saline water is a feasible technique. The cost of fresh water produced for each of the previous studies varies due to different locations' circumstances and economics. Additionally, the cost of fresh water produced increases when coupling the vacuum desalination units with solar collectors and auxiliary equipment.

2.1 Objectives of the study

The objectives of this thesis are:

1. To develop and construct a mathematical model that describes the natural vacuum desalination system (NVD).
2. To solve the mathematical model of the NVD system numerically and compare the results to previous similar studies. A set of energy and exergy balance equations are to be solved simultaneously to find the required variables that describe the system.
3. Conducting sensitivity analysis on a group of parameters and studying their effect on the performance of the system.
4. Perform an economic analysis of the NVD system.

CHAPTER 3

THEORETICAL MODELING

In this chapter the theory behind the natural vacuum desalination technique is explained, the model will be studied from a thermo dynamical point of view to show how the phase change desalination works. Heat and mass transfer formulas are presented for each different control volume for each different part of the system.

3.1 Principle of NVD

The principle behind the NVD (natural vacuum desalination) system is to create a state of vacuum to allow water to evaporate at relatively low temperature, thus needing low amounts of energy to vaporize it. As the name implies the vacuum is generated naturally without the need for a vacuum pump to generate the required operation conditions. FIG. 3-1 shows a schematic illustration of an inverse U-shaped NVD system, first the system ground level and the roof level valves are opened, a water pump pumps the water and fills the system completely, after that the pump stops and the ground level valves are closed, in this mode the system is fully loaded with water, now the roof level valve is closed and the ground level valves are opened, in this case the water level will drop to a certain point where this point is 10.33 meters above the ground level, this elevation of water is achieved due to the fact that the atmospheric pressure pushes the water hence requiring no additional pumping power to maintain this height. As the water drops in the NVD system, vacuum is generated in the inversed U- shaped tank on the roof.

Establishing vacuum condition in the system helps the water to evaporate at lower temperatures, thus less energy is used to drive the desalination process. The idea

is to create a pressure difference between the two chambers, otherwise for two water chambers connected in vacuum state at the same temperature, there won't be enough pressure difference to drive the process, in fact the vapor will transfer from the fresh water chamber to the saline water chamber, this is because fresh water saturation pressure is slightly higher than saline water saturation pressure at a given temperature. A relation between the salinity of water and its saturated vapor pressure can be represented as (Sharqawy, et al., 2010):

$$\frac{P_f}{P_s} = 1 + 0.57357 \left(\frac{S}{1000-S} \right) \quad (3.1)$$

Where P_f and P_s are saturated vapor pressure (kPa) of fresh and saline water, respectively. S is salinity (g/kg). FIG. 3-2 shows the saturated pressure for both fresh and saline water with $S=120$ g/kg. When the temperature is 80°C the pressure of fresh water is 47.41 kPa (point 1) and for saline water the pressure is 43.98 kPa (point 2), this pressure difference increases as the temperature increase.

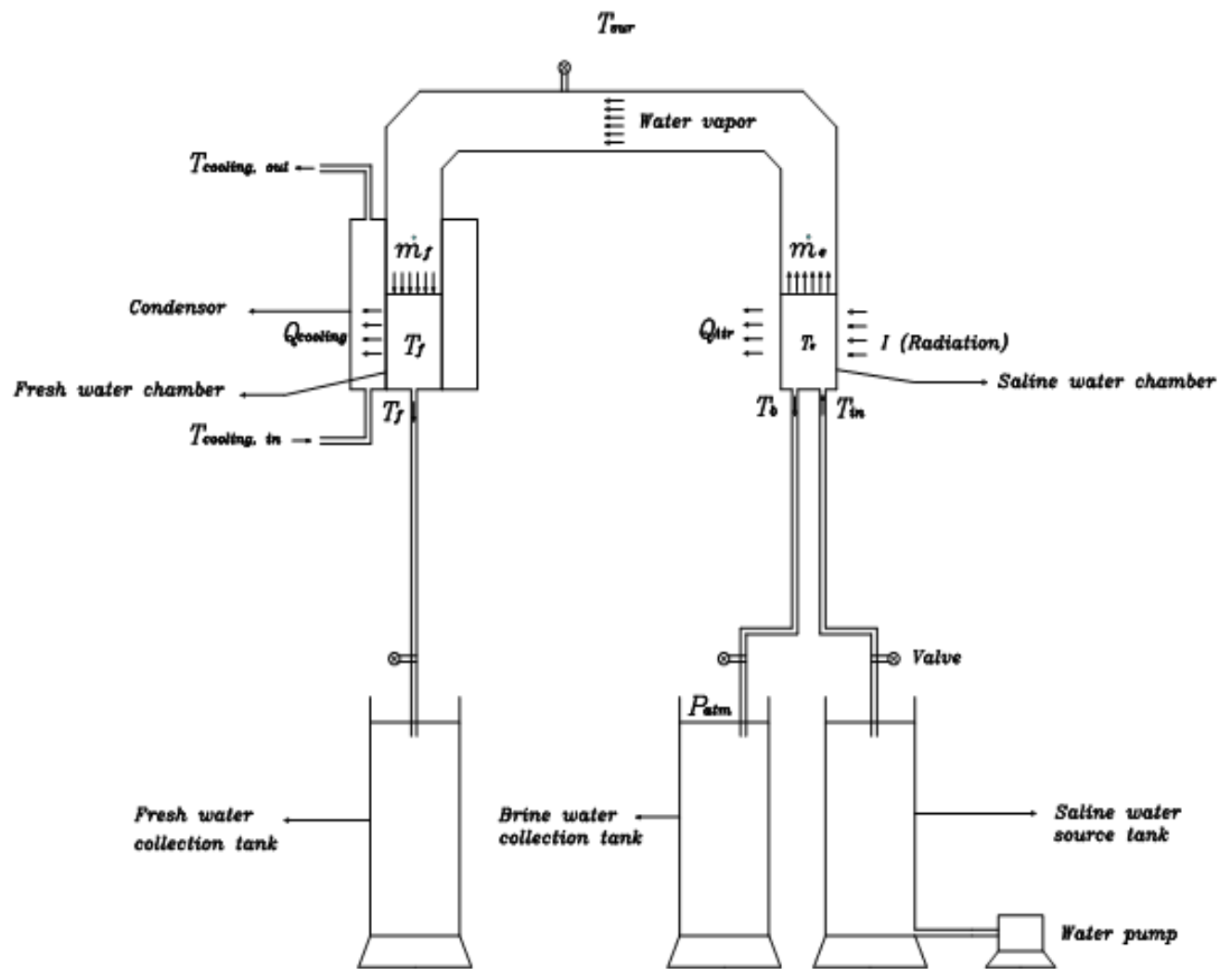


FIG. 3-1 NVD System

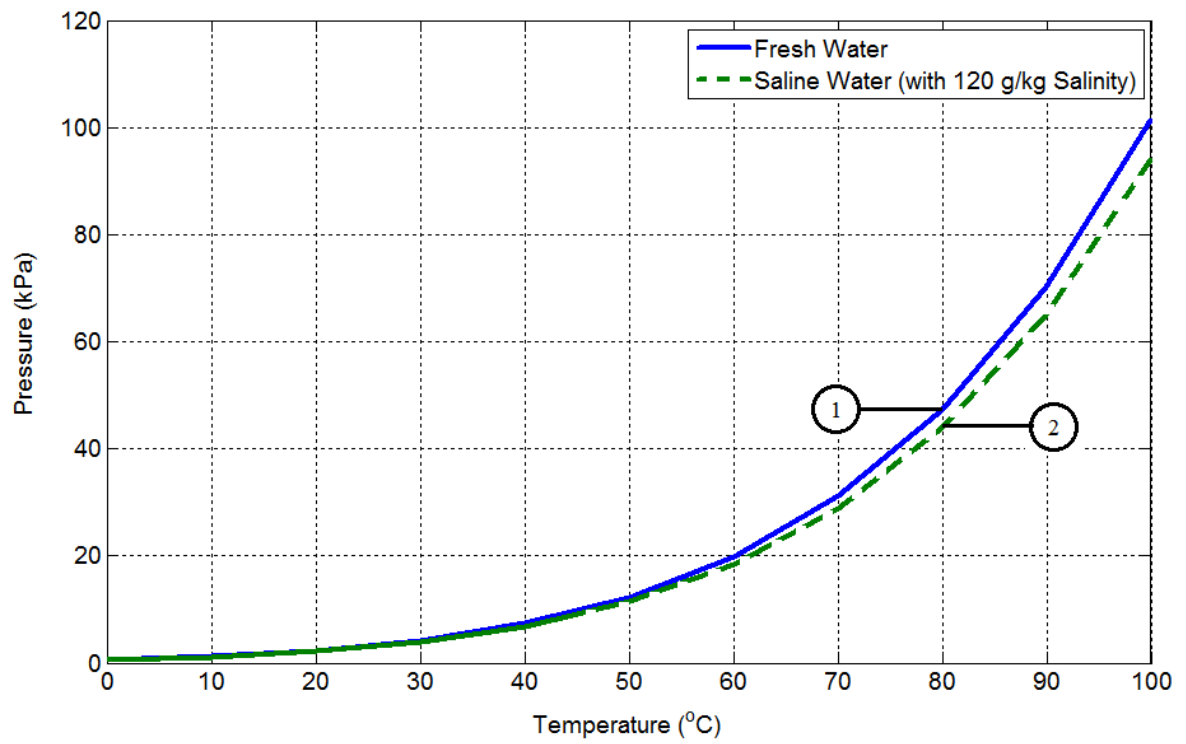


FIG. 3-2 Fresh and saline water saturated vapor pressure curves

To illustrate the energy requirement for this system, FIG. 3-3 shows the control volume taken for the upper part (which is essentially the core of the system) of the NVD unit.

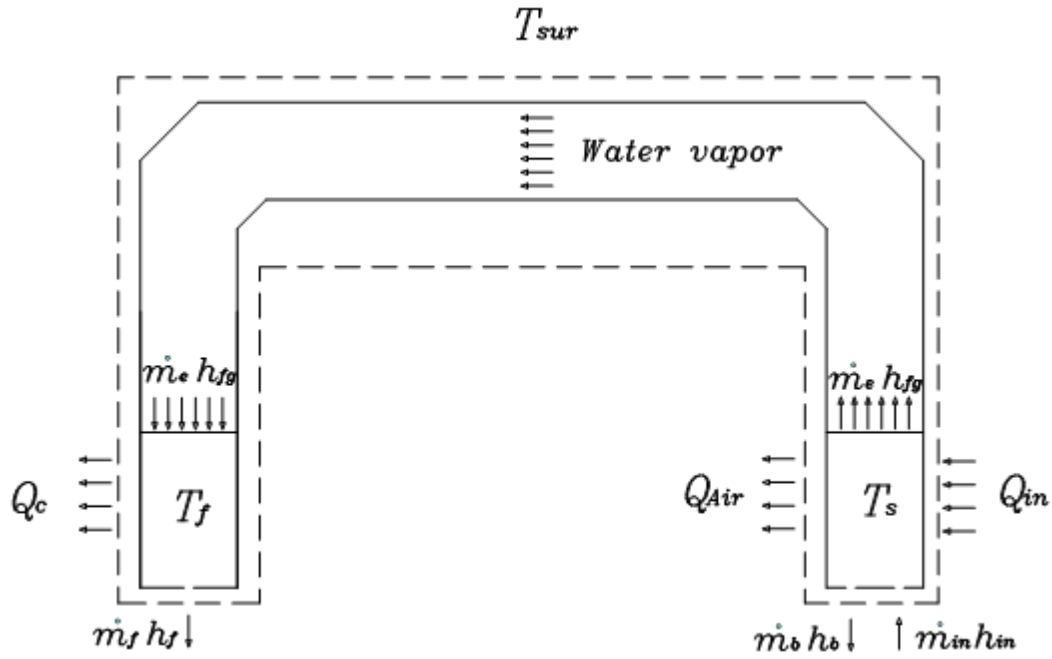


FIG. 3-3 Control volume of the NVD upper part

The energy balance of the FIG. 3-3 :

$$\dot{m}_{in} h_{in} + Q_{in} = \dot{m}_b h_b + \dot{m}_f h_f + Q_{Air} + Q_c \quad (3.2)$$

The mass balance:

$$\dot{m}_{in} = \dot{m}_b + \dot{m}_f \quad (3.3)$$

where

Q_{in} : Heat input (kJ/hr)

Q_{Air} : Heat losses to the environment (kJ/hr)

Q_c : Evaporation heat lost (kJ/kg)

To show how evaporation requires less energy at lower evaporation temperatures, a case study is investigated on the control volume shown in FIG. 3-3. Equation 3.2 yields to:

$$m_f = \frac{(Q_{in} - Q_{Air}) + m_{in} (h_{in} - h_b)}{h_{fg} + h_f - h_b} \quad (3.4)$$

Assuming a water salinity of 40 g/kg, heat input $Q_{in} = 1000$ kJ/hr, $UA_{eva}=1$ kJ/hr. °C, and a fresh water temperature of 25 °C, and m_{in} that changes from 1-5 kg/hr, different m_f contours can be found from equation 3.4.

FIG. 3-4 shows the effect of evaporation rate on fresh water production rate for different saline water mass flow rates m_{in} . For $m_{in} = 1$ kg/hr at 40 °C evaporation temperature the fresh water production rate is 0.3799 kg/hr (point 1), while at 60 °C evaporation temperature the fresh water production rate decreased to 0.333 kg/hr (point 2), also the fresh water production rate decreases as the saline water feed m_{in} increases.

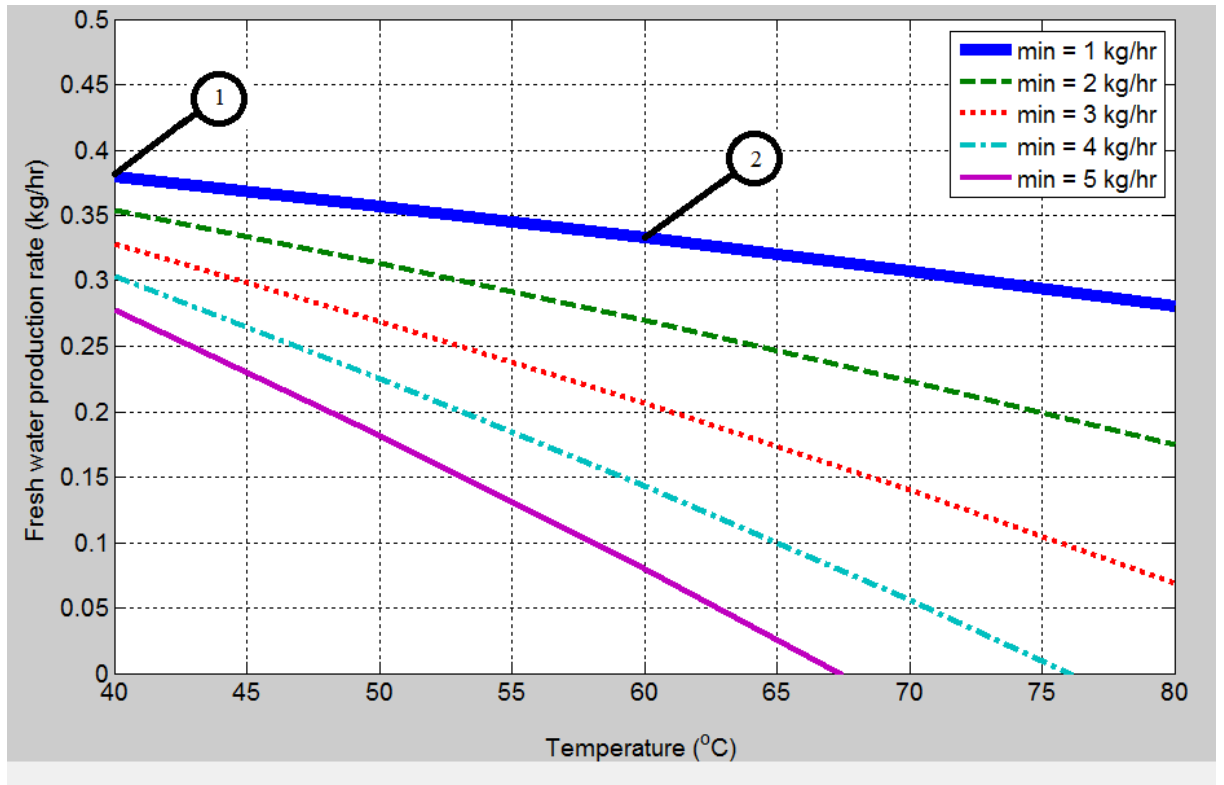


FIG. 3-4 Effect of evaporation temperature on fresh water production rate for different saline water mass flow rates

To explain the processes of evaporation and condensation, FIG. 3-5 shows pressure values for each state shown in FIG. 3-6. At state (1) the temperature of the feed water is high (in this case 40 °C) with a pressure of 11.093 kPa which is the result of the water column pressure ($1081.1 \text{ kg/m}^3 * 9.81 \text{ m/s}^2 * 0.4 \text{ m}$) and the vapor pressure at that temperature; at state (2) the temperature of the water is still 40 °C (assuming feed water has the required energy for evaporation) and the pressure here is the saturated pressure of 6.848 kPa, hence the state is at the saturation line.

As the vapor travels with a temperature of 40 °C to the condensation chamber and hits the cold water (which has a temperature of 20 °C) surface, the vapor condensate and the temperature drops to the 20 °C which is state (3), here the pressure is the saturated pressure of 2.339 kPa at 20 °C. Assuming the temperature at the outlet of the condensation chamber stays constant, the pressure at state (4) is 6.256 kPa which is the pressure due to the water column ($998.2 \text{ kg/m}^3 * 9.81 \text{ m/s}^2 * 0.4 \text{ m}$) and the vapor pressure at 20 °C. Condensation is assumed to be a direct contact condensation (Incropera, et al., 2007) which includes the vapor hitting the cold surface of the other fluid directly resulting in the condensation.

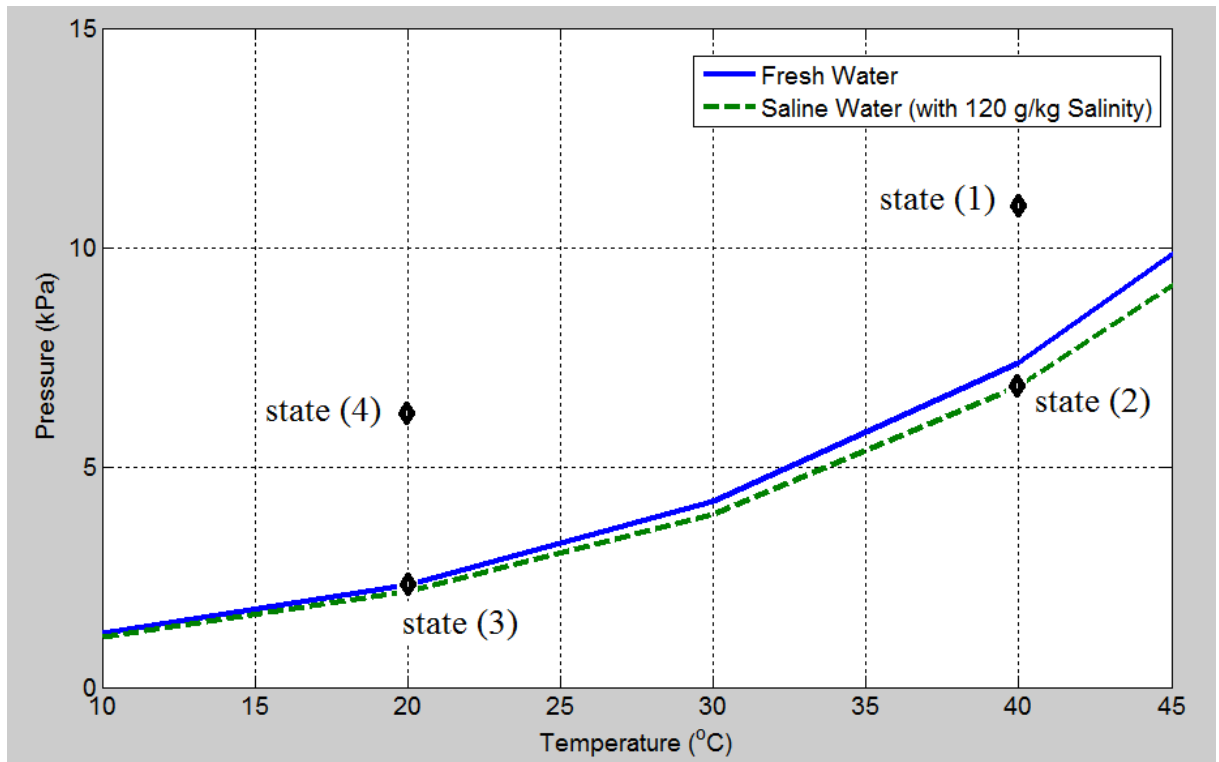


FIG. 3-5 Pressure values for different states

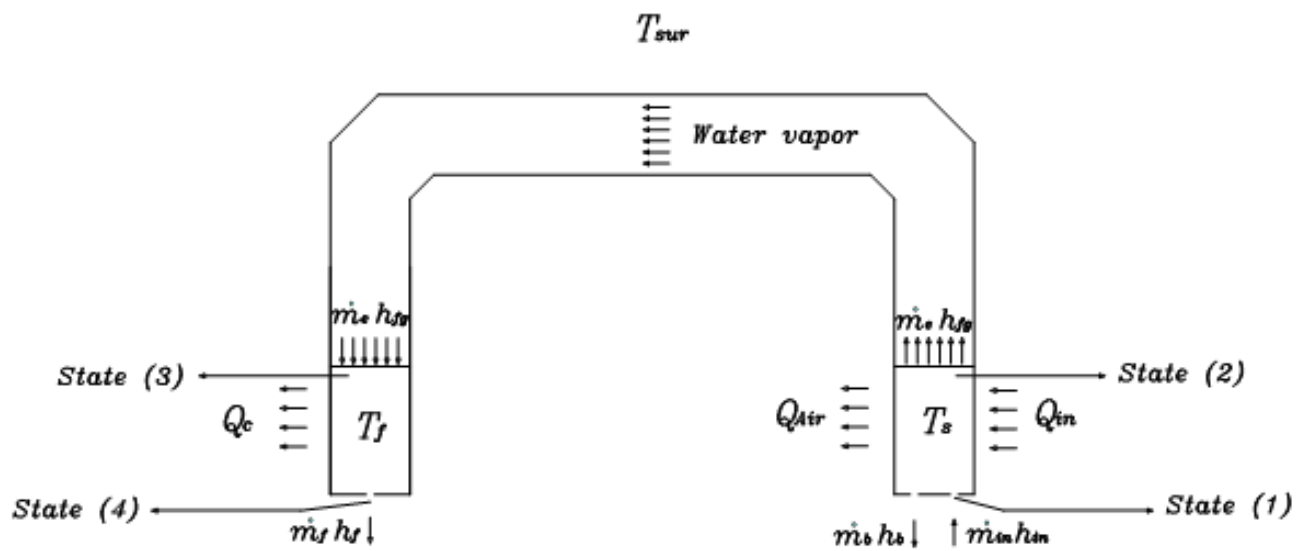


FIG. 3-6 Evaporation and condensation states

3.2 The Model

The evaporation of water in a vacuum space has been studied by Bemporad (Bemporad, 1995). He used a correlation for the mass transfer that depends on the difference between the vapor partial pressure between two chambers connected via a pipe in vacuum condition (which is the scope of this study), since the only substance inside the chambers are pure and saline water, the resultant pressure should be the saturation pressure. Never the less, non-condensable gases are freed into the vacuum space and mixed with the vapor of the water.

Equation 3.5 shows the correlation of mass transfer used in this study (Bemporad, 1995):

$$v_e = \frac{\alpha_m A_s}{\rho_f} \left[f_c \frac{P_s}{\sqrt{T_s + 273.15}} - \frac{P_f}{\sqrt{T_f + 273.15}} \right] \quad (3.5)$$

Where

v_e : Volumetric evaporation rate from the saline water chamber (m^3 / s)

α_m : Experimental coefficient (Fujikawa & Akamatsu, 1980) which varies between 10^{-7} to 10^{-6} ($\text{kg} \cdot \text{K}^{0.5} / \text{m}^2 \cdot \text{Pa} \cdot \text{s}$). In this study $\alpha_m = 10^{-6}$

P_s and P_f : Saline and fresh water saturation vapor pressure, respectively (Pa). This vapor pressure is a function of the water temperature (Bemporad, 1995):

$$P(T) = e^{(63.042 - \frac{7139.6}{T+273.15} - 6.2558 \ln(T+273.15))} * 100 \quad (3.6)$$

f_c : Solute concentration factor (%). This factor accounts for the salinity increase in the saline water chamber which can be defined as (Bemporad, 1995):

$$f_c = 1 - \alpha_c C \quad (3.7)$$

Where $\alpha_c = 0.0054$ is an empirical coefficient factor (dimensionless).

A number of assumptions are made before modeling of the NVD system:

1. The connecting pipe wall between the saline and fresh water chambers is adiabatic (no heat is transferred from or to the vapor travelling between the two chambers, hence, the temperature of vapor does not change before it reaches the fresh water chamber).
2. Non-condensable gases released from saline and fresh water masses have no effect on the vapor pressure inside the system.
3. The corners of the pipe connecting the two chambers do no effect the pressure of the vapor travelling from saline to fresh water chamber.

3.2.1 Saline water chamber

FIG. 3-7 shows energy conservation of saline water, the energy conservation for this chamber can be modeled as:

$$M_s C_{p,s} \frac{dT_s}{dt} = m_{in} h_{in} + Q_{in} - m_b h_b - Q_e \quad (3.8)$$

In this case Q_e (Watts) would be the evaporation losses due to the evaporation occurring in the system, which is:

$$Q_e = \rho_f v_e h_{fg} \quad (3.9)$$

Where $h_{fg} = (3146 - 2.36 T) * 1000$ (Bemporad, 1995), which is the latent heat of evaporation (J/kg).

As explained in equation 3.4, Q_{in} is the heat supplied to the system to drive the evaporation process, in this case the heat comes from the saline water chamber steel wall:

$$Q_{in} = h_{saline} A_{eva} (T_{saline-wall} - T_s) \quad (3.10)$$

Where

h_{saline} : The convection coefficient between the saline water and the internal surface of the saline water chamber (Watt/m². °C). The heat transfer occurring between the wall and the saline water is assumed by free convection because the mass flow rate of the saline water is very low, hence it has a small and negligible Reynolds number, the calculation procedure of the convection coefficient can be found in appendix (B).

$T_{saline-wall}$: Saline water-wall interface temperature (°C).

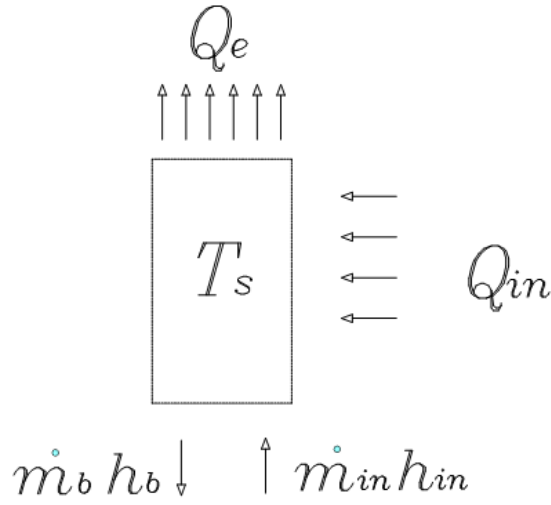


FIG. 3-7 Energy conservation of saline water

To find $T_{\text{saline-wall}}$, energy conservation is written for the wall of the saline water chamber (shown in FIG. 3-8):

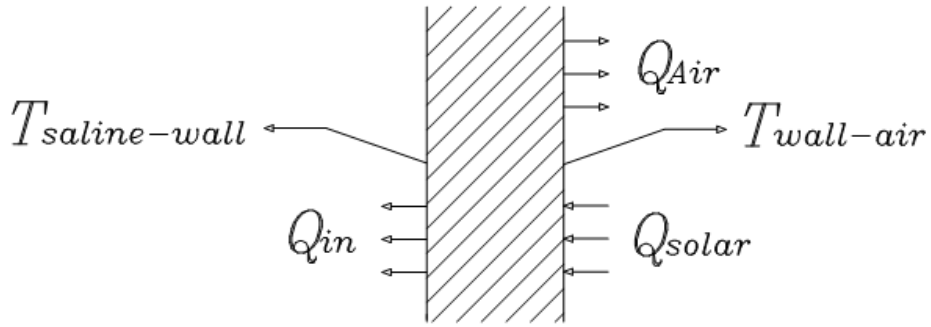


FIG. 3-8 Energy conservation of saline water chamber wall

$$Q_{\text{solar}} - Q_{\text{Air}} = \frac{2 \pi r_{e,\text{in}} d_e (T_{\text{wall-air}} - T_{\text{saline-wall}})}{\ln(r_{e,\text{out}}/r_{e,\text{in}})} \quad (3.11)$$

Q_{solar} : Heat supplied as solar irradiance (Watt)

And

$$Q_{solar} = \alpha_{steel} I 2 \pi r_{e,out} d_e \quad (3.12)$$

Where

I : The solar irradiance per unit area as a function of time (Watts/m²).

α_{steel} : Absorptivity of steel which is 0.5 (Dimensionless)

$$Q_{Air} = h_{air} 2 \pi r_{e,in} d_e (T_{wall-air} - T_{sur}) \quad (3.13)$$

Where

h_{air} : Convection coefficient of air (Watt/m². °C)

$T_{wall-air}$: Wall-air interface temperature (°C).

Additional unknown which is $T_{wall-air}$ must be found, to find this temperature and $T_{saline-wall}$, equation 3.10 and 3.11 must be solved simultaneously. The Q_{Air} shown in equation 3.13 can either be treated as heat loss, in case of $T_{wall-air} > T_{sur}$, or as heat gain, if $T_{wall-air} < T_{sur}$.

The saline water used in this study simulates the seawater, seawater consist of various types of dissolved salts and organic matters. Approximately, seawater consists of 3.5% of salts and organic matters (OM) (Neumann & Pierson, 1966), the salts which are shown in TABLE 3 are the major composition of the seawater and, therefore they affect the physical properties of water.

TABLE 3 Salts composition in seawater, adapted from
(Neumann & Pierson, 1966)

Constituent	Mass, kg/1000kg
NaCl	28.014
MgCl ₂	3.812
MgSO ₄	1.752
CaSO ₄	1.283
K ₂ SO ₄	0.816
CaCO ₃	0.122
KBr	0.101
SrSO ₄	0.028
H ₂ BO ₃	0.028

In addition to the constituents shown in TABLE 3, dissolved organic carbon matters make a small percentage of the total dissolved matters (approximately 2ppm), they consists of different components varying from vitamins, fatty acids and urea to free sugar, carbohydrates and amino acids (Skopintsev, 1981).

FIG. 3-9 shows the conservation of saline water mass and salts, for the saline water mass, saline water (presumably from seawater) goes inside the chamber as m_{in} , which has a fixed salt concentration of 3.5%, and brine water leaves the chamber carrying the instantaneous salinity of the saline water. As saline evaporates, it losses m_e amount from the chamber. The amount of salt concentration entering to the chamber C_o will increase the salinity level in the chamber, since no salt leaves the saline water with evaporation but the amount that leaves the system with the brine.

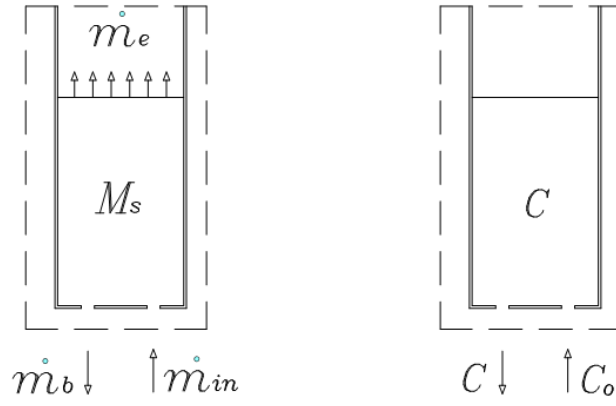


FIG. 3-9 Conservation of saline water mass (left) and salt (right)

$$\frac{dM_s}{dt} = m_{in} - m_b - m_e \quad (3.14)$$

Where

$$m_{in} = \rho_{s,in} v_{in} \quad (3.15)$$

$$M_s \frac{dC}{dt} = m_{in} C_o - m_b C \quad (3.16)$$

Where

C : Salt concentration (%).

C_o : Salt concentration in saline water feed (%).

3.2.2 Fresh water chamber

This chamber contains the fresh water accumulated during the process, the evaporation process will not be sustained if the vapor pressure difference between the two chambers is diminished, and thus the two chambers must operate at different

temperatures to achieve this. In order to find the evaporation rate, the temperature in saline and fresh water chambers must be calculated, and since this process is transient and some parameters change with time, a set of differential equations must be solved to find T_s and T_f , previously T_s was introduced in the saline water chamber energy balance equation (equation 3.8), the following equation shows the energy conversation for the fresh water chamber:

$$M_f C_{p,f} \frac{dT_f}{dt} = Q_e - m_f h_f - Q_{fresh-wall} \quad (3.17)$$

Where

M_f : The fresh water mass inside the fresh water chamber (kg).

$C_{p,f}$: Specific heat capacity of fresh water (J/kg. °C).

$$Q_{fresh-wall} = h_{fresh} A_{con} (T_f - T_{fresh-wall}) \quad (3.18)$$

Where

$Q_{fresh-wall}$: Heat transferred from the fresh water to its wall (Watt).

$T_{fresh-wall}$: Fresh water-wall interface temperature (°C).

h_{fresh} : The convection coefficient between the fresh water and the internal surface of the fresh water chamber (Watt/m².°C). The main mode of heat transfer is assumed to be by free convection, calculation of this coefficient is shown in appendix (B).

In equation 3.17 condensation occurs in two methods:

1. Either the hot vapor coming from the saline water chamber hits the cold surface and directly condensates, which is the case in this research, since the NVD system evaporation and condensation processes follow the phenomenon found in Bemporad study (Bemporad, 1995), based on his model, it is presumed that in order for the evaporation to start and continue, a flow of vapor must be sustained between the two chambers. In his study no condenser was used, and the fresh water chamber was kept at low temperature, thus the assumption of a direct condensation.
2. Or the vapor condensates on the internal surface of the pipe connecting the two chambers and losing the latent heat, becoming liquid and entering the fresh water chamber carrying only a liquid enthalpy.

FIG. 3-10 shows the energy conservation of the fresh water; the cooling load is controlled here; hence it's an input to the system, using a tube-in-tube heat exchanger with cold water working fluid to keep the fresh water chamber relatively cold to avoid reverse evaporation (evaporation from the fresh water chamber).

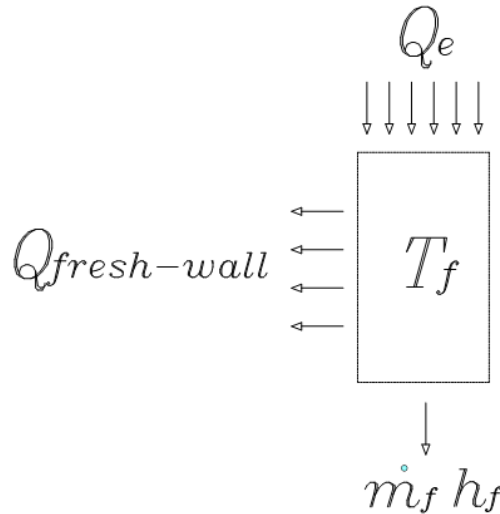


FIG. 3-10 Fresh water energy conservation

When the vapor hits the relatively colder fresh water it condenses releasing the latent heat carried with it, which increases the fresh water temperature. To keep the

fresh water chamber cold, a heat exchanger carries the heat from the chamber via a cold water stream. In FIG. 3-10 heat is transferred from the fresh water through the wall then to the coolant, to find $Q_{fresh-wall}$, $T_{fresh-wall}$ must be found, FIG. 3-11 shows the energy conservation of the fresh water chamber wall.

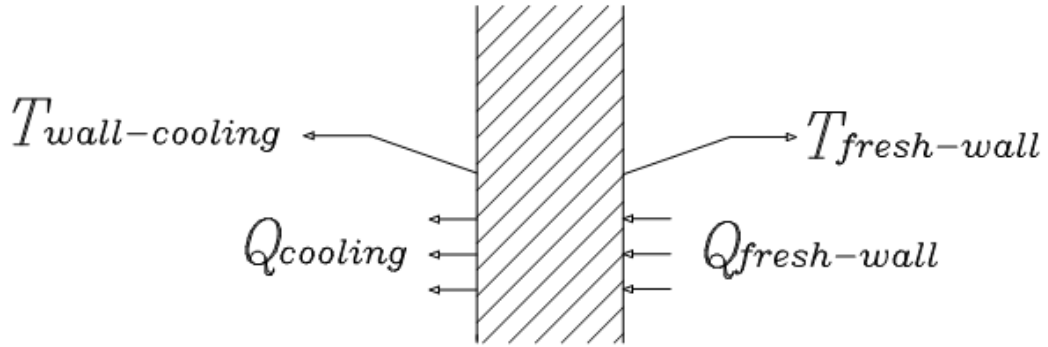


FIG. 3-11 Energy conservation of fresh water chamber wall

Where:

$$Q_{cooling} = \frac{2 \pi r_{c,in} d_c (T_{fresh-wall} - T_{wall-cooling})}{\ln(r_{c,out}/r_{c,in})} \quad (3.19)$$

Where

$T_{wall-cooling}$: Wall-coolant interface temperature ($^{\circ}\text{C}$).

$$Q_{cooling} = h_{cooling} 2 \pi r_{c,in} d_c (T_{wall-cooling} - T_{cooling}) \quad (3.20)$$

Where

$Q_{cooling}$: Heat transferred from the fresh water chamber wall to the cooling water (Watt)

$h_{cooling}$: Convection coefficient of cooling water (Watt/m². °C). Heat is transferred from the fresh water chamber wall to the cooling water by forced convection, calculation of this coefficient is shown in appendix (B).

$T_{cooling}$: Cooling water temperature (°C).

3.2.3 Thermal efficiency

The thermal efficiency of the system is the ratio of useful product to the supplied heat. The saline water chamber works as an evaporator, taking solar irradiance and saline water feed to evaporate and produce water vapor, if the $T_{sur} > T_{wall-air}$ additional heat is supplied from the environment, hence it enters the efficiency definition as an input, otherwise it is considered a loss, equation 3.21(a) & (b) show the thermal efficiency.

$$\eta_{th} = \left\{ \begin{array}{ll} \frac{Q_e}{Q_{air} + Q_{solar} + m_{in} h_{in}} & 3.21(a) \quad , T_{sur} > T_{wall-air} \\ \frac{Q_e}{Q_{solar} + m_{in} h_{in}} & 3.21(b) \quad , T_{sur} < T_{wall-air} \end{array} \right\}$$

3.2.4 Exergy analysis

Exergy can be defined as the maximum useful work obtained from a system when it is brought to equilibrium with its surroundings (Cengel & Boles, 2007). Neglecting the kinetic, potential, and chemical energies, the exergy per unit mass is:

$$e = (h - h_o) - T_o (s - s_o) \quad (3.22)$$

Where:

e : Exergy per unit mass (J/kg)

T_o : Dead state temperature (K).

h_o : Specific enthalpy at dead state temperature (J/kg)

s_o : Specific entropy at dead state temperature (J/kg. K)

During a process, system's energy is always conserved, but a certain amount of exergy is destroyed because of process irreversibility's due to entropy generation, which will decrease the amount of useful work produced. Studying and analyzing the exergy destroyed and lost for the saline and fresh water chambers will help identify opportunities to enhance and improve the NVD efficiency and to make better design decisions.

The exergy of saline water feed is:

$$\dot{X}_{saline,in} = \dot{m}_{in} (h_{in} - h_o) - \dot{m}_{in} T_o (s_{in} - s_o) \quad (3.23)$$

Where

$\dot{X}_{saline,in}$: Exergy of saline water feed (Watt)

The exergy of convective heat transferred from (or to) the environment is:

$$\dot{X}_{air} = Q_{air} \left(1 - \frac{T_o}{T_{wall-air} + 273.15} \right) \quad (3.24)$$

Where:

$\dot{X}_{air}$: Exergy of surrounding air (Watt)

The exergy of solar irradiance is (Kumar & Tiwari, 2011):

$$\dot{X}_{solar} = Q_{solar} \left(1 + \frac{1}{3} \left(\frac{T_o}{T_{sun}} \right)^4 - \frac{4}{3} \left(\frac{T_o}{T_{sun}} \right) \right) \quad (3.25)$$

Where:

$\dot{X}_{solar}$: Exergy of solar irradiance (Watt)

T_{sun} : Temperature of the sun which is taken as 6000 K (Kumar & Tiwari, 2011).

The exergy of vapor produced from the saline water chamber is (Kianifar, et al., 2012):

$$\dot{X}_{vapor} = Q_e \left(1 - \frac{T_o}{T_s + 273.15} \right) \quad (3.26)$$

Where:

$\dot{X}_{vapor}$: Exergy of vapor (Watt)

The exergy of brine is:

$$\dot{X}_b = m_b (h_b - h_o) - m_b T_o (s_b - s_o) \quad (3.27)$$

Where

$\dot{X}_b$: Exergy of brine (Watt)

To find the exergy destruction of the saline water chamber, exergy balance for the wall and saline water must be found, generally the exergy balance of any system is:

$$\dot{X}_{in} - \dot{X}_{out} - \dot{X}_{destroyed} = \frac{dX}{dt} \quad (3.28)$$

Exergy balance for wall:

$$\dot{X}_{solar} - \dot{X}_{air} - \dot{X}_{wall-saline} - \dot{X}_{destroyed,wall,saline} = \frac{dX_{wall,saline}}{dt} \quad (3.29)$$

Where:

$\dot{X}_{wall-saline}$: Exergy of heat transferred from the saline chamber wall to the saline water (Watt), and can be found as:

$$\dot{X}_{wall-saline} = Q_{in} \left(1 - \frac{T_o}{T_{saline-wall} + 273.15} \right) \quad (3.30)$$

$\dot{X}_{destroyed,wall,saline}$: Exergy destruction of saline water chamber wall (Watt).

$\frac{dX_{wall,saline}}{dt}$: The rate of exergy change of saline water chamber wall (Watts), which can be found as (Nunez, et al., 2008):

$$\begin{aligned} \frac{dX_{wall,saline}}{dt} = M_{wall,saline} C_{p,wall,saline} & \left(1 - \frac{T_o}{T_{wall,saline} + 273.15} \right) \frac{dT_{wall,saline}}{dt} \end{aligned} \quad (3.31)$$

Where:

$$T_{wall,saline} = \frac{T_{saline-wall} + T_{wall-air}}{2} \quad (3.32)$$

Exergy balance for saline water:

$$\dot{X}_{wall-saline} + \dot{X}_{saline,in} - \dot{X}_{vapor} - \dot{X}_b - \dot{X}_{destroyed,saline} = \frac{dX_s}{dt} \quad (3.33)$$

Where:

$\dot{X}_{destroyed,saline}$: Exergy destruction of saline water (Watt).

$\frac{dX_s}{dt}$: The rate of exergy change of saline water (Watts), which can also be found as:

$$\frac{dX_s}{dt} = M_s C_{p,s} \left(1 - \frac{T_o}{T_s + 273.15} \right) \frac{dT_s}{dt} \quad (3.34)$$

The exergy of fresh water feed is:

$$\dot{X}_{fresh,out} = m_f (h_f - h_o) - m_f T_o (s_f - s_o) \quad (3.35)$$

Where

$\dot{X}_{fresh,out}$: Exergy of fresh water leaving the fresh water chamber (Watt)

The exergy of convective heat transferred to the coolant is:

$$\dot{X}_{cooling} = Q_{cooling} \left(1 - \frac{T_o}{T_{wall-cooling} + 273.15} \right) \quad (3.36)$$

Where:

$\dot{X}_{cooling}$: Exergy of heat transferred from the fresh water wall to the cooling water (Watt)

Exergy balance for fresh water chamber wall:

$$\dot{X}_{fresh-wall} - \dot{X}_{cooling} - \dot{X}_{destroyed,wall,fresh} = \frac{dX_{wall,fresh}}{dt} \quad (3.37)$$

Where:

$\dot{X}_{destroyed,wall,fresh}$: Exergy destruction of fresh water chamber wall (Watt)

$\dot{X}_{fresh-wall}$: Exergy of heat transferred from the fresh water to its wall (Watt), which can be calculated as:

$$\dot{X}_{fresh-wall} = Q_{fresh-wall} \left(1 - \frac{T_o}{T_{fresh-wall} + 273.15} \right) \quad (3.38)$$

$\frac{dX_{wall,fresh}}{dt}$: The rate of exergy change of fresh water chamber wall (Watts), which can be found as (Nunez, et al., 2008):

$$\frac{dX_{wall,fresh}}{dt} = M_{wall,fresh} C_{p,wall,fresh} \left(1 - \frac{T_o}{T_{wall,fresh} + 273.15} \right) \frac{dT_{wall,fresh}}{dt} \quad (3.39)$$

Where:

$$T_{wall,fresh} = \frac{T_{fresh-wall} + T_{wall-cooling}}{2} \quad (3.40)$$

Exergy balance for fresh water:

$$\dot{X}_{vapor} - \dot{X}_{fresh,out} - \dot{X}_{fresh-wall} - \dot{X}_{destroyed,fresh} = \frac{dX_f}{dt} \quad (3.41)$$

Where:

$\dot{X}_{destroyed,fresh}$: Exergy destruction of fresh water (Watt).

$\frac{dX_f}{dt}$: The rate of exergy change of fresh water (Watt), which can also be found as:

$$\frac{dX_f}{dt} = M_f C_{p,f} \left(\left(1 - \frac{T_o}{T_f + 273.15} \right) \frac{dT_f}{dt} \right) \quad (3.42)$$

Exergy efficiency (also known as the second law efficiency) measures how the available energy is utilized and how much of it was used to produce useful work. It is the ratio of exergy produced to the exergy supplied to a system.

Total exergy efficiency of the saline water chamber is:

$$\eta_{II,saline} = \left\{ \begin{array}{ll} \frac{\dot{X}_{vapor}}{\dot{X}_{air} + \dot{X}_{solar} + \dot{X}_{saline,in}} & \mathbf{3.43(a)} \quad , T_{sur} > T_{wall-air} \\ \frac{\dot{X}_{vapor}}{\dot{X}_{solar} + \dot{X}_{saline,in}} & \mathbf{3.43(b)} \quad , T_{sur} < T_{wall-air} \end{array} \right\}$$

Total exergy efficiency of the fresh water chamber is:

$$\eta_{II, fresh} = \frac{\dot{X}_{fresh, out}}{\dot{X}_{vapor}} \quad (3.44)$$

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter the theoretical results of the present model of the NVD system performance were presented and discussed. Two cases were studied; the system's performance in hot and cold weather operating conditions. Then, a sensitivity analysis was conducted on a group of parameters. Each parameter was changed within acceptable range, and the effect of the change was discussed.

4.1 Case (1) NVD performance in hot environment

In Bahrain, July is one of the hottest months during the year; ambient temperature and solar irradiance are at their maximum. FIG. 4-1 shows the solar irradiance for 3 consecutive days in the month of July, the 26 of July is taken to simulate a hot day as it represents an average. FIG. 4-2 shows the ambient temperature corresponding to 26 of July.

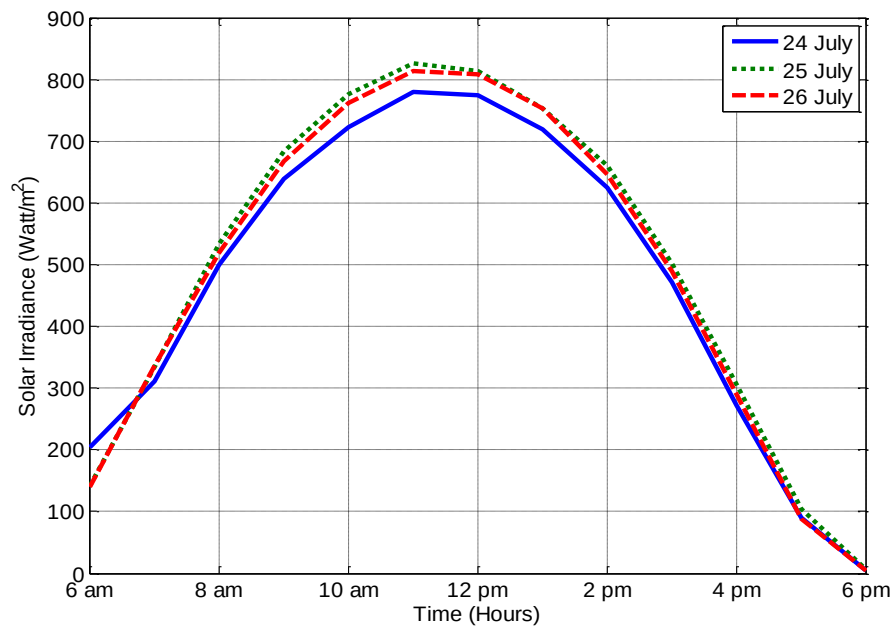


FIG. 4-1 Solar irradiance per unit area on a horizontal plane for hot weather (24, 25, and 26 July)

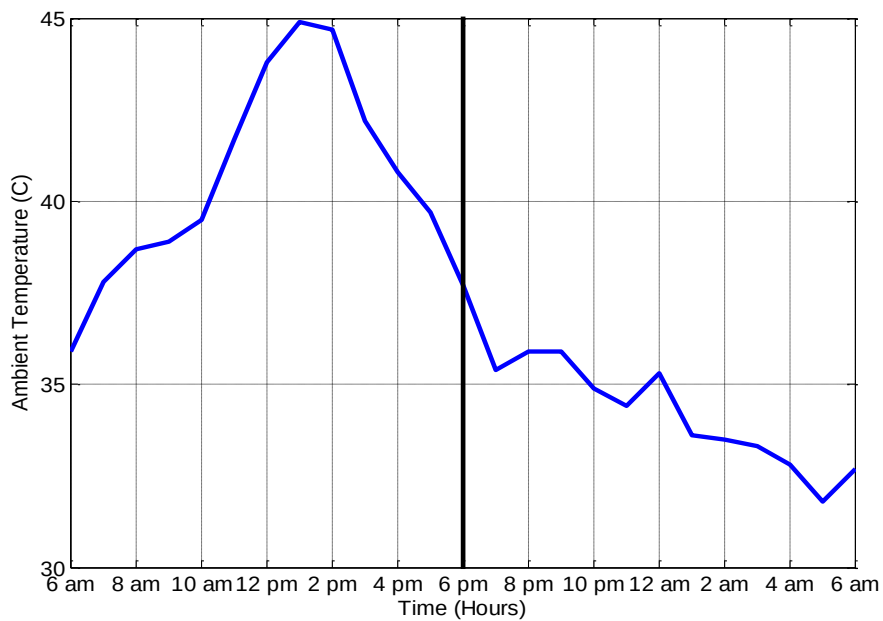


FIG. 4-2 Ambient temperature for a hot day (26 July)

In FIG. 4-1 the maximum value of solar irradiance for 26 of July is 808.8 Watt/m², the values shown for the solar irradiance are for 12 hours (6 am to 6 pm),

from FIG. 4-2 the maximum ambient temperature is 44.9 °C, and the data of ambient temperature are for 24 hours (6 am to 6 am). The wind speed is taken as 7 m/s it is assumed constant. All data are provided by Bahrain Civil Aviation Affairs.

The solar irradiance data in FIG. 4-1 cannot be used for the current configuration of the NVD system, because the saline water chamber is a vertical cylinder and the solar irradiance falling on the perimeter of the chamber is not equal to the solar irradiance falling on a horizontal plane. The sun radiation falling on earth consists of three components (Duffie & Beckman, 1980); direct solar radiation that comes directly from the sun, diffused solar radiation which originates from the dispersing of the direct solar radiation in the atmosphere, and the reflected radiation which accounts for radiation reflected from nearby and surrounding objects.

Numerous studies were conducted researching solar irradiance on tilted and vertical surfaces, calculating the solar irradiance falling on a certain volume is a complex and intricate process, in this research SOLIDWORKS 2013 was used to simulate the total solar irradiance falling on the saline water chamber from 6 am to 6 pm in local time, the latitude and day of the year were plugged in and the results of the solar irradiance falling on the saline water chamber was calculated and is shown in FIG. 4-3.

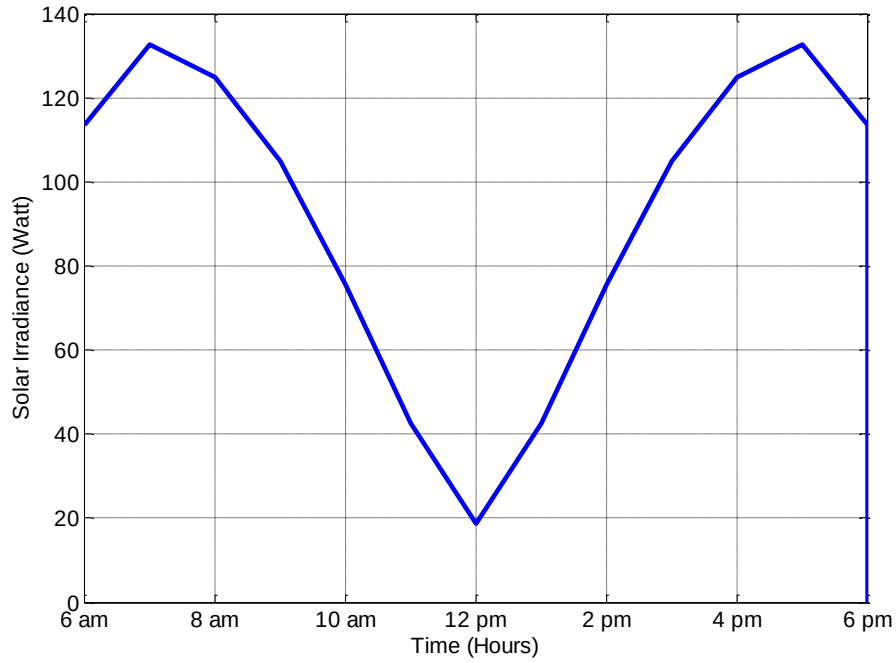


FIG. 4-3 Solar irradiance falling on saline water chamber for hot weather

The shape of the data of solar irradiance shown in FIG. 4-3 indicates that the maximum solar irradiance value is in the beginning and ending of the day which reaches 132.6 Watts, the cause for this pattern is the location of the sun relative to the saline water chamber, at the sun rise and sun set, the sun rays are approximately perpendicular to the axis of the cylinder chamber, supplying the maximum irradiance. The lowest irradiance falling on the chamber can be seen at the mid of the day which is 18.85 Watts, at that time the sun is directly over the NVD system making zero angle between the norm of the cylinder chamber and the sun rays.

Chapter 3 showed the required mathematical relations that models the system, the most important two variables and the ones that must be found are the saline and fresh water temperatures, finding T_s and T_f using numerical solution of a the set of differential equations defined in chapter 3 is the main goal, the rest of the variables are calculated based on the saline and fresh water temperatures.

A MATLAB code was developed to solve the model equations. The technique used is a fourth order Rounge Kutta function, the time step used was 60 seconds. The initial conditions were 30 °C for both saline and fresh water, 3.5% salt concentration, and the cooling temperature of water used is 30 °C (Office of Satellite and Product Operations, 1998). All the subroutines of the code are shown in appendices (D) and (E).

FIG. 4-4 shows the temperatures profile for the saline and fresh water. During sunshine hours, the saline water temperature started rising under the influence of solar irradiance and ambient conditions, the maximum temperature is 43.84 °C, this temperature was reached at 5 pm, after sunrise the ambient temperature decreases and the saline water temperature decreases as well. The irregular shape pattern of saline water temperature is the result of using the ambient temperature data shown in FIG. 4-2 directly without fitting them to an equation. At the mid of sunshine time (approximately 12 pm) the saline water temperature slope decreases because at that time solar irradiance reaches its lowest value, then the slope starts increasing again when the solar irradiance starts increasing.

Fresh water temperature shown in FIG. 4-4 faces a slight increase, at the end of sunshine time the temperature reaches 30.57 °C, at that time the temperature difference between the saline and fresh water chambers is at its greatest, thus maximum evaporation rate is achieved, and water vapor produced has the highest temperature. As saline water temperature starts decreasing from its maximum value, fresh water decreases too, because the water vapor condensing in the fresh water chamber has low temperature in addition to the low temperature of vapor produced, the evaporation rate decreases as the temperature difference between saline and fresh water chambers decrease.

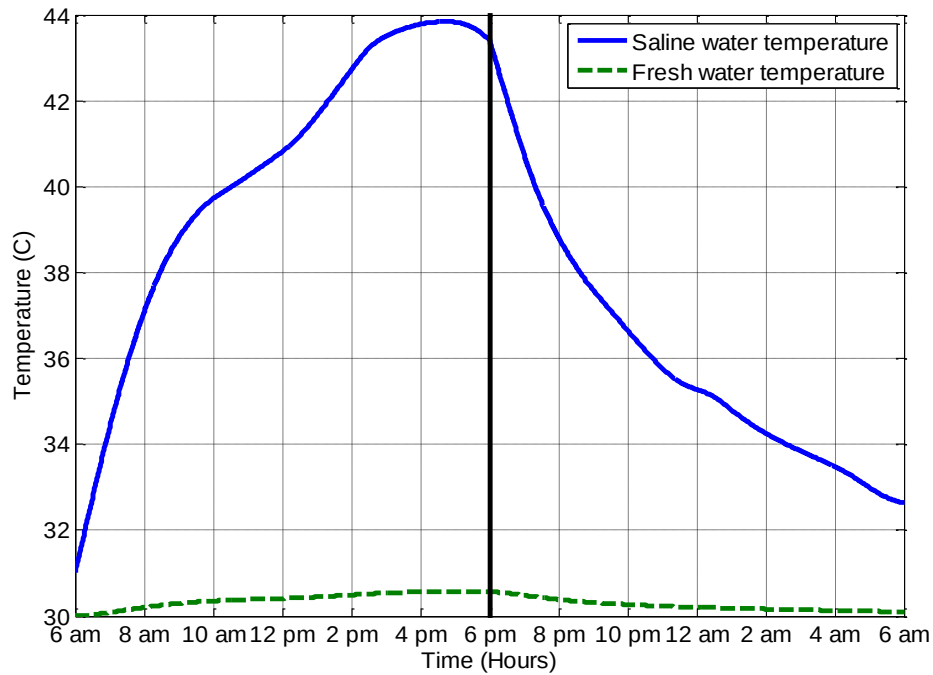


FIG. 4-4 Temperature of saline and fresh water for hot weather

The vapor pressure of saline and fresh water are shown in FIG. 4-5, both temperature profiles exhibit similar trend of saline and fresh water temperature shown in FIG. 4-4, the reason for this similarity is the saturated temperature-pressure relation for water where the saturated pressure is a function of saturated temperature. The saline water vapor pressure starts increasing as the temperature increases, the maximum value is 8867 Pa at 5 pm, after sunset the vapor pressure decreases with decreasing heat supplied from the environment during nocturnal time. Vapor pressure of fresh water exhibit a slight change, the maximum value is 4327 Pa at the end of sunshine time, after that it starts decreasing with the decreasing saline water vapor pressure.

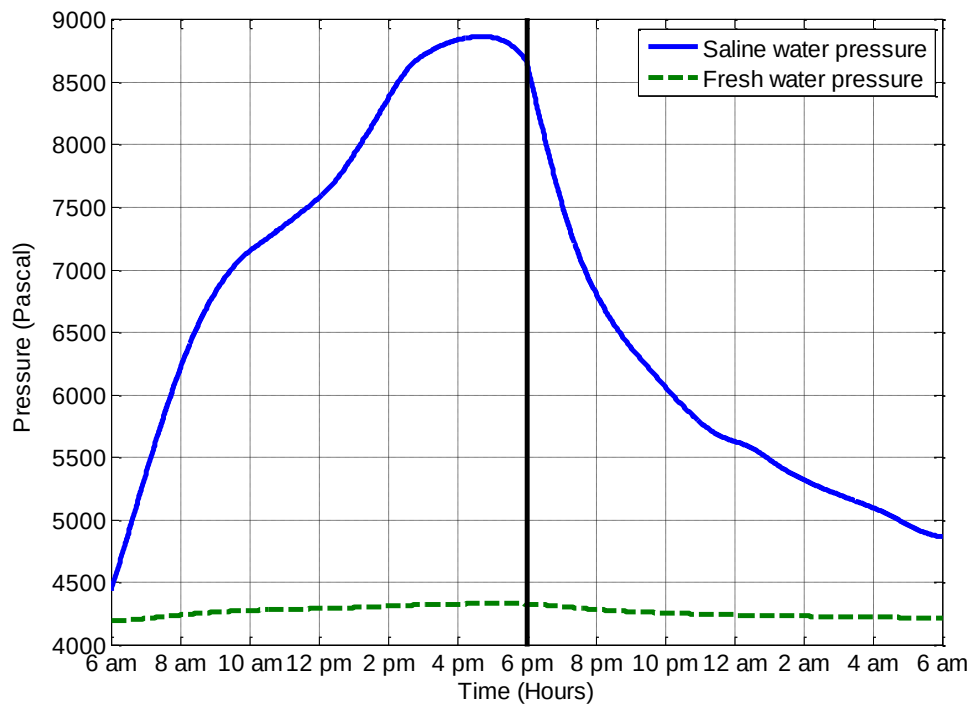


FIG. 4-5 Vapor pressure of saline and fresh water for hot weather

FIG. 4-6 shows the evaporation rate which follows the same trend and pattern that of temperature and pressure of saline water, the maximum rate is 0.042 kg/hr which occurs near the end of sunshine time at 5 pm, the evaporation rate is a function of temperature of saline and fresh water, and the surface area of the saline water, the surface area of saline water is 0.05 m^2 (radius of the saline water chamber is 0.125 m).

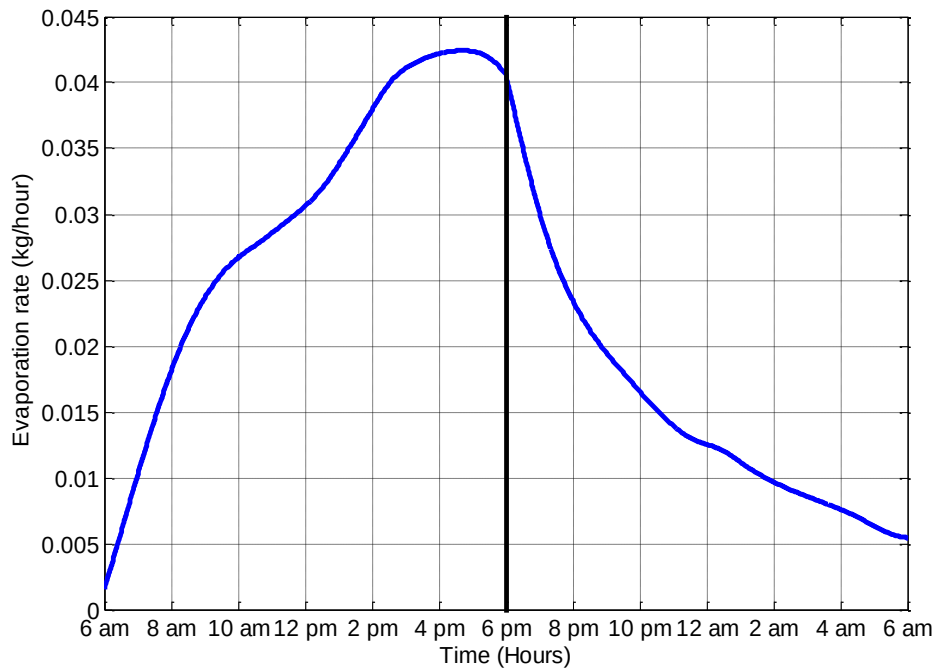


FIG. 4-6 Evaporation rate for hot weather

The fresh water produced is shown in FIG. 4-7, assuming all of the vapor produced is condensed in the fresh water chamber, and the effect of non-condensable gases are negligible, the amount of fresh water collected for 24 hours is 0.54 kg. Approximately 67% fresh water is produced during sunshine time, the rest is produced during nocturnal hours where no heat is supplied, and the saline water evaporates utilizing the stored energy. As saline water keeps producing vapor, the stored energy decreases as the vapor carries away with it latent heat, thus the decreases in temperature and eventually evaporation ceases.

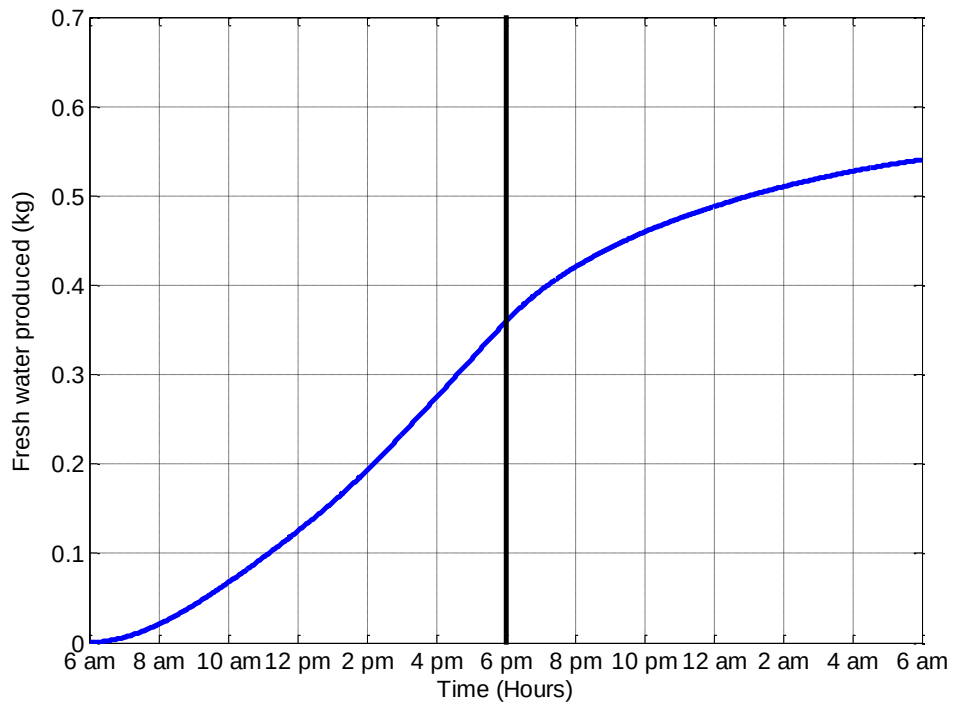


FIG. 4-7 Fresh water produced for hot weather

When the saline water chamber produces vapor the concentration of salts increases, in this study no brine is withdrawn from the saline water chamber. FIG. 4-8 shows the salt concentration, at the end of the 24 hours run time, the concentration increases to 3.577% which is a small value compared to the initial condition of 3.5%.

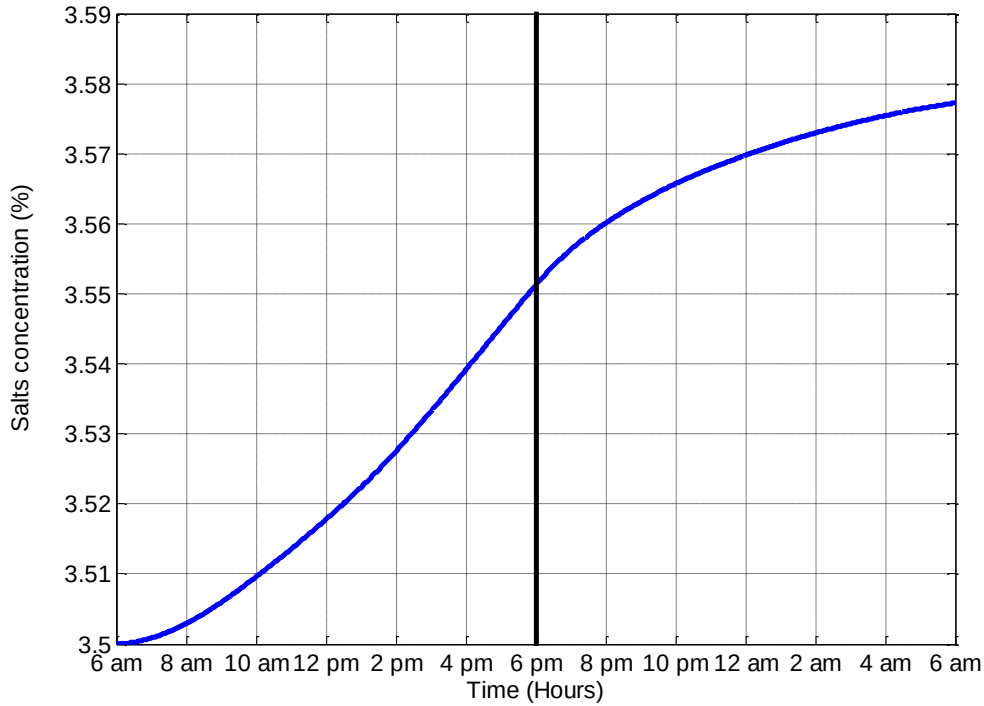


FIG. 4-8 Salts concentration for hot weather

The efficiency of the evaporation process is shown in FIG. 4-9, the maximum value is 44.58% at the mid of sunshine time (approximately at 12 pm), then it decreases to 23.42%. Thermal efficiency is at its highest at the mid of sunshine time because of the amount of heat supplied is minimum, in FIG. 4-3 the solar irradiance is minimum at that time, thus, the production is optimum relative to the low amount of energy supplied. Another cause for the low efficiency is the solar irradiance loss, the material of the saline water chamber is mild steel, the absorptivity of the chamber wall is no more than 0.5, and thus 50% of the solar irradiance is not exploited and it is reflected to the environment.

Efficiency at the 2 pm indicates a change in the heat supply process, at the mentioned time the nature of heat transfer between the saline water chamber and the environment (surrounding air) changes from heat gain (when $T_{wall-air} < T_{sur}$) to heat loss (when $T_{wall-air} > T_{sur}$). Even though the efficiency still decreases as a results of

heat losses, the slope of efficiency experiences a slight increase as an effect of the increase of solar irradiance after mid of sunshine time.

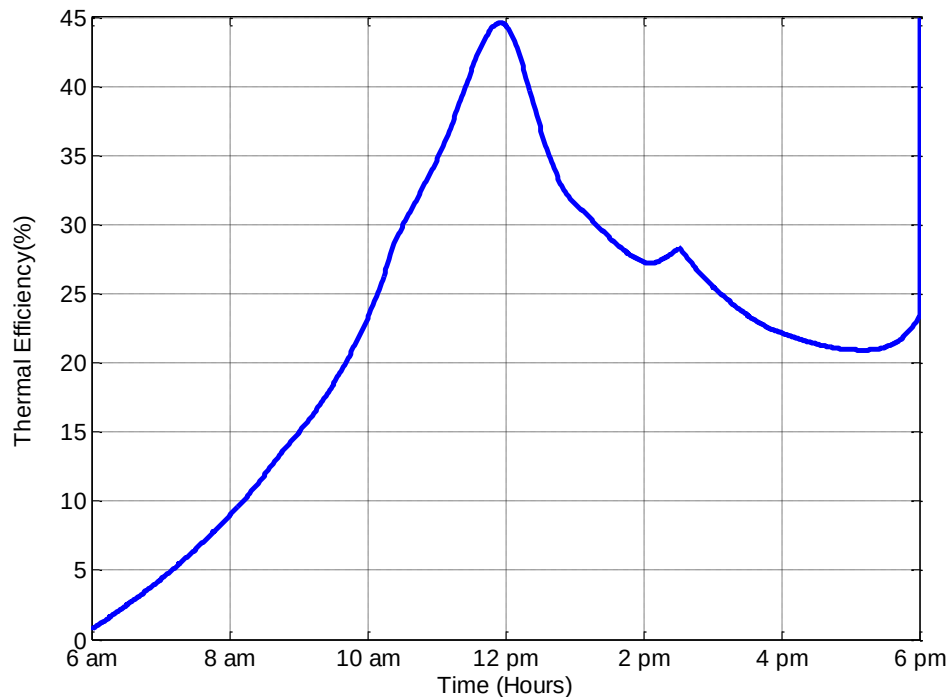


FIG. 4-9 Thermal efficiency for hot weather

The exergy efficiency of the saline water is shown in FIG. 4-10, the total exergy efficiency of the saline water chamber reaches its maximum at the mid of sunshine time (approximately 12 pm), the value is 5.44% which is considerably low, which is a result from high exergy destruction and losses. A considerable amount of exergy destruction and loss is attributed to the saline water chamber wall, from FIG. 4-10 the exergy efficiency of the wall has a maximum value of 9.86 %, first, half of the solar exergy is lost as a result of the wall material reflection, and what is left is destroyed through the wall.

Approximately at 5 pm, before sunset, the total exergy efficiency exceeds the exergy of the saline water chamber wall, since the solar irradiance starts diminishing and the losses to the surrounding increase, the amount of heat transferred through the wall decreases, while the exergy of vapor still exits since there is still exergy stored in

the mass of saline water. The exergy destruction of the saline water chamber wall is shown in FIG. 4-11, the pattern exergy destroyed is analogous to that of the solar irradiance, suggesting that exergy coming from solar irradiance is heavily destroyed. 50% of solar exergy is lost as a result of wall reflection.

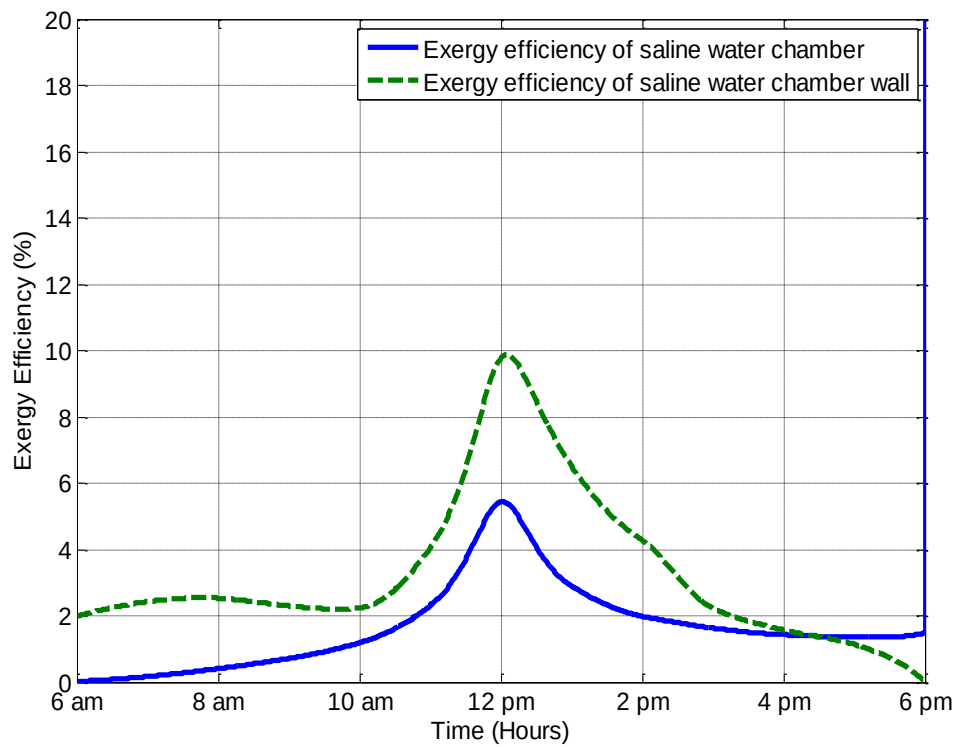


FIG. 4-10 Exergy efficiency of saline water chamber and its wall for hot weather

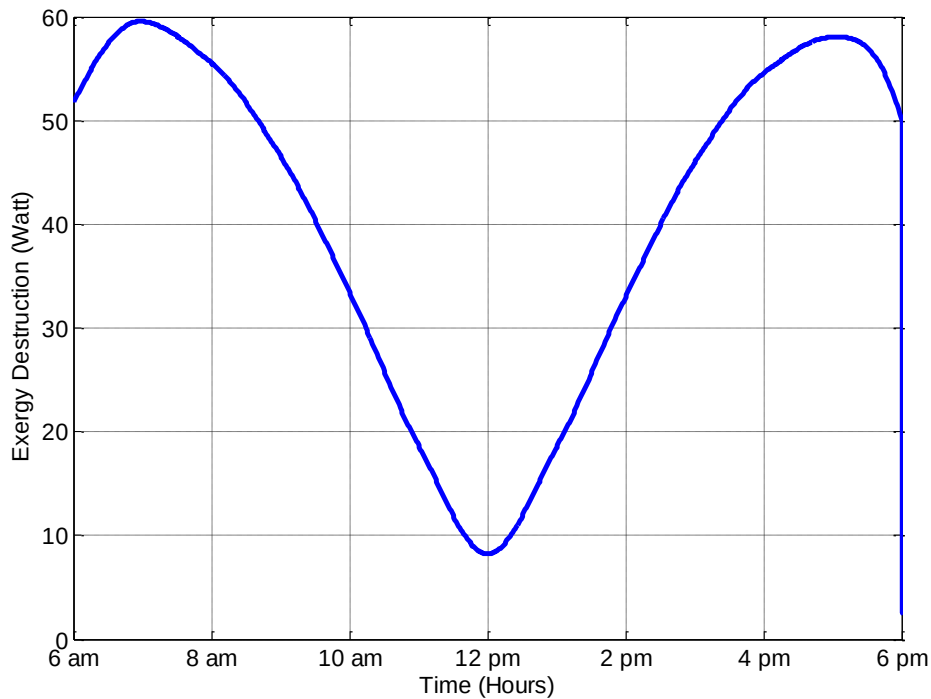


FIG. 4-11 Exergy destruction of saline water chamber wall for hot weather

The total exergy efficiency of fresh water chamber is shown in FIG. 4-12, at the beginning of sunshine time the efficiency is at its maximum which 6.02 %, then it starts decreasing reaching its minimum at the end of sunshine time, the decreases is a result of the increase of exergy of vapor entering the fresh water chamber, during sunshine time the amount of vapor entering the fresh water increases and more vapor is destroyed, hence the decreases in efficiency. During nocturnal hours, the exergy efficiency increases to 4.77% at the end of 24hours run, the increase in exergy efficiency is related to the exergy of vapor entering the fresh water chamber, less vapor produced during nocturnal hours results in less destruction of vapor exergy, which explains the rise in exergy efficiency of the fresh water chamber.

The exergy efficiency of fresh water chamber wall is also shown in FIG. 4-12. The exergy efficiency is not defined at the first 2 hours of sunshine time, this is because the fresh water temperature has not risen yet and no heat is transferred through the wall.

The lowest exergy efficiency of the fresh water wall occurs at the end of sunshine time which is 95.55%.

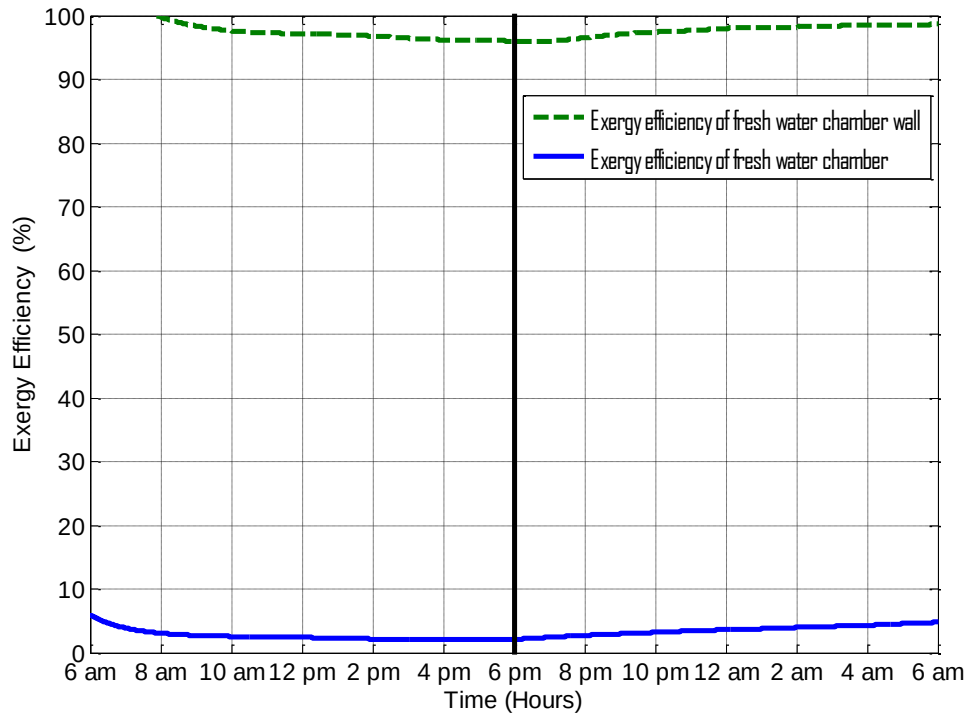


FIG. 4-12 Exergy efficiency of fresh water chamber and its wall for hot weather

FIG. 4-13 shows exergy destruction in fresh water chamber, the maximum amount destroyed is 1.155 Watt which occurs at 5 pm where the vapor production is at its highest hence the destruction as well. The exergy destroyed shown is the result of vapor condensing on the fresh water surface. After sunset, the destruction of vapor decreases with the decrease of evaporation rate.

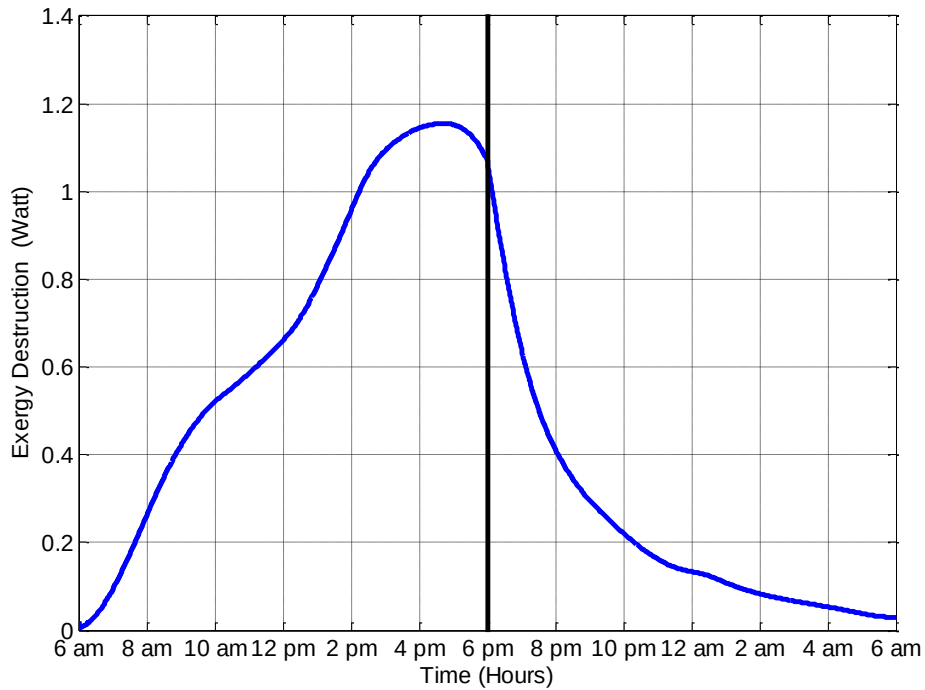


FIG. 4-13 Exergy destruction of fresh water for hot weather

4.2 Case (2) NVD performance in cold conditions

To simulate cold conditions, the month of January is chosen, FIG. 4-14 shows the solar irradiance per unit area on a horizontal plane for a cold weather for 4 consecutive days, the 10th of January represents an average and it will be used in the subsequent calculations. The maximum value is 560 Watt/m² compared to 808 Watt/m² for the hot weather operation conditions discussed in case (1). In winter time the sunshine hours are less than summer time, the sun sets early (approximately 5pm).

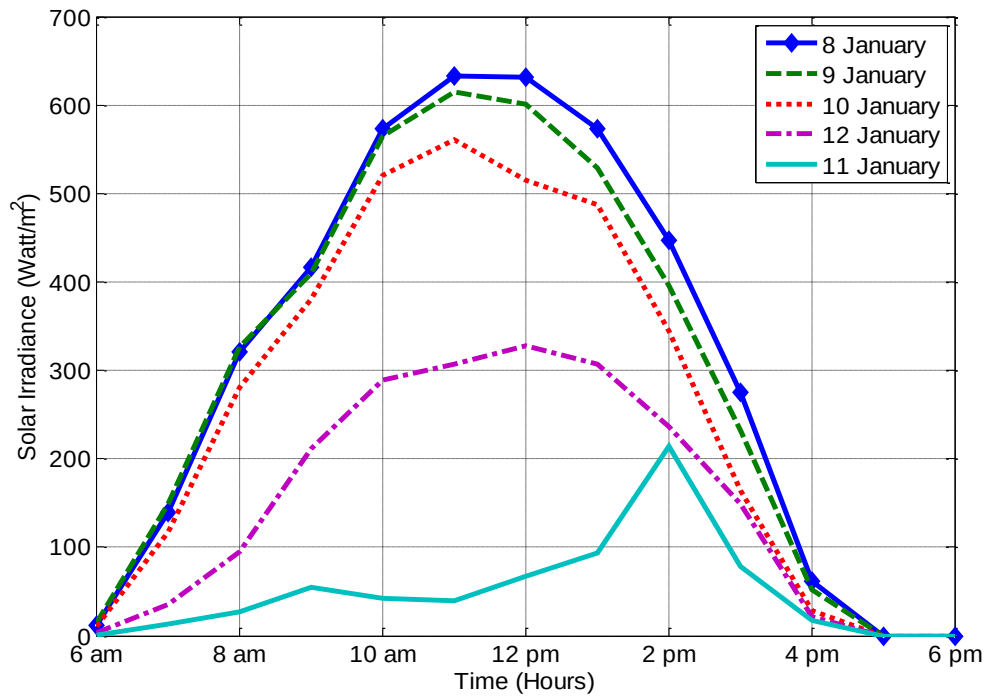


FIG. 4-14 Solar irradiance per unit area on a horizontal plane for cold weather (8-12 January)

FIG. 4-15 shows the ambient temperature for 24 hours for cold weather, the maximum value is 17.2 °C and it is reached at the mid of sunshine time (12pm). During nocturnal hours the ambient temperature varies between 15 °C and 16 °C.

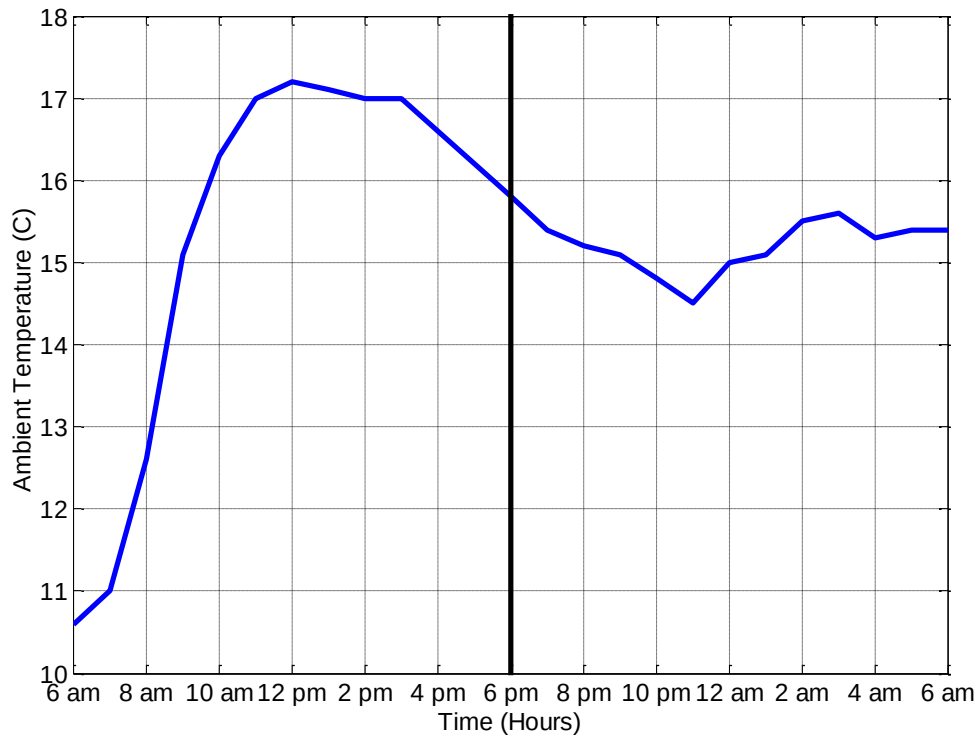


FIG. 4-15 Ambient temperature for cold weather

The solar irradiance falling on the saline water chamber is shown in FIG. 4-16, the maximum irradiance is 132.3 Watts, and it can be seen at 9 am and 3 pm. At the mid of sunshine time (12 pm) the solar irradiance drops to 116 Watts, unlike solar irradiance in hot conditions, this value is not the minimum, this indicates that sun still makes an angle between the axis of the saline water chamber cylinder and the solar irradiance. The sunshine time is less than summer sunshine time by approximately 2 hours (7 am to 5pm), in winter the sun position is different than of it in summer.

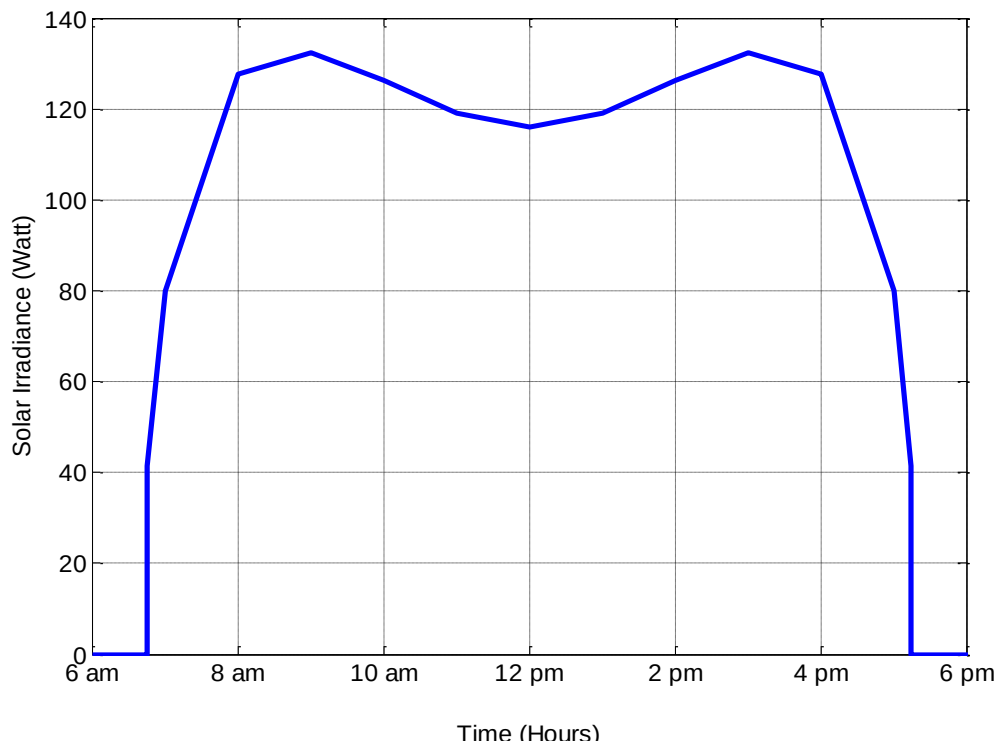


FIG. 4-16 Solar irradiance falling on saline water chamber for cold weather

The set of coupled equations that describes the system are solved simultaneously, the initial temperature for saline and fresh water is 12 °C, and the salt concentration is 3.5%, the temperature of the cooling water used to cool the fresh water chamber is 11 °C (Office of Satellite and Product Operations, 1998).

FIG. 4-17 shows the temperature of saline and fresh water for 24 hours run, the temperature of the saline water increases to a maximum of 21.73 °C at 4 pm, after sunset the temperature decreases under the influence of the ambient temperature then it stabilizes around 15 °C. The constant saline water temperature after 12 am is a result of the little change of ambient temperature during nocturnal hours. The fresh water temperature remains approximately constant at 11 °C.

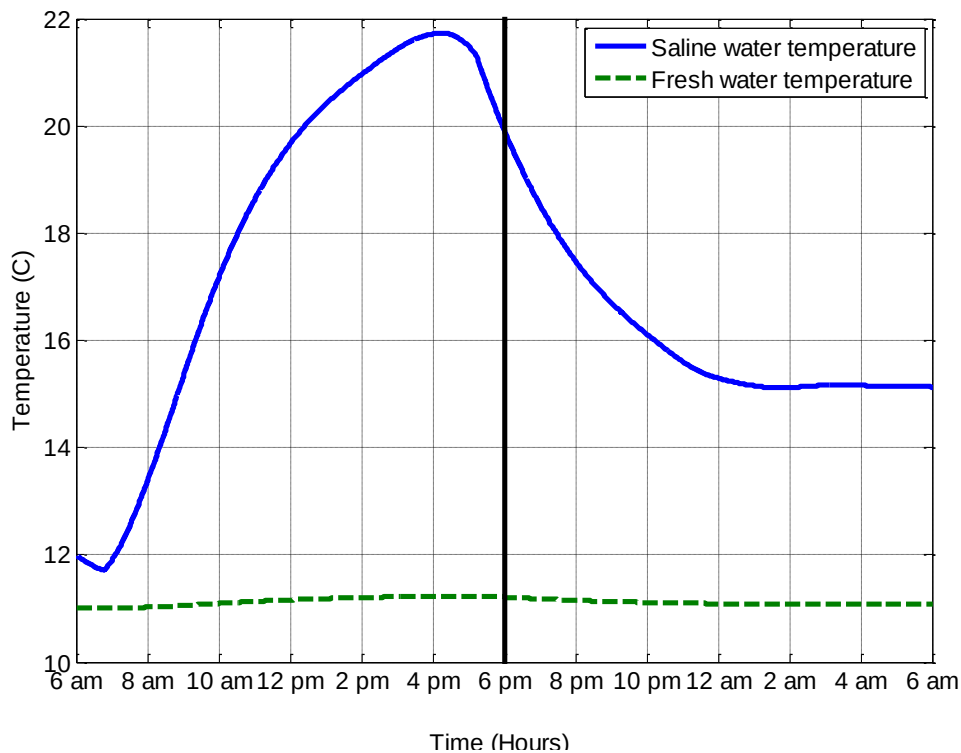


FIG. 4-17 Temperature of saline and fresh water for cold weather

The vapor pressure of the saline and fresh water is shown in FIG. 4-18, the pattern of the curves shown comply with the temperature pattern shown in FIG. 4-17. The saline water maximum vapor pressure of 2571Pa is attained at 4 pm then it decreases after sunset. As for the fresh water vapor pressure, the maximum value is 1319 Pa at 4 pm, the vapor pressure of fresh water does not exhibits high changes with time.

The pressure measured inside the system will not indicate the vapor pressure of saline nor fresh water; instead it will measure the pressure difference between the two chambers, which is the driving force of vapor.

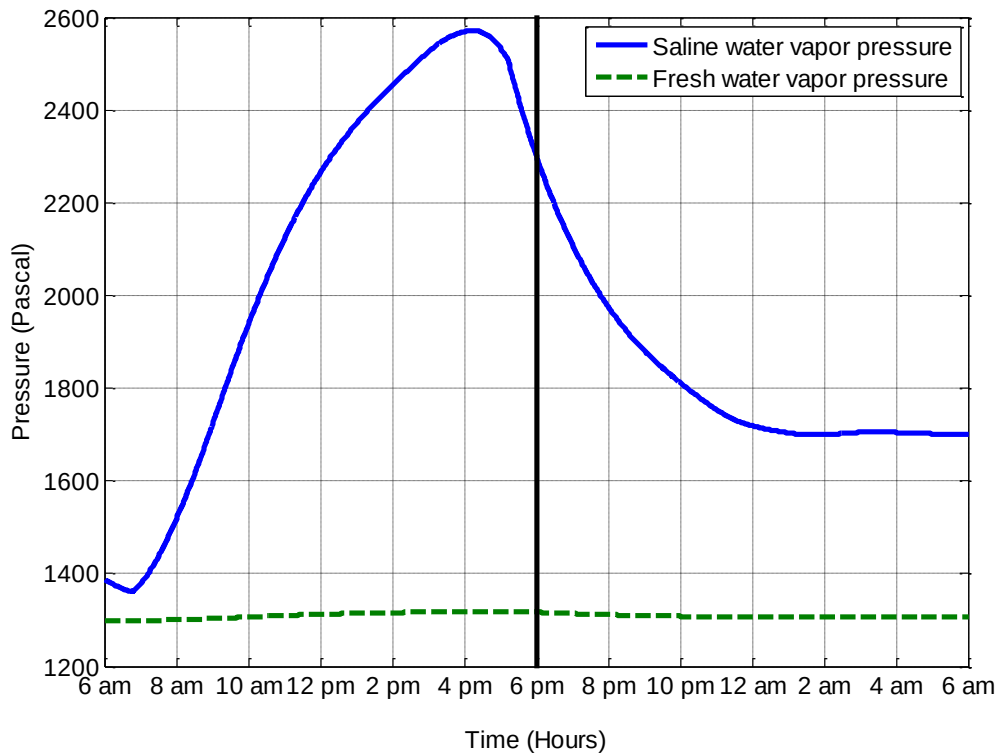


FIG. 4-18 Vapor pressure of saline and fresh water for cold weather

FIG. 4-19 shows the evaporation rate, rate increases to 0.0121 kg/hr at the mid of sunshine time then starts decreasing with sunset, the pattern of evaporation rate shown in FIG. 4-19 has a similar shape to the vapor pressure and temperature of saline and fresh water shown in FIG. 4-18 and FIG. 4-17, respectively.

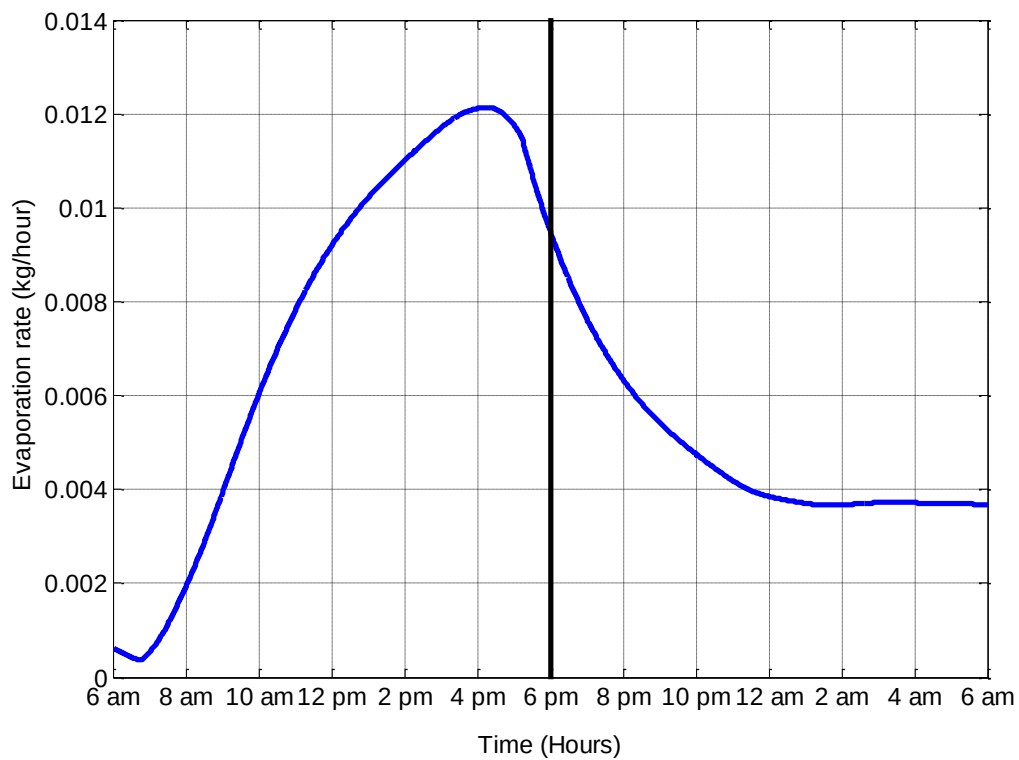


FIG. 4-19 Evaporation rate for cold weather

The fresh water produced at the end of the 24 hours run time is shown in FIG. 4-20, 0.149 kg is collected at the end of run time, more than half of that amount collected (61.74%) is produced during sunshine time.

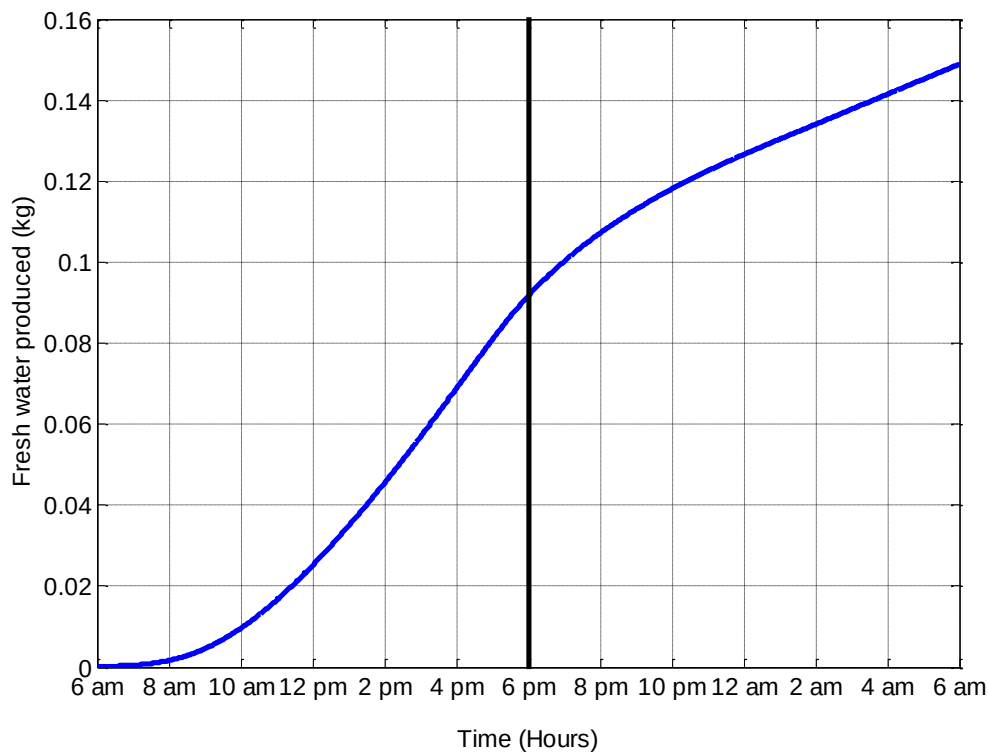


FIG. 4-20 Fresh water produced for cold weather

Salts concentration increases as shown in FIG. 4-21, the final value at the end of the 24 hours run is 3.521%, a small amount compared to the initial concentration.

FIG. 4-22 shows thermal efficiency of the saline water chamber, the sunshine hours are less than of it at summer time; hence, the solar irradiance as an input starts from at 7 am and ends at 5pm in local time, as a result the thermal efficiency domain must confirm to the time domain of the solar irradiance. The maximum efficiency is achieved at the end of sunshine hours, the final value is 9.98%, the low thermal efficiency is a result of the solar irradiance reflection from the saline water chamber and heat losses to the environment.

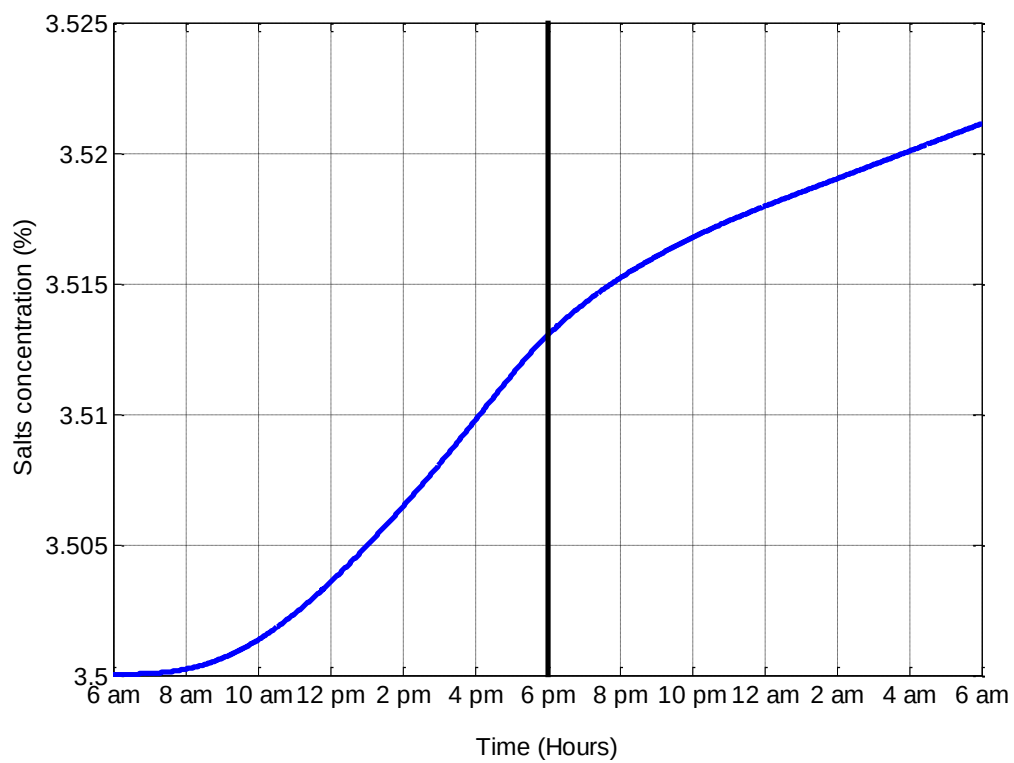


FIG. 4-21 Salts concentration for cold weather

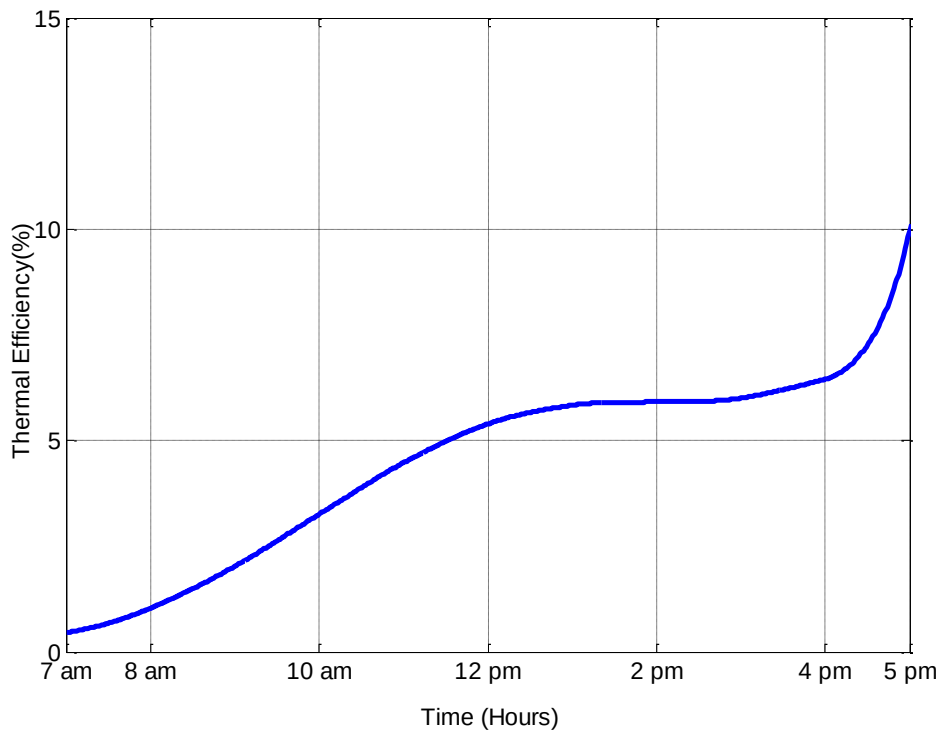


FIG. 4-22 Thermal efficiency for cold weather

Exergy efficiencies for the saline water chamber and its wall are shown in FIG. 4-23, the total exergy efficiency of the saline water chamber has a maximum value of 0.375 %, this value is attained at the end of sunshine hours, the exergy efficiency of saline water chamber exhibits a similar trend to thermal efficiency pattern shown in FIG. 4-22. Exergy destruction and losses are the reason for such low exergy efficiency combined with low yield of fresh water production. A considerable amount of exergy is either destroyed or lost in the saline water chamber wall, FIG. 4-23 shows the exergy efficiency of the saline water chamber wall, the maximum value of 0.985% is achieved at the mid of sunshine time, the low ambient temperature mainly contributes to the low exergy efficiency of the wall. Between 4 pm and 5 pm exergy efficiency of the saline water chamber exceeds the exergy efficiency of its wall, the cause of this change is the exergy of vapor being produced relying on the exergy stored in the saline water.

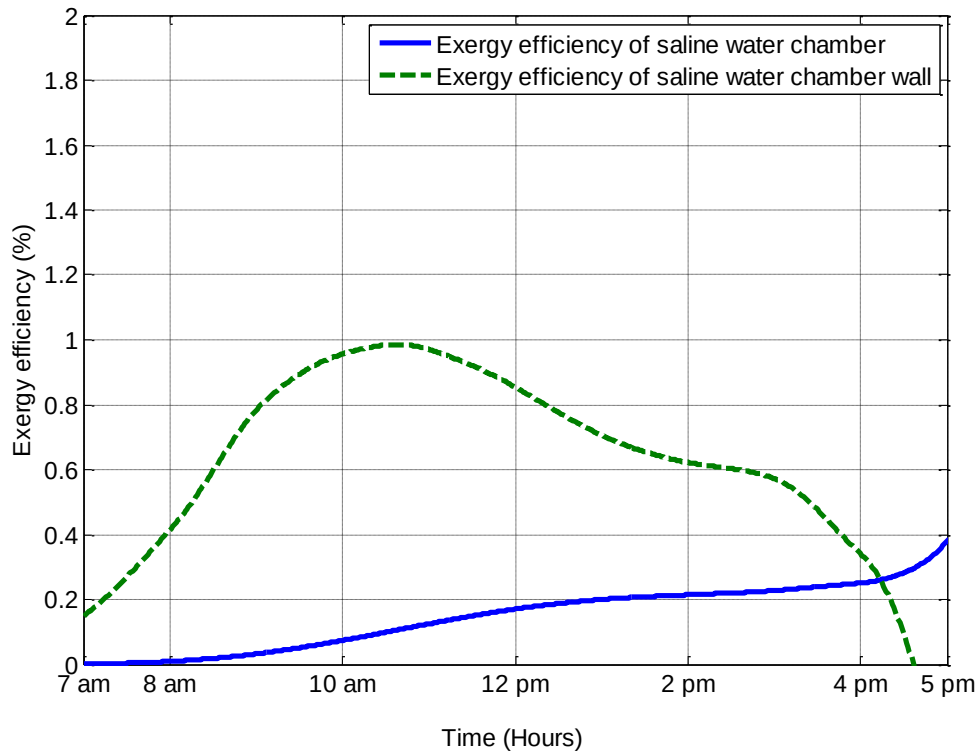


FIG. 4-23 Exergy efficiency of the saline water chamber and its wall for cold weather

Exergy destroyed through the saline water wall is shown in FIG. 4-24, the maximum exergy destruction occurs approximately at 9 am and 3 pm, 60.88 Watts are destroyed at those times. The pattern of the exergy destruction shown in FIG. 4-24 indicates that a considerable portion of solar exergy is destroyed. Additionally, exergy is lost to the environment via heat transfer to the ambient air.

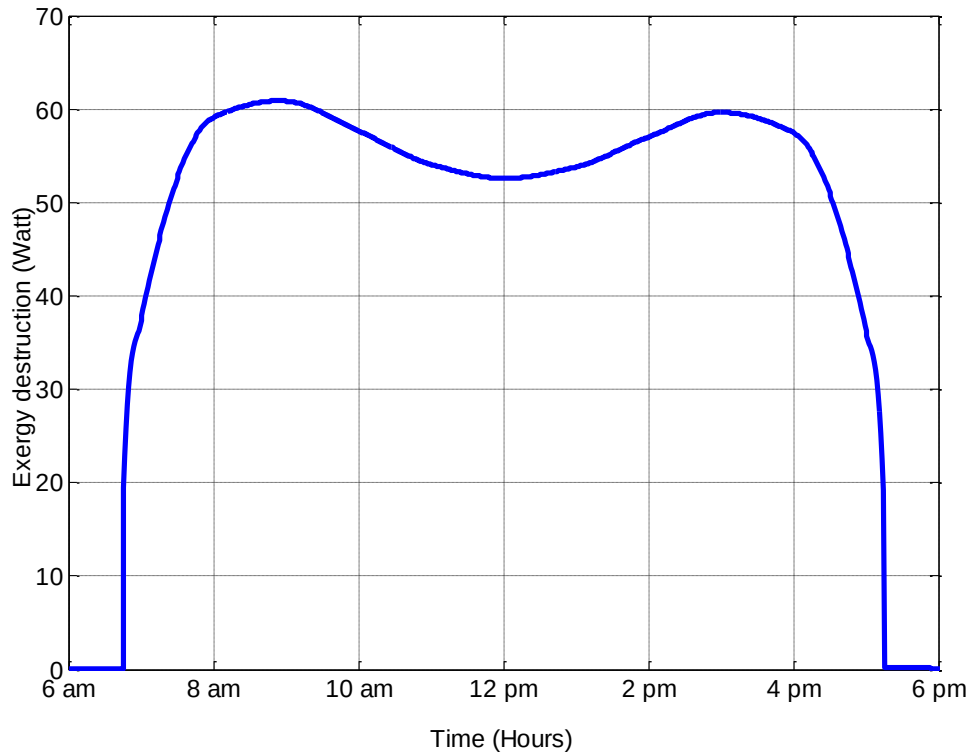


FIG. 4-24 Exergy destruction of saline water chamber wall for cold weather

For the fresh water chamber, the exergy efficiency is shown in FIG. 4-25, at the beginning the exergy efficiency experience a sudden rise to 41.47% then starts decreasing, the cause of the sudden rise is related to the temperature initial condition of saline water, initially its 12 °C then experience a drop and starts increasing, the drop in temperature lowers the evaporation rate, hence less vapor exergy is produced and destroyed thus exergy efficiency becomes high. When the sunshine time starts the saline water temperature increases producing more vapor, as higher amounts of exergy of vapor is destroyed, the lower exergy efficiency becomes.

The exergy of fresh water chamber wall is shown in FIG. 4-25. The maximum efficiency is 59.17%, which is reached at the end of sunshine time; the increase is a result of increasing exergy of vapor entering the fresh water chamber. During nocturnal hours, the efficiency starts dropping because of less exergy of vapor reaching the chamber.

The exergy destruction of fresh water is shown in FIG. 4-26 the maximum exergy destruction is 0.286 Watts which occurs at 4 pm, the exergy destruction decreases during nocturnal time as a results of lower amount of vapor production.

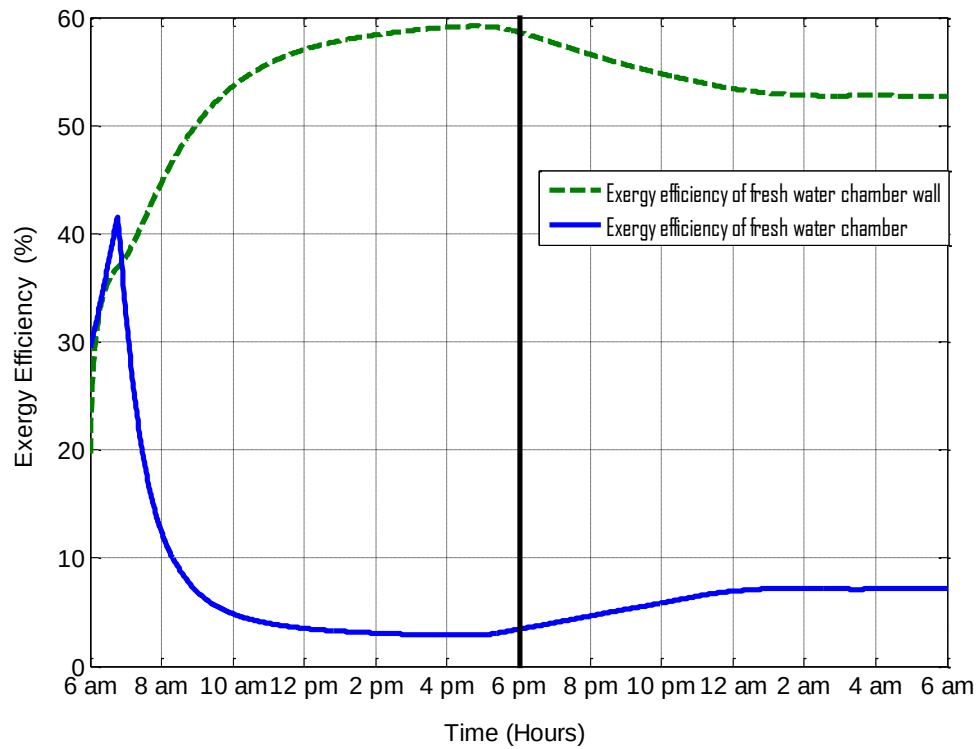


FIG. 4-25 Exergy efficiency of fresh water chamber and its wall for cold weather

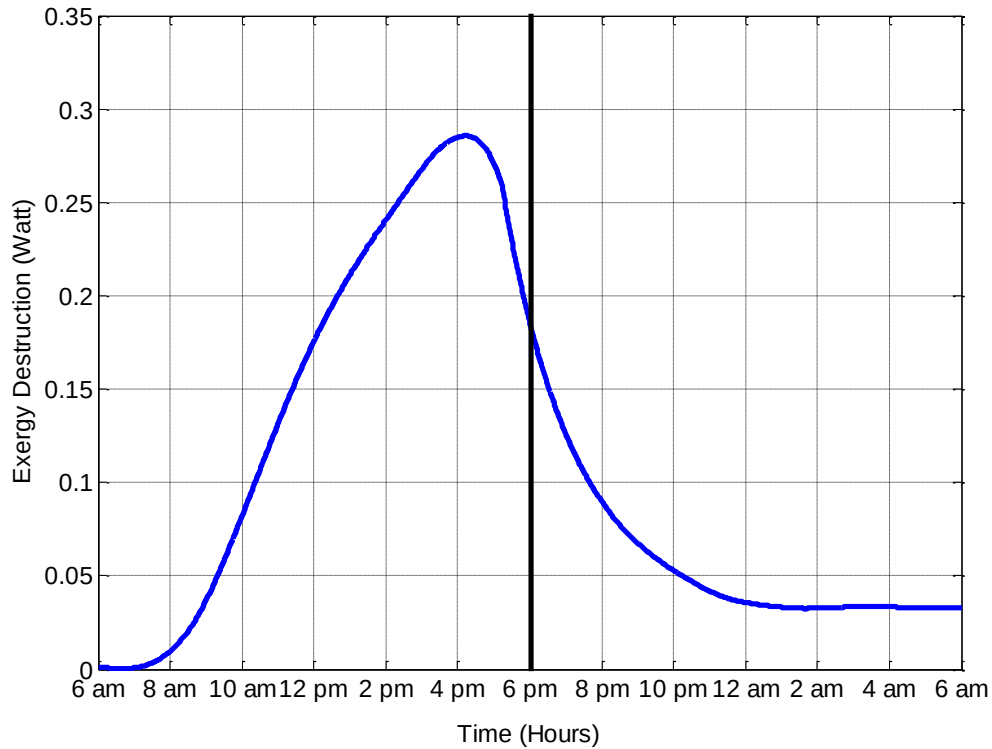


FIG. 4-26 Exergy destruction of fresh water for cold weather

4.3 Summary of hot and cold weather results

FIG. 4-27 shows the saline and fresh water temperature for hot and cold weathers, respectively. The saline water temperature for hot and cold weathers exhibits the same trend. At 6 am the saline water temperature during the hot weather starts increasing immediately, while the saline water temperature during the cold weather starts increasing at 7 am. The difference is related to the sunshine hours, the sun rises earlier during the hot weather. The temperature of the saline water during the hot weather is higher than the temperature during cold weather (approximately two times higher). The fresh water temperature of both hot and cold weather operating conditions remains relatively constant (around their initial conditions).

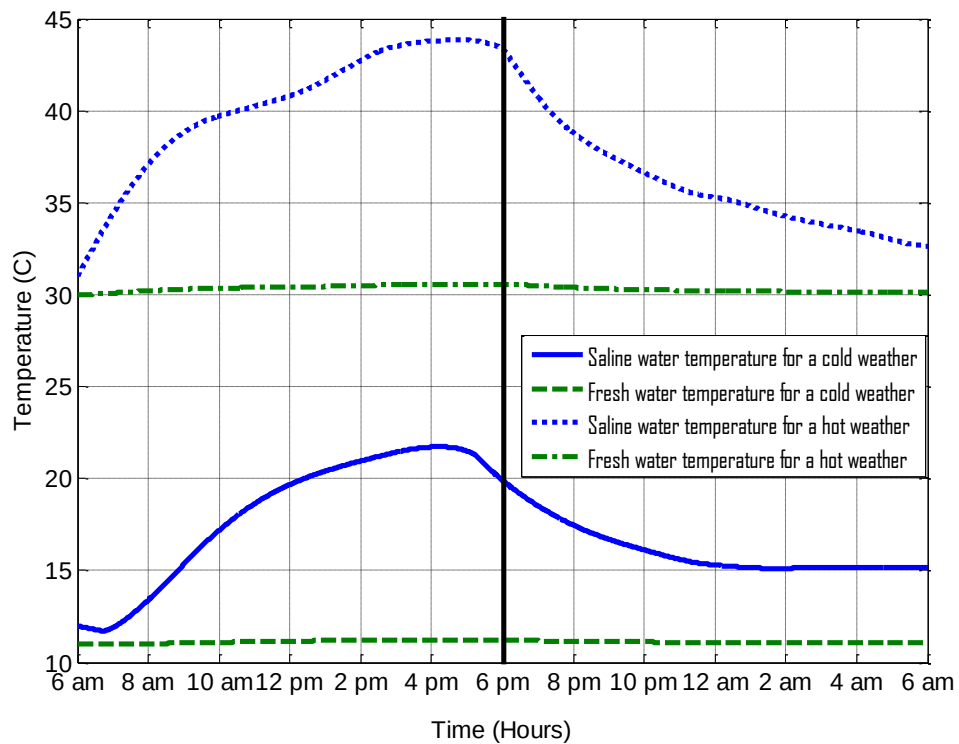


FIG. 4-27 Temperature of saline and fresh water for hot and cold weather

The evaporation rate for hot and cold operating conditions is shown in FIG. 4-28. Both rates share a similar trend. The maximum evaporation rate during the hot weather (0.042 kg/hr) is three to four times higher than the evaporation rate during the cold weather (0.0121 kg/hr). The evaporation for the hot weather starts earlier than the cold weather due to the difference in sunrise time.

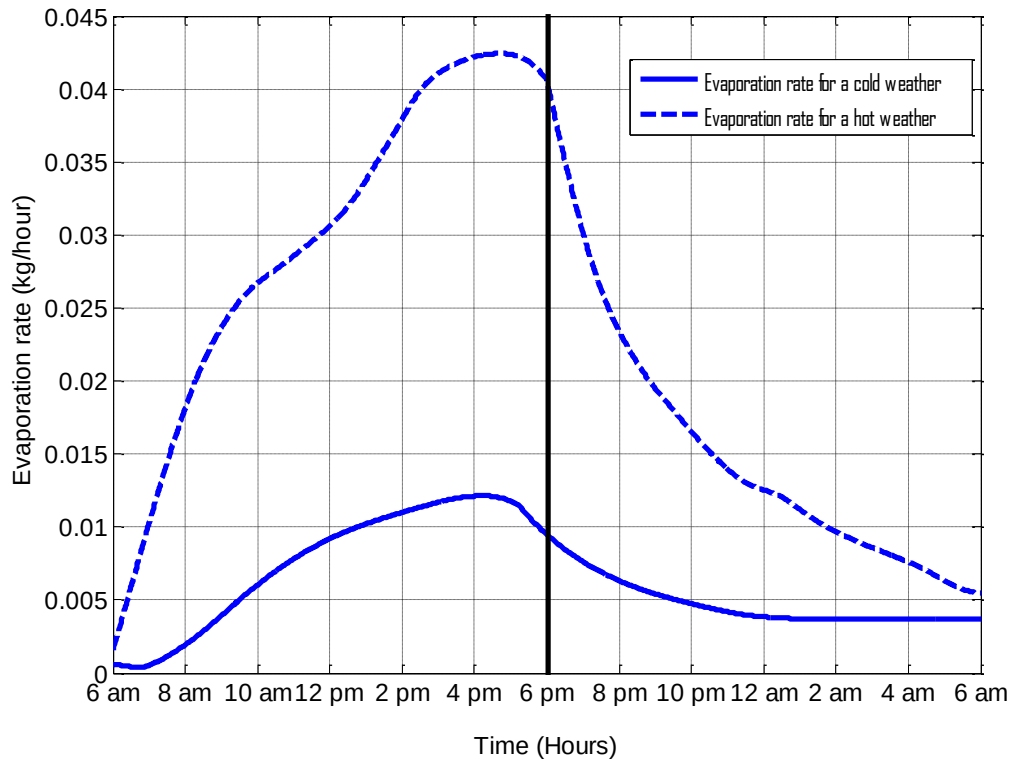


FIG. 4-28 Evaporation rate for hot and cold weather

Thermal efficiency (shown in FIG. 4-29) for hot and cold weather operating conditions are different. The thermal efficiency during a hot weather increases reaching its maximum value at 12 pm, then it decreases. The solar irradiance for a hot weather is minimum at 12 pm, hence, thermal efficiency becomes maximum because the evaporation rate is maximum relative to the low solar irradiance supplied. As for the cold weather, the thermal efficiency increases with time because the solar irradiance pattern is different for a cold weather, although the solar irradiance drops at 12 pm, it is not the minimum value. At 5 pm the sun sets and the thermal efficiency is maximum relative to the low solar irradiance supply.

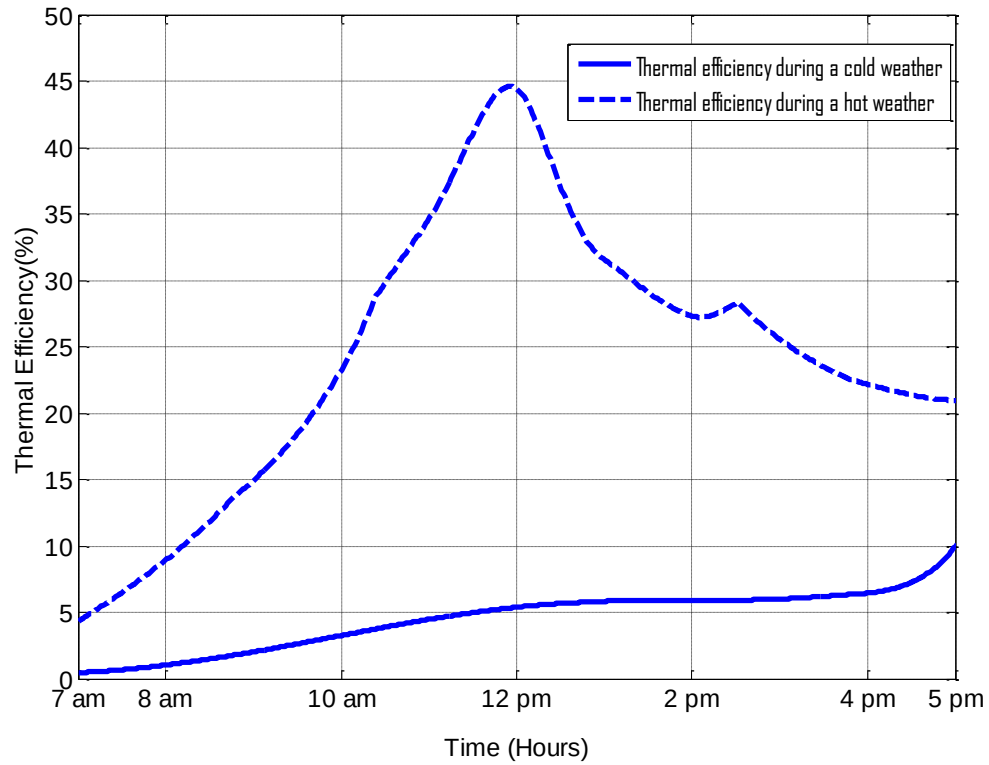


FIG. 4-29 Thermal efficiency for hot and cold weather

Exergy efficiency of the saline water chamber for hot and cold weather operating conditions exhibits the same pattern of thermal efficiency (shown in FIG. 4-30). The exergy efficiency during a hot day has a maximum value at 12 pm as a result of the lowest amount of solar exergy supplied. The exergy efficiency during the cold weather increases with time, at 5 pm the exergy efficiency is maximum due to the lowest amount of solar exergy supplied at sunset.

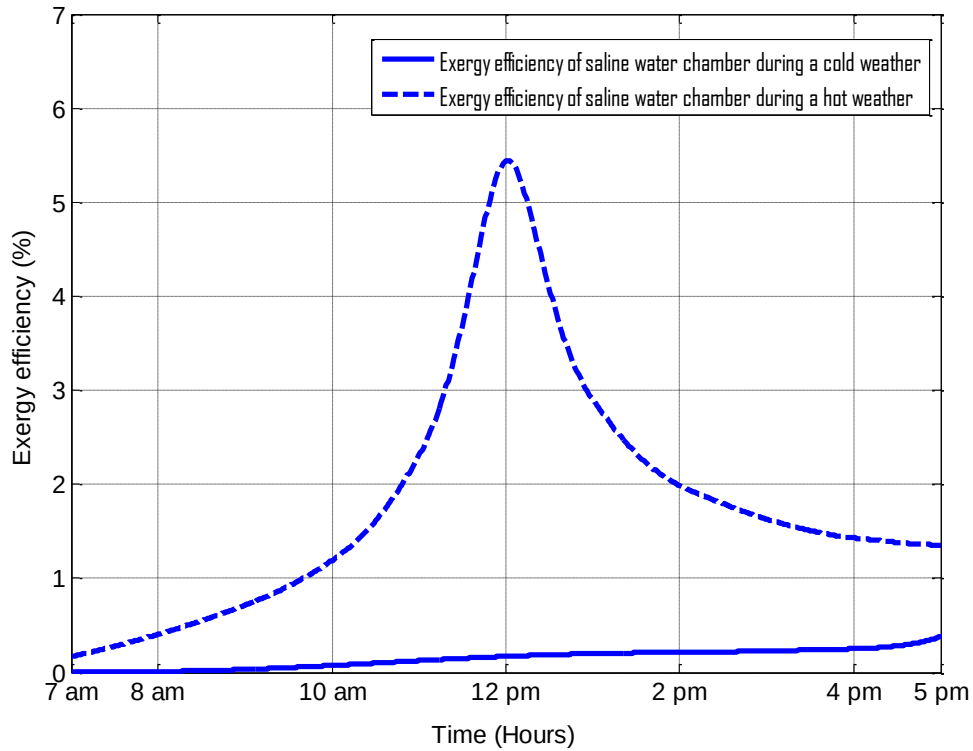


FIG. 4-30 Exergy efficiency of saline water chamber for hot and cold weather

Exergy efficiency of fresh water chamber during hot and cold weather operating conditions is shown in FIG. 4-31. Generally, both hot and cold weather exergy efficiency experience a decrease with time. The exergy efficiency of fresh water chamber for a cold weather is less than the exergy efficiency for a hot weather, since less vapor is produced during cold weather which means less destruction of vapor exergy. The cold weather exergy efficiency rises from 6 am to 7 am, this rise is a result of less vapor entering the fresh water chamber which leads to less exergy destruction and an increase in exergy efficiency.

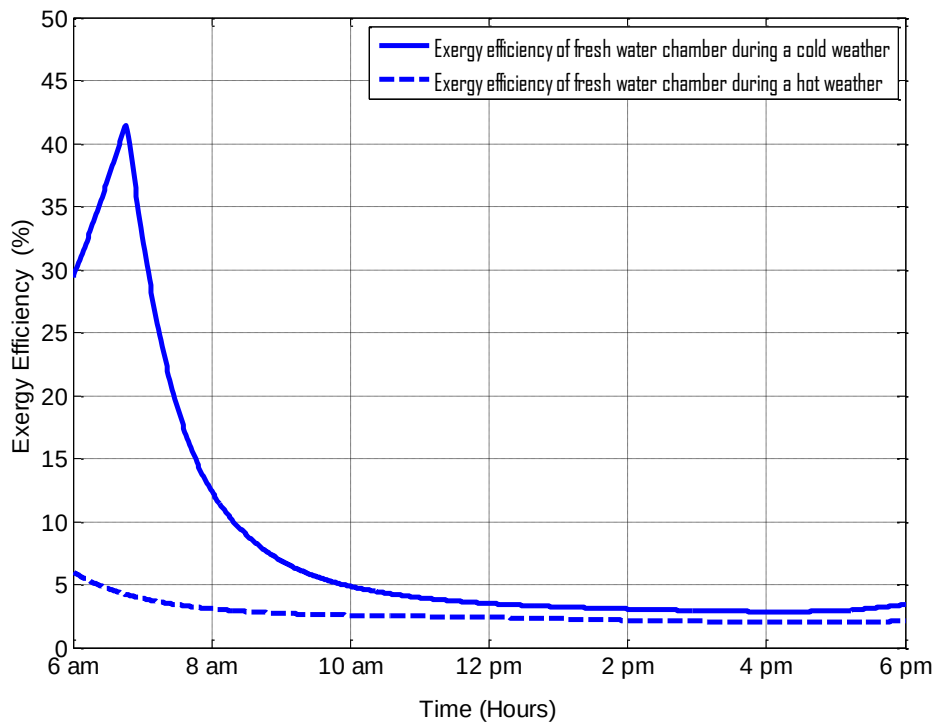


FIG. 4-31 Exergy efficiency of fresh water chamber for hot and cold weather

TABLE 4 shows the summary of the main variables' values of the NVD system.

TABLE 4 NVD system result summary for hot and cold weather

Parameter (Maximum Value)	Hot weather	Cold weather
Temperature (Saline, Fresh)	(43.84 °C, 30.57 °C)	(21.73 °C, 11 °C)
Pressure (Saline, Fresh)	(8867 Pa, 4327 Pa)	(2571Pa, 1319 Pa)
Evaporation rate	0.042 kg/hr	0.0121 kg/hr
Fresh water produced	0.54 kg	0.149 kg
Salts concentration	3.577%	3.521%
Thermal efficiency	44.58%	9.98%
Exergy efficiency (Saline, Fresh)	(5.44%, 6.02 %)	(0.375 %, 41.47%)

4.4 Sensitivity Analysis

In this section, a group of parameters' values were changed, and their effect on the main output variables was investigated. Solar irradiance for different saline water chamber sizes is shown in appendix (C).

4.4.1 Area analysis

The saline water chamber surface area is changed (the radius of the saline water cylinder is changed). The original surface area of evaporation is approximately 0.05 m^2 , three area values are to be investigated; 1, 2, and 3 m^2 .

FIG. 4-32 shows the effect of evaporation area on the saline water temperature, the saline water temperature decreases dramatically when the area is increased to 1 m^2 . Generally, as the area of evaporation surface increases the temperature of the saline water decreases, the cause for this decrease is the amount of saline water that is heated, as the radius of the saline water chamber increases, the volume of saline water increases which takes longer time and higher amount of energy to increase the temperature. The maximum temperature for 1, 2, and 3 m^2 surface area of evaporation is 36.86 , 35.47 , and $34.87 \text{ }^\circ\text{C}$ respectively.

The trend of the saline water temperature profile exhibits a triangular shape, during sunshine time, the temperature of the saline water experience a linear increase, a result of a continuous heat gain from the solar irradiance and hot surrounding air. For nocturnal hours, the absence of solar irradiance decreases the temperature of the saline water.

The effect of evaporation area is shown in FIG. 4-33, the fresh water temperature increases with increasing the evaporation area as a result of amount of vapor condensing in the fresh water chamber which in turn raises the temperature. The maximum temperature for 1, 2, and 3 m^2 surface area of evaporation is 32.69 , and

32.96, and 32.96 °C respectively. For 2 and 3 m² the temperature of the fresh water shows negligible difference between the two area configurations.

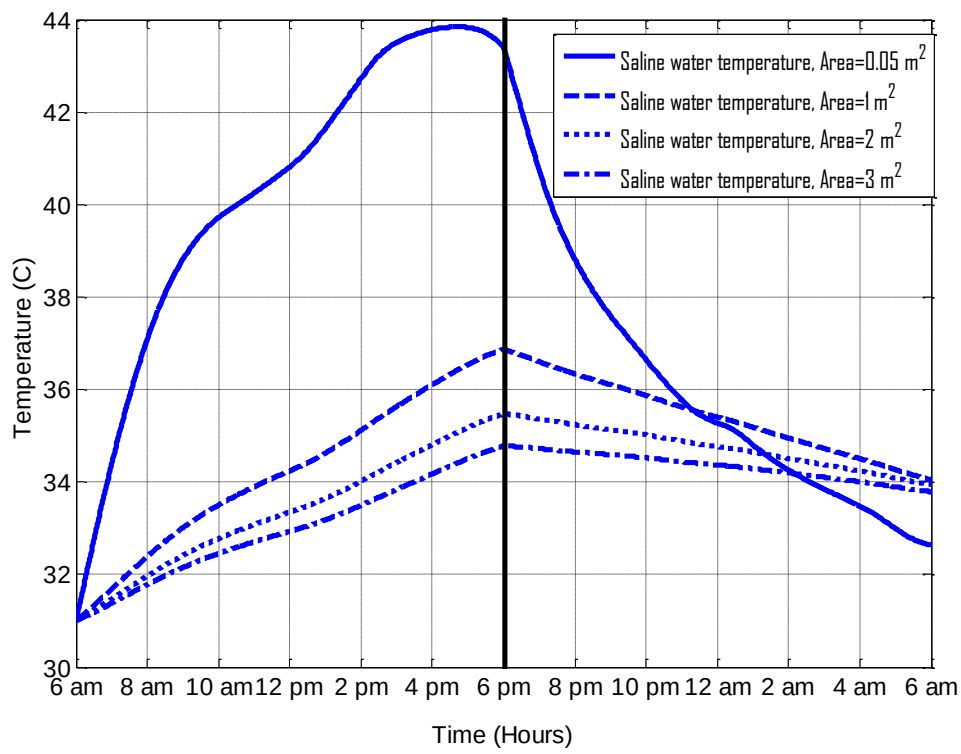


FIG. 4-32 Effect of evaporation area on the saline water temperature

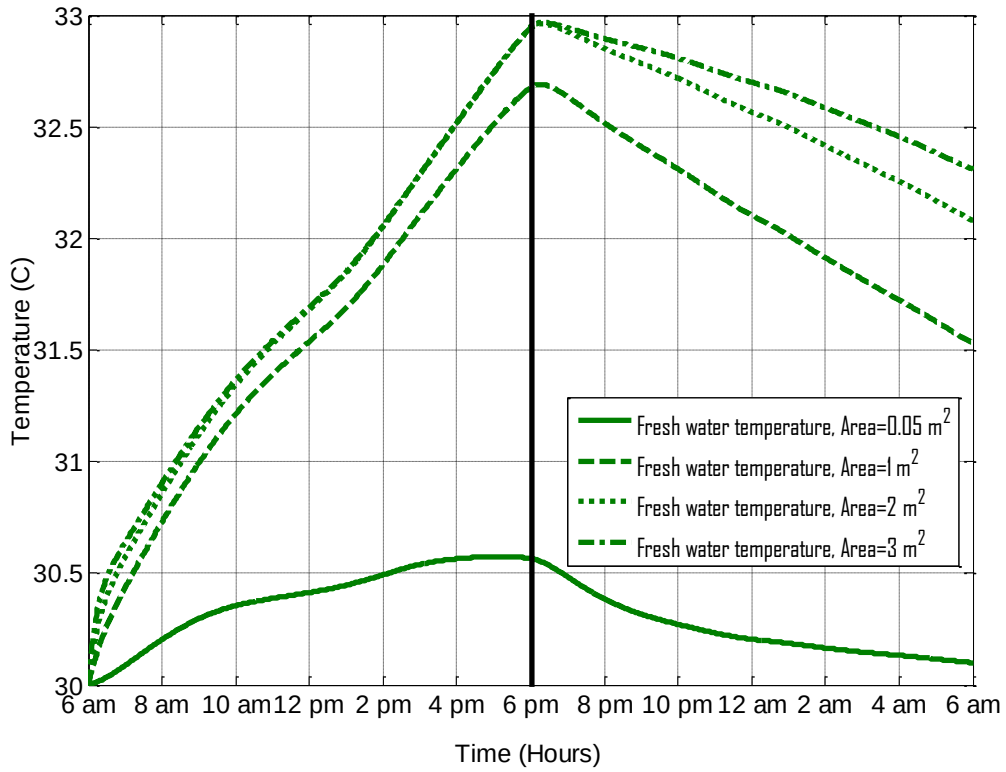


FIG. 4-33 Effect of evaporation area on the fresh water temperature

The effect of evaporation area on saline water vapor pressure is shown in FIG. 4-34, when increasing the area of evaporation the vapor pressure of saline water decreases, which is an expected outcome since the vapor pressure is a function of the saturated saline temperature. The profile pattern of vapor pressure confirm with their corresponding temperature profile shown in FIG. 4-32. The maximum pressure for 1, 2, and 3 m² surface area of evaporation is 6131, 5687, and 5475 Pa respectively. The vapor pressure decrease is attributed to the decreases of temperature.

The maximum fresh water vapor pressure (shown in FIG. 4- 35) for 1, 2, and 3 m² surface area of evaporation is 4877, 4951, and 4591 Pa respectively. The increase in vapor pressure is a result of increase in the fresh water temperature.

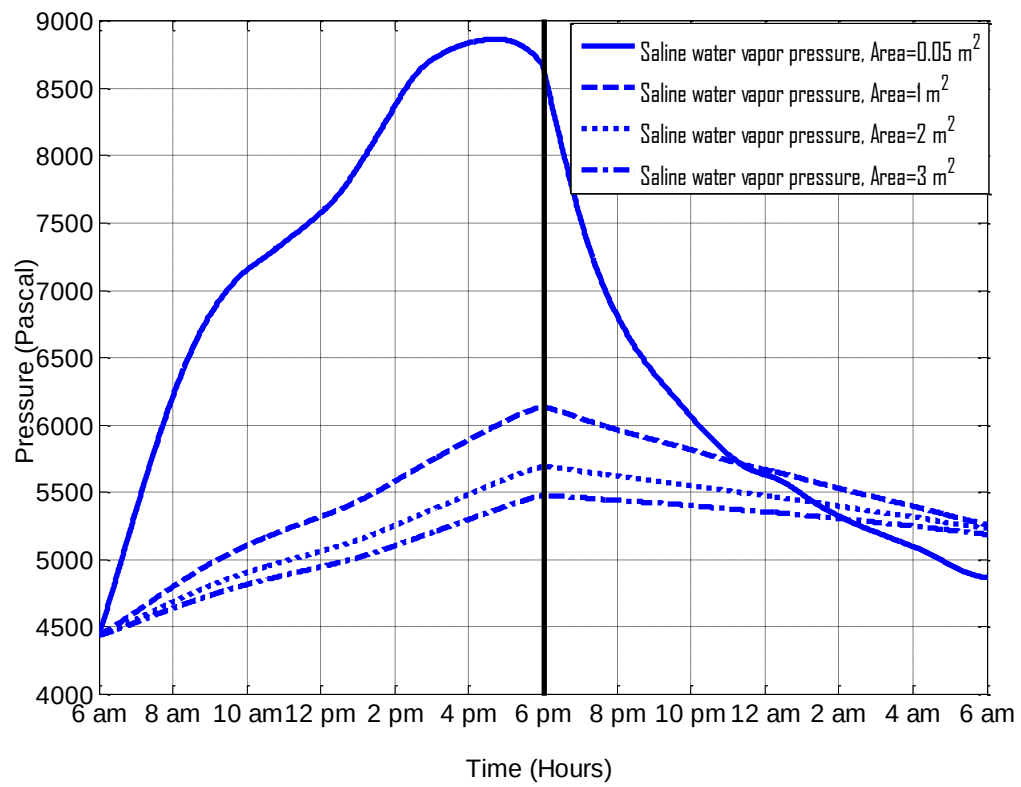


FIG. 4-34 Effect of evaporation area on the vapor pressure of saline water

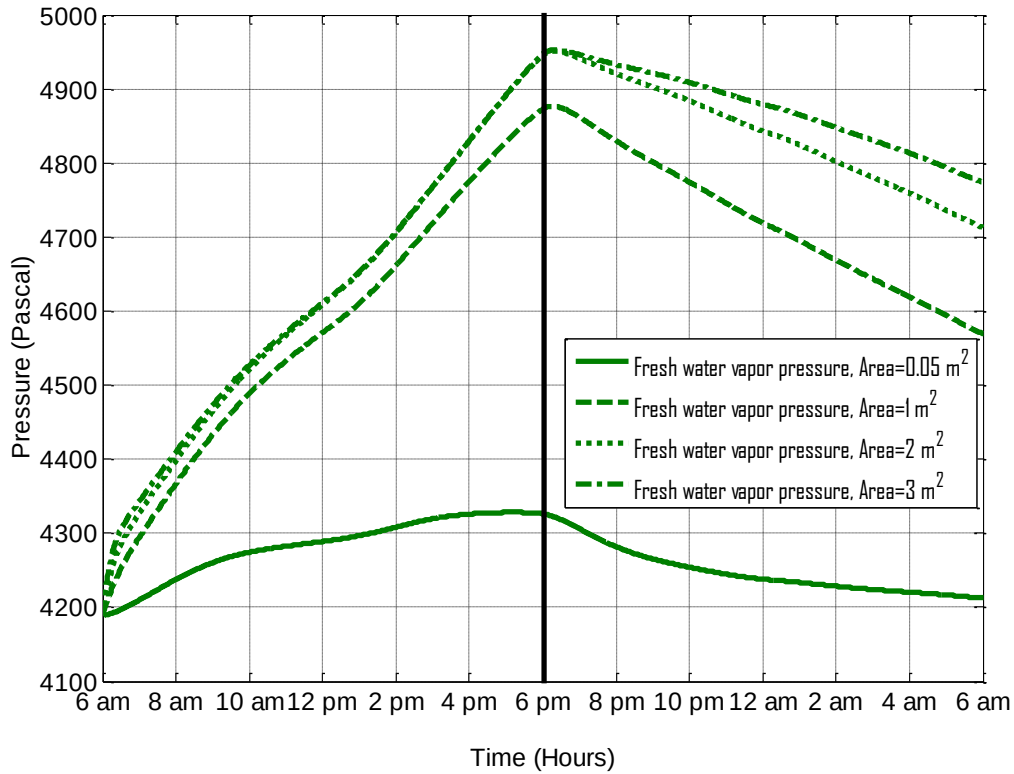


FIG. 4- 35 Effect of evaporation area on vapor pressure of fresh water

FIG. 4-36 shows the effect of evaporation area on evaporation rate. Generally, the evaporation rate increases with increasing the area of evaporation, the maximum evaporation rate for 1, 2, and 3 m² surface area of evaporation is 0.2269, 0.2524, and 0.2530 kg/hr. From FIG. 4-36, it is clear that the evaporation rate difference between the 1m² and 2m² is higher than the difference between 2m² and 3m², hence increasing the area after 2m² gives relatively less enhancement regarding the rate of evaporation, this can also be seen from the evaporation rate for 2m² and 3m² areas, where the 3m² has a slight margin of increase in the evaporation over the 2m² during the sunshine time. The reason behind the 2m² and 3m² areas evaporation rate minor difference is the temperature difference of saline water between the two areas, the maximum difference occurring at the sunset time is less than 1 °C.

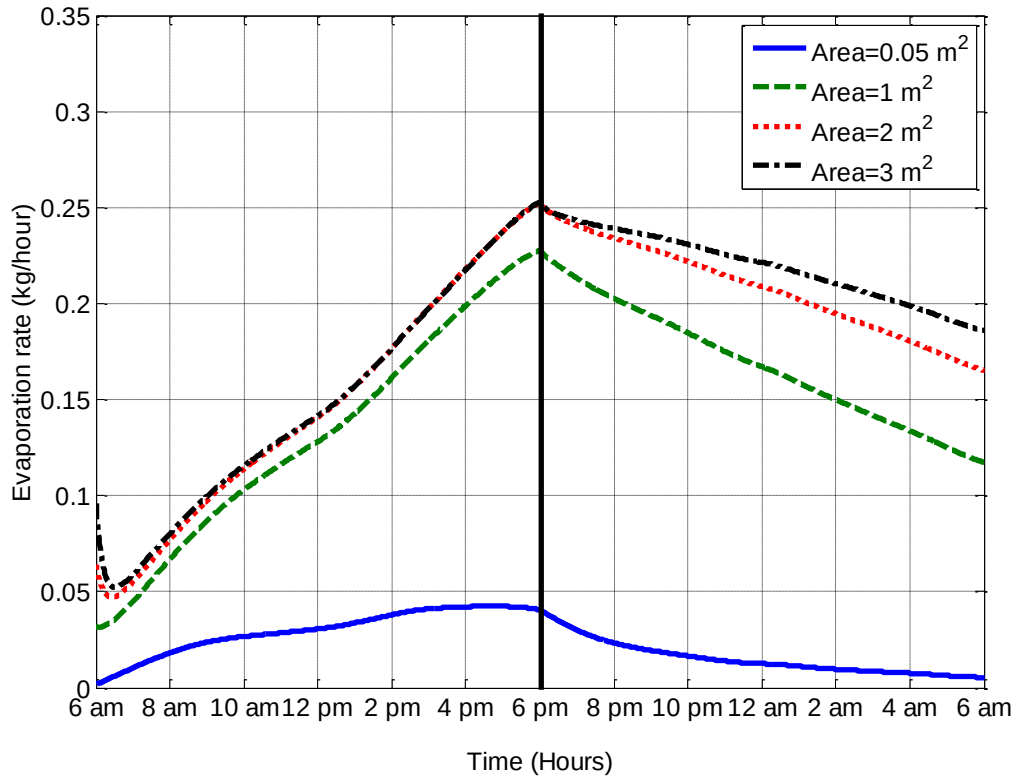


FIG. 4-36 Effect of evaporation area on evaporation rate

The amount of collected fresh water is shown in FIG. 4-37, the amounts are 3.60, 4.24, and 4.38 kg/day for 1, 2, and 3 m² surface area of evaporation. Al-Karaghoul (Al-Karaghoul & Alnaser, 2004) reported 2.84 kg/m².day of fresh water production during summer time for a conventional single solar still, the present NVD system enhances the yield of fresh water produced by 21.11%.

In FIG. 4-37, increasing the area from 1m² to 2m² increases the output by 15.09%, and increasing the area from 2 m² to 3 m² increases the output by 3.20%, hence increasing the area more than 2 m² lead to no significant increase in output.

To validate the results of the current model, fresh water output produced using 1 m² of evaporation surface area is compared to the results of the studies mentioned in the literature review. This model can produce up to 3.6 kg/m².day compared to 4.9 kg/m².day production reported by Veeragnaneswar (Veeragnaneswar &

Nermalakhandan, 2007) and $6.5 \text{ kg/m}^2 \cdot \text{day}$ production reported by Al-Kharabsha (Al-Kharabsha & Goswami, 2003), the difference is due to the considerable lower efficiency of the current configuration studied compared to Veeragnaneswar's unit efficiency which achieved a maximum of 80%. Additionally, Al-Kharabsha's unit was coupled with a solar collector, which enhanced the performance of the desalination unit. FIG. 4-38 shows the evaporation rate comparison between the current configuration and Veeragnaneswar's unit. Both evaporation rates have the same trend; the large difference between the two results is attributed to the thermal efficiency, the current configuration produces more fresh water than Veeragnaneswar's unit during nocturnal hours because the current system stores more water due to the higher depths of saline water, hence, the more energy stored to be utilized for desalination.

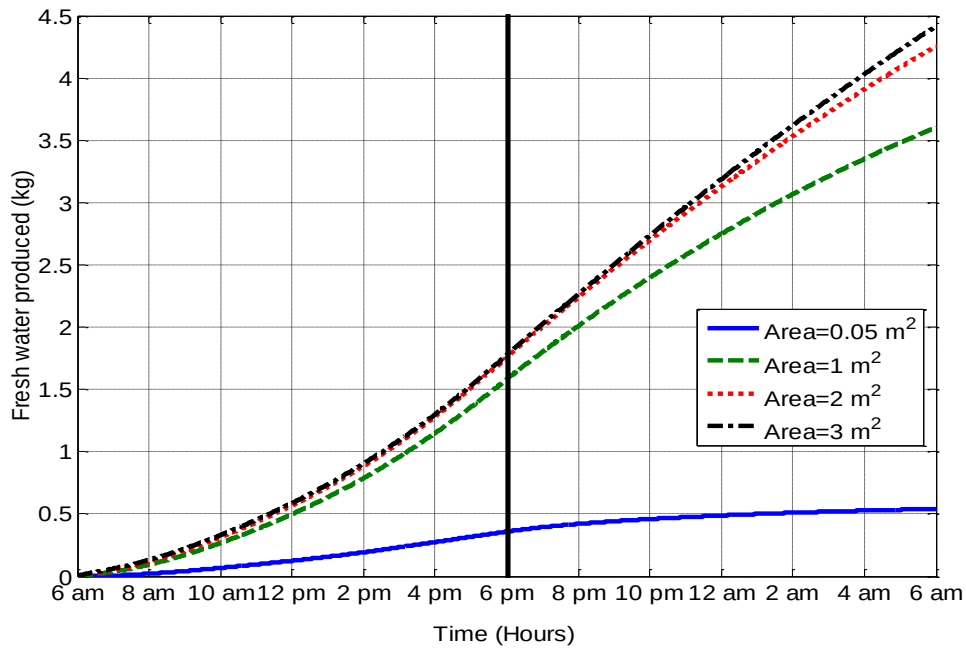


FIG. 4-37 Effect of evaporation area on fresh water production

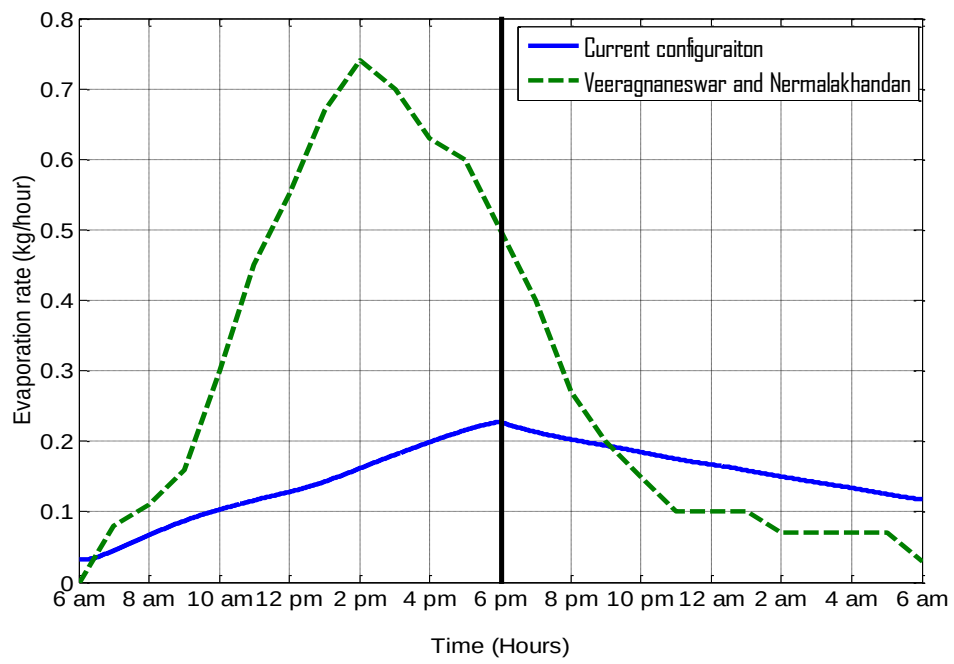


FIG. 4-38 Comparison between the current configuration of this study and Veeragnaneswar's

FIG. 4-39 shows the effect of evaporation area on salts concentration, as the area increases, the mass inside of saline water increases, thus, the change in salts concentration with is less. The concentration at the end of 24 hours run for 1, 2, and 3 m² surface area of evaporation is 3.525, 3.515, and 3.510% respectively.

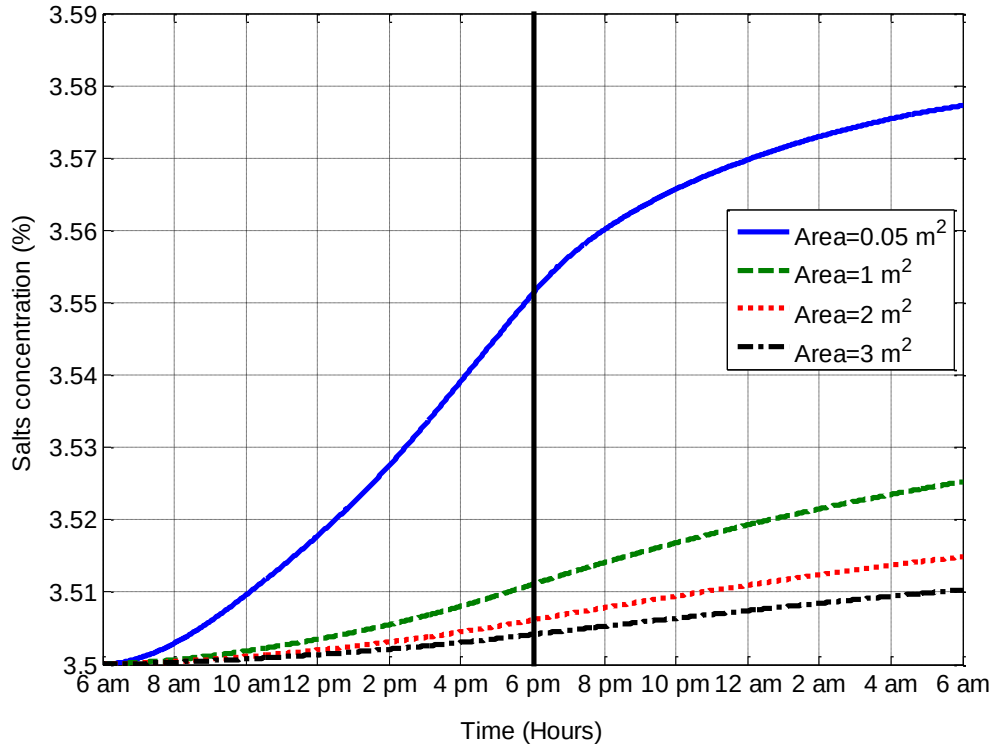


FIG. 4-39 Effect of evaporation area on salts concentration

The effect of evaporation area on thermal efficiency is shown in FIG. 4-40, increasing the area decreases the thermal efficiency, in spite of the increase in output of vapor when increasing the surface area of saline water chamber, the ratio of increase in solar irradiance is higher than of it in the vapor produced, i.e., as the area increases the ratio between the vapor produced as an output and the solar irradiance as an input increases as well. From FIG. 4-40 the thermal efficiency for 1, 2, and 3 m² surface area of evaporation is 27.71, 21.06, and 17.56% respectively.

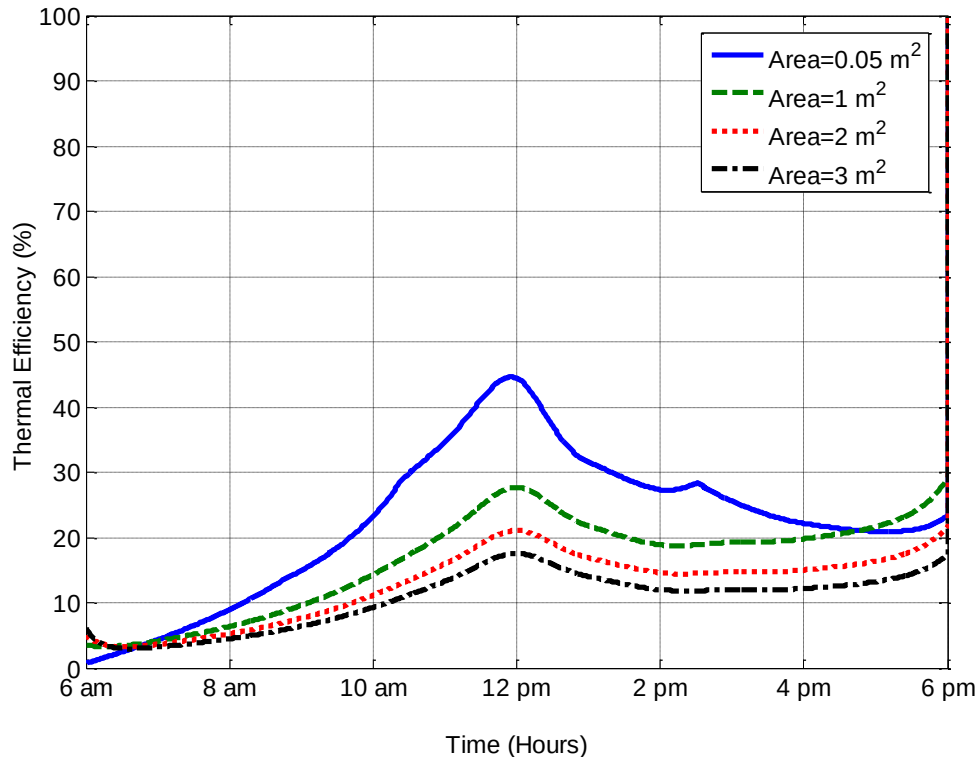


FIG. 4-40 Effect of evaporation area on thermal efficiency

FIG. 4-41 shows the effect of evaporation area on exergy efficiency of saline water chamber. It's clear from FIG. 4-41 that the exergy efficiency drops when increasing the surface area of evaporation, the maximum efficiency for 1, 2, and 3 m² surface area of evaporation is 3.42, 2.15, and 1.68%, the low value of exergy efficiency are a result of great amount of solar irradiance exergy destruction and loss, increasing the area provide an increase in the solar irradiance which is not fully utilized.

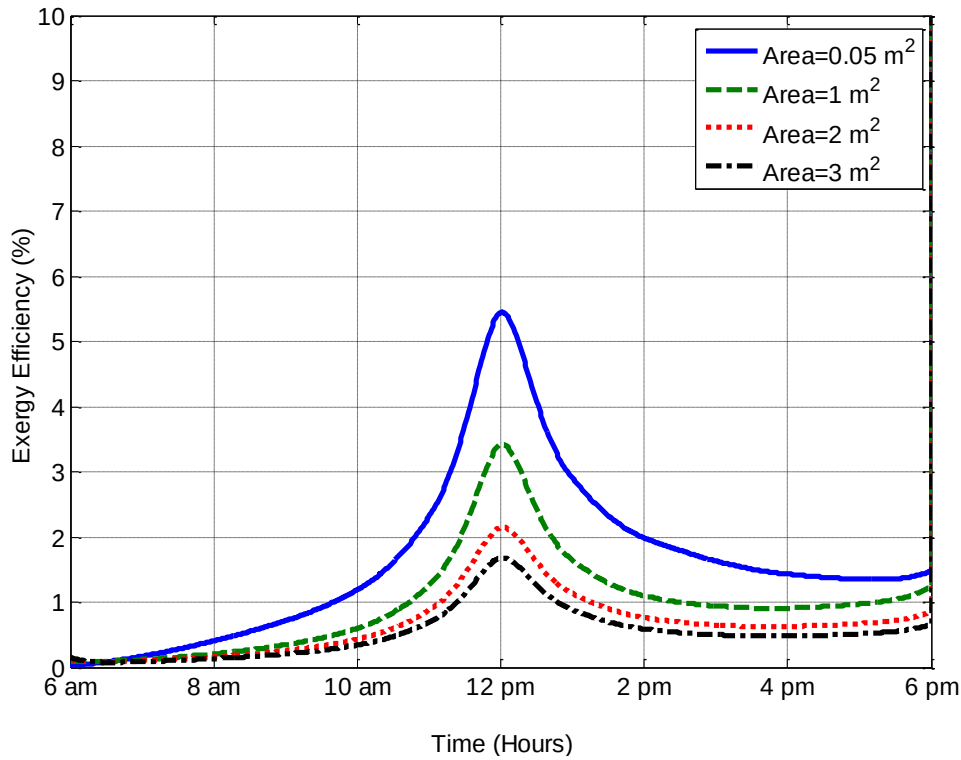


FIG. 4-41 Effect of evaporation area on exergy efficiency of saline water chamber

The effect of evaporation area on exergy efficiency of fresh water chamber is shown in FIG. 4-42, generally as the area of surface evaporation increases the exergy efficiency of the fresh water chamber increases, the cause of the increase is the exergy of vapor entering the fresh water chamber, although the relatively higher amount of vapor is produced, the exergy content of vapor produced by each area is different, higher areas produce higher amount of vapor, but vapor with lower temperature, thus the percentage of exergy efficiency enhancement decreases. The minimum exergy efficiency for 1, 2, and 3 m² surface area of evaporation is 3.37, 3.83, and 4.09%.

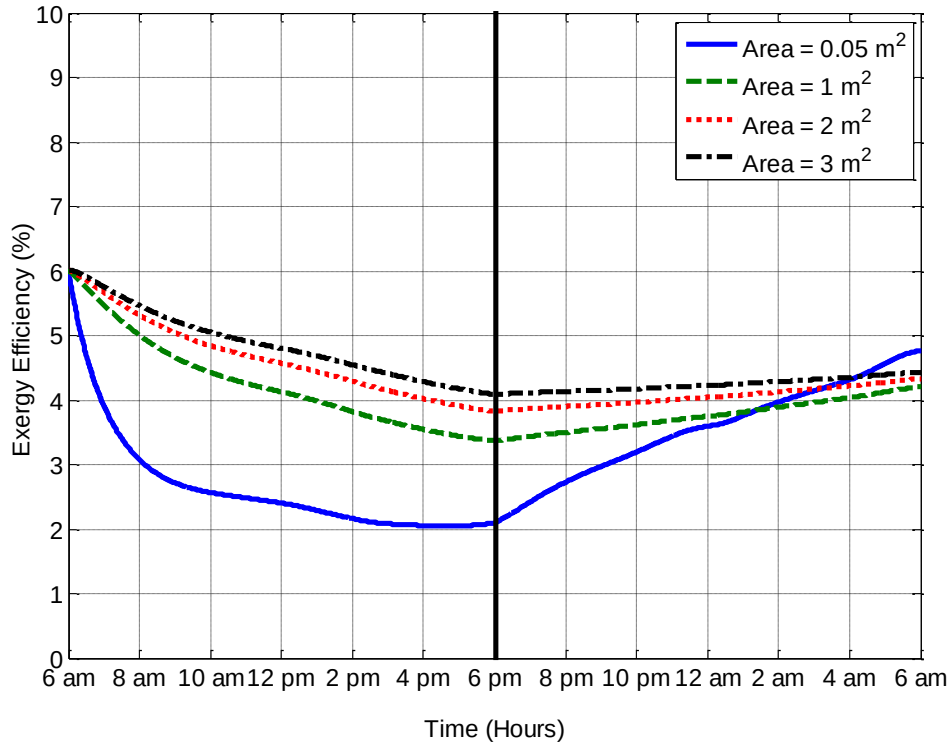


FIG. 4-42 Effect of evaporation area on exergy efficiency of fresh water chamber

4.4.2 Depth analysis

The depth of saline water is changed from 0.5 to 0.1 m, and the effect on the main variables is investigated in this section.

FIG. 4-43 shows the effect of depth on saline water temperature. The saline water temperature decreases with decreasing the depth of saline water, decreasing the depth of saline water will decrease the area subjected to the solar irradiance, thus, the temperature of saline water is less. The maximum temperature of saline water for 0.4, 0.3, 0.2, and 0.1m saline water depth is 43.23, 42.53, 41.35, and 39 °C respectively.

The change in fresh water temperature when changing the depth of saline water is relatively small (shown in FIG. 4-44), decreasing the depth of saline water lowers its

temperature, and evaporation rate gets lower with lowering saline water temperature, thus, less vapor enters the fresh water chamber to raise its temperature.

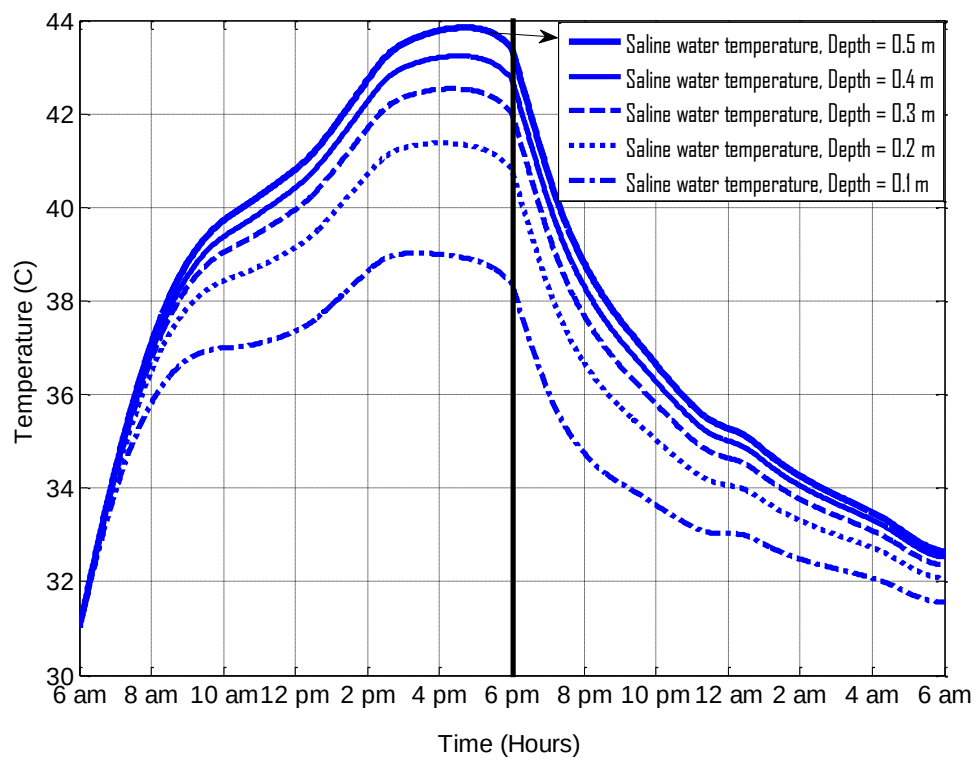


FIG. 4-43 Effect of depth on saline water temperature

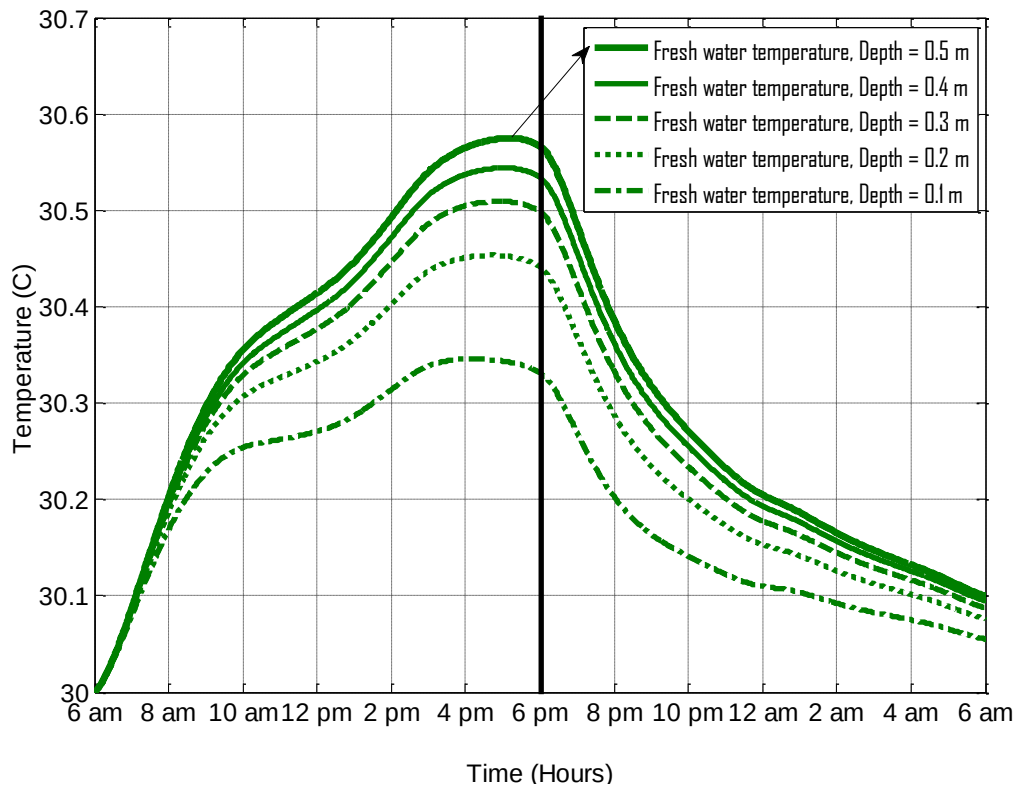


FIG. 4-44 Effect of depth on fresh water temperature

FIG. 4-45 shows the effect of depth on saline water vapor pressure. The vapor pressure of both saline and fresh decreases with decreasing the depth, the pressure is affected by the temperature decrease, hence the lower the temperature the lower the vapor pressure. The maximum vapor pressure for 0.4, 0.3, 0.2, and 0.1 m saline water depth is 8593, 8288, 7800, and 6864 Pa respectively. The vapor pressure of fresh water (shown in FIG. 4-46) decreases slightly as its temperature decreases as well.

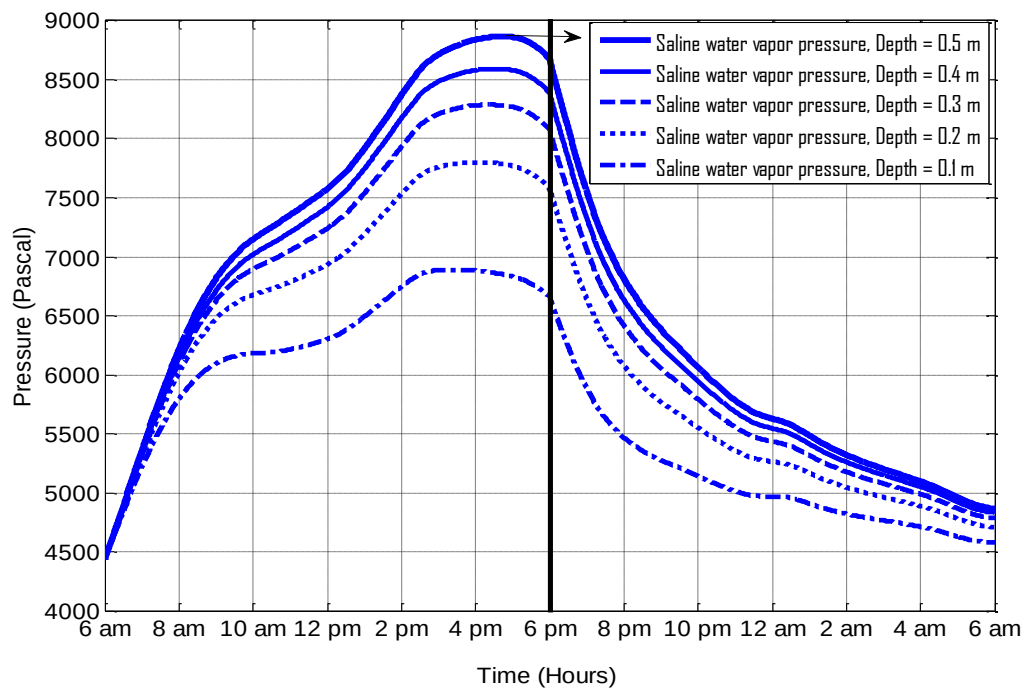


FIG. 4-45 Effect of depth on saline water vapor pressure

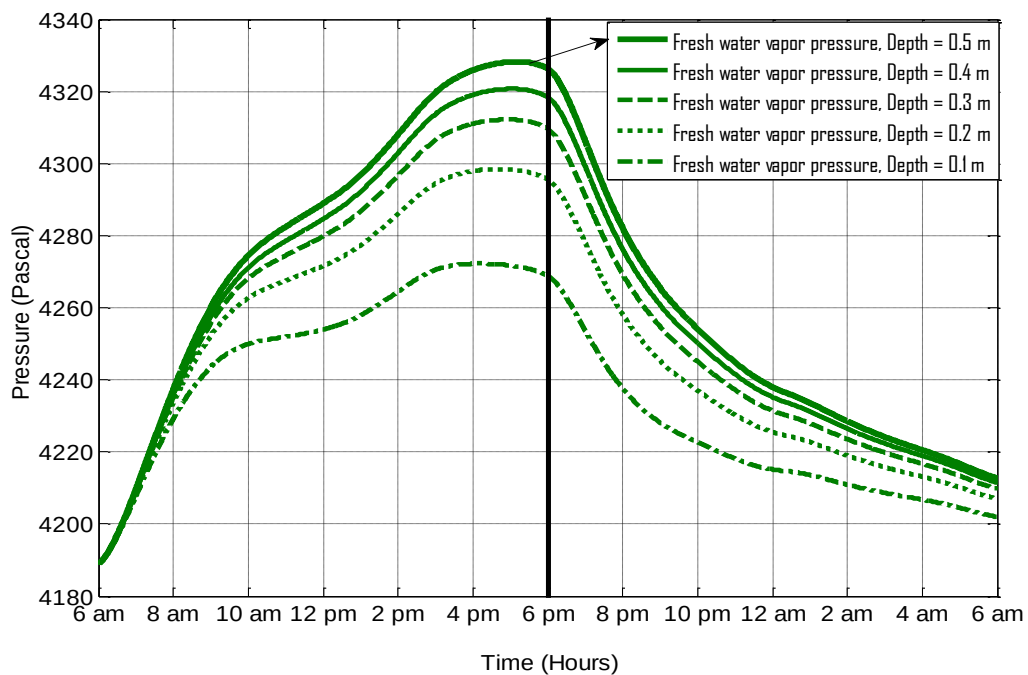


FIG. 4-46 Effect of depth on fresh water vapor pressure

The effect of depth is on evaporation rate is shown in FIG. 4-47, decreasing the depth of saline water decreases the evaporation rate, caused by the decrease of saline

water temperature. The maximum evaporation rate for 0.4, 0.3, 0.2, and 0.1m saline water depth is 0.040, 0.037, 0.033, and 0.024 kg/hr respectively.

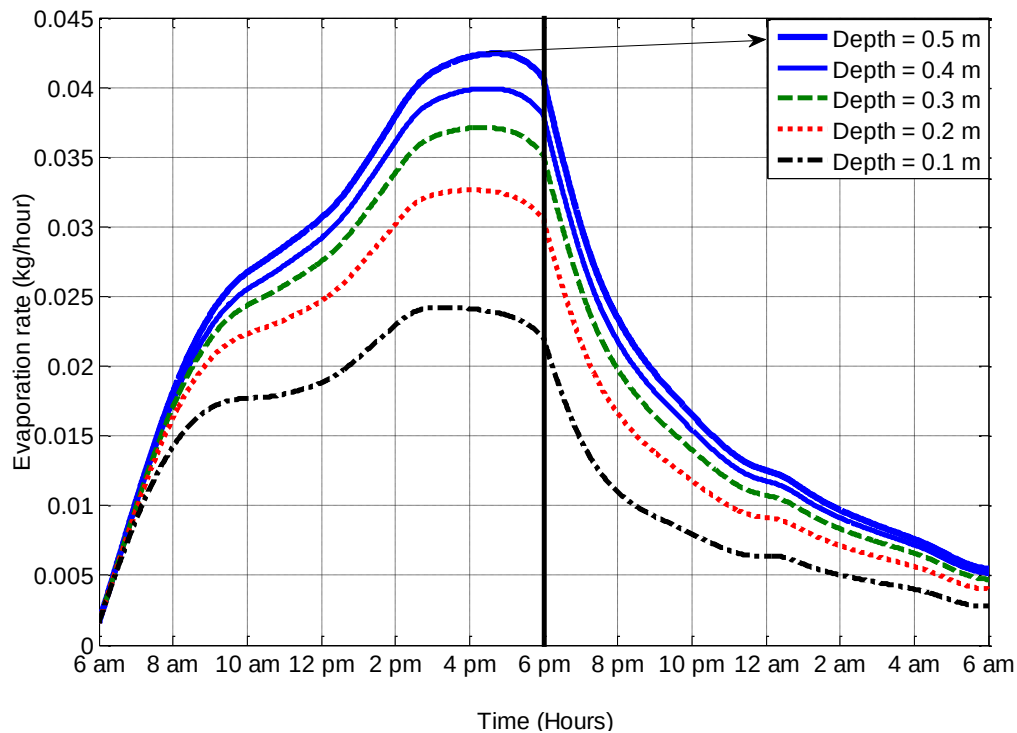


FIG. 4-47 Effect of depth on evaporation rate

FIG. 4-48 shows the effect of depth on fresh water production, it's clear that decreasing the depth results in reduction of fresh water, the cause of the output reduction is the decrease of evaporation rate as a result of decreasing saline water temperature. The production of fresh water for 0.4, 0.3, 0.2, and 0.1m saline water depth is 0.511, 0.476, 0.421, and 0.313 kg respectively.

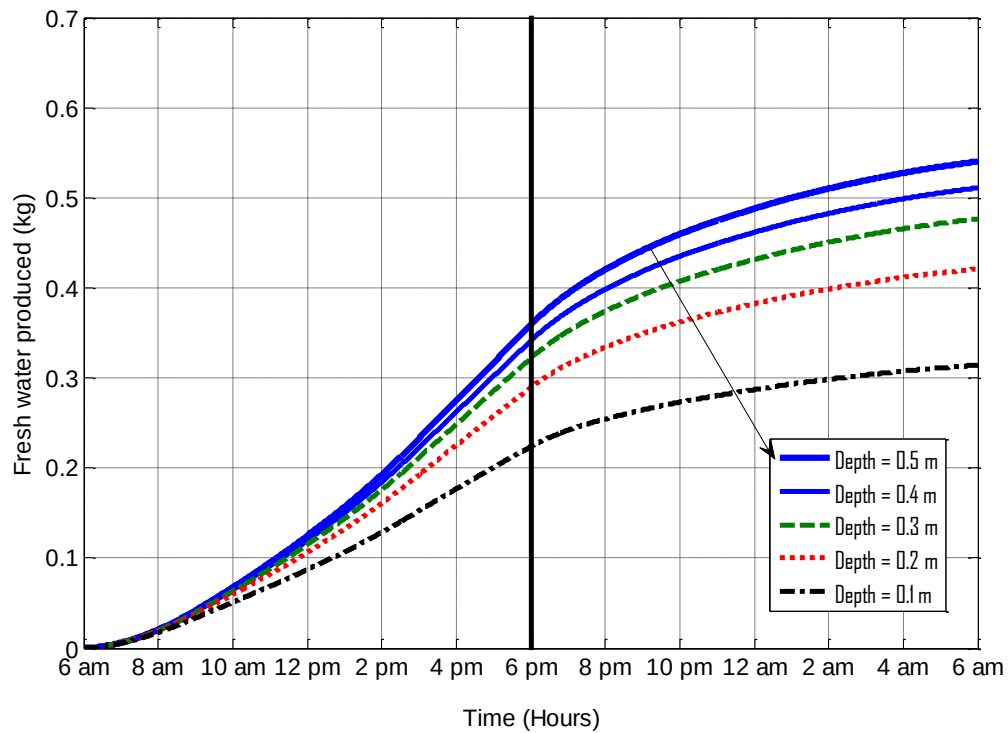


FIG. 4-48 Effect of depth on fresh water production

As the saline water evaporates, the salts concentration will increase, FIG. 4-49 show the effect of depth on salts concentration, when the depth decreases, the amount of saline water decreases, in spite of the decreases of evaporation rate when the depth is decreases. As the depth is decreased the rate of salts concentration is higher compared to the lower amount of saline water it accumulates in. The salts concentration for 0.4, 0.3, 0.2, and 0.1m saline water depth is 3.591, 3.613, 3.650, and 3.724% respectively.

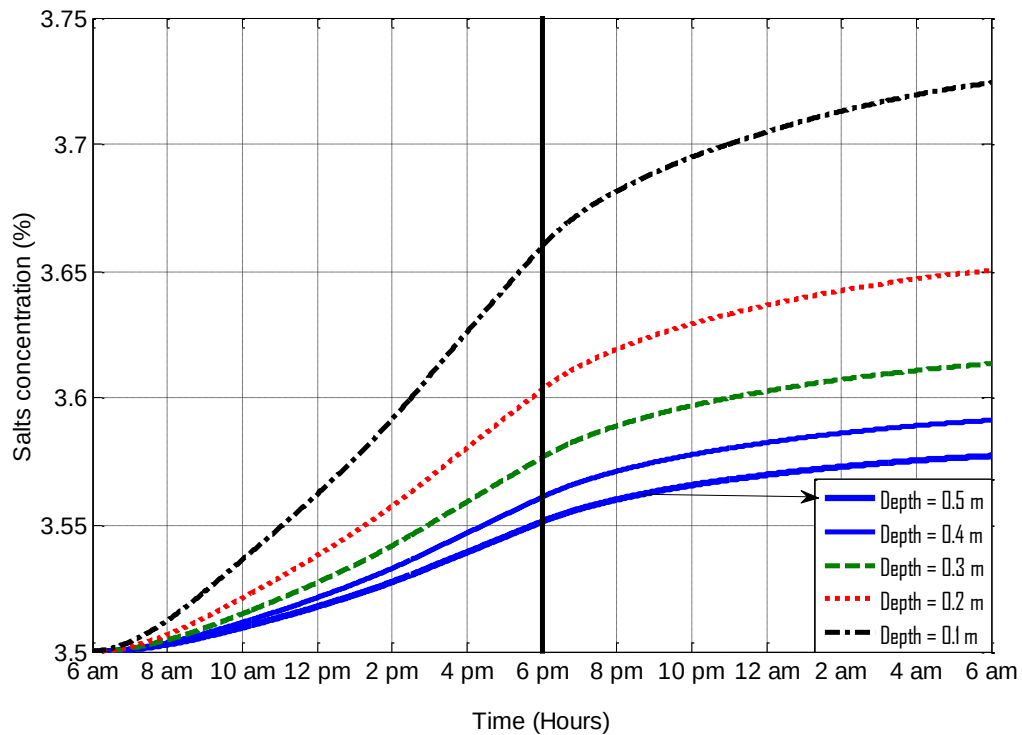


FIG. 4-49 Effect of depth on salts concentration

When the depth decreases, the thermal efficiency of the saline water chamber increases as shown in FIG. 4-50, the increase in thermal efficiency can be attributed to the amount of energy utilized, for lower depths the effect of solar irradiance as the main source of energy becomes less, and the heat entering the saline water chamber from the air becomes the main contributor, i.e. the portion of energy in form the surrounding air is higher than of it for solar irradiance for lower depths. As the salts concentration increases dramatically with decreasing the saline water depth, the need for withdrawing and changing the saline water becomes significant, since the increases in salinity decreases the evaporation rate, thus, the lower the depth the more frequent the saline water must be changed.

The maximum thermal efficiency for 0.4, 0.3, 0.2, and 0.1m saline water depth is 49.74, 57.20, 67.04, and 79.85% respectively.

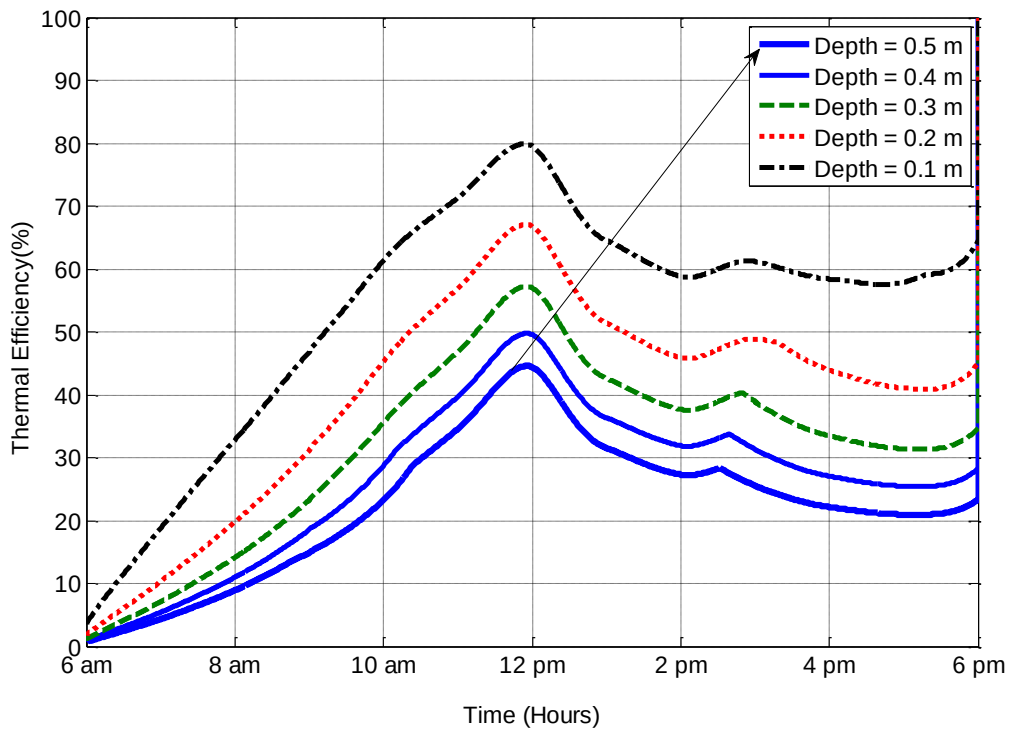


FIG. 4-50 Effect of depth on thermal efficiency

FIG. 4-51 and FIG. 4-52 show the effect of depth on saline and fresh water exergy efficiency, respectively. Exergy efficiency of saline water chamber increases with decreasing the depth of saline water inside the chamber, because the solar irradiance is no longer the main source of energy supplied, and its exergy decreases with decreasing depth (as a result of decreasing the area subjected to the solar irradiance), the exergy of heat supplied from the surrounding air has is less destroyed in the chamber wall than the solar exergy. The maximum exergy efficiency of saline water chamber for 0.4, 0.3, 0.2, and 0.1m saline water depth is 6.51, 7.88, 9.86, and 12.97% respectively.

The exergy efficiency of the fresh water chamber experience an increase as the depth of saline water decreases, the evaporation rate decreases and the amount of vapor entering the fresh water chamber decreases when decreasing the depth of saline water, which results in less destruction of vapor exergy, additionally, the lower amounts of vapor reaching the fresh water chamber have lower exergy content because of its low

temperature. The minimum exergy efficiency at the end of sunshine time for 0.4, 0.3, 0.2, and 0.1m saline water depth is 2.11, 2.19, 2.33, and 2.66% respectively.

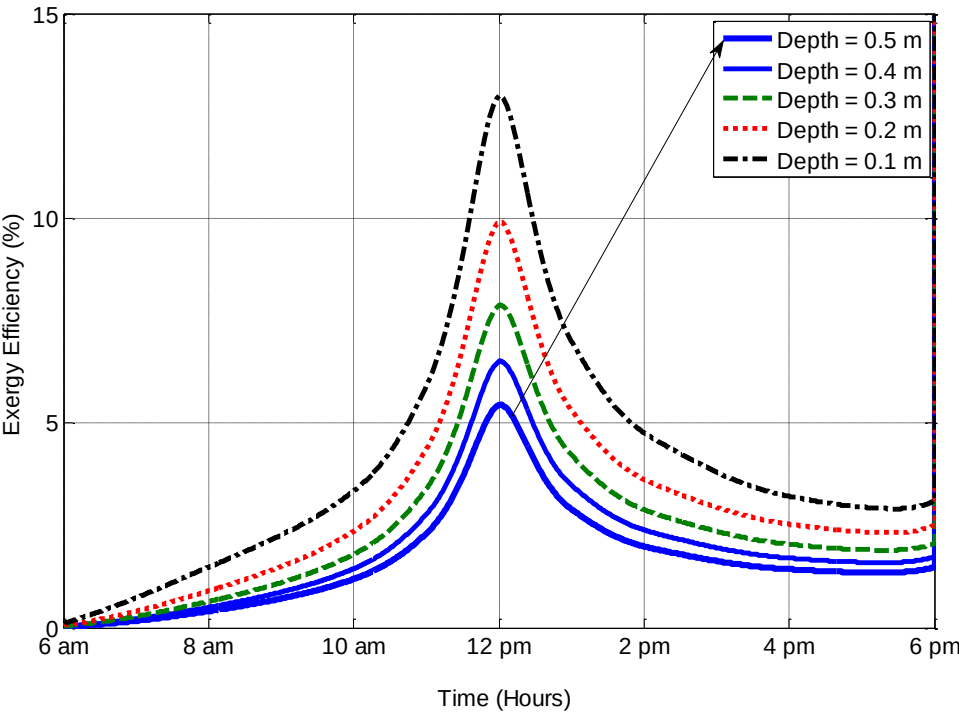


FIG. 4-51 Effect of depth on saline water chamber exergy efficiency

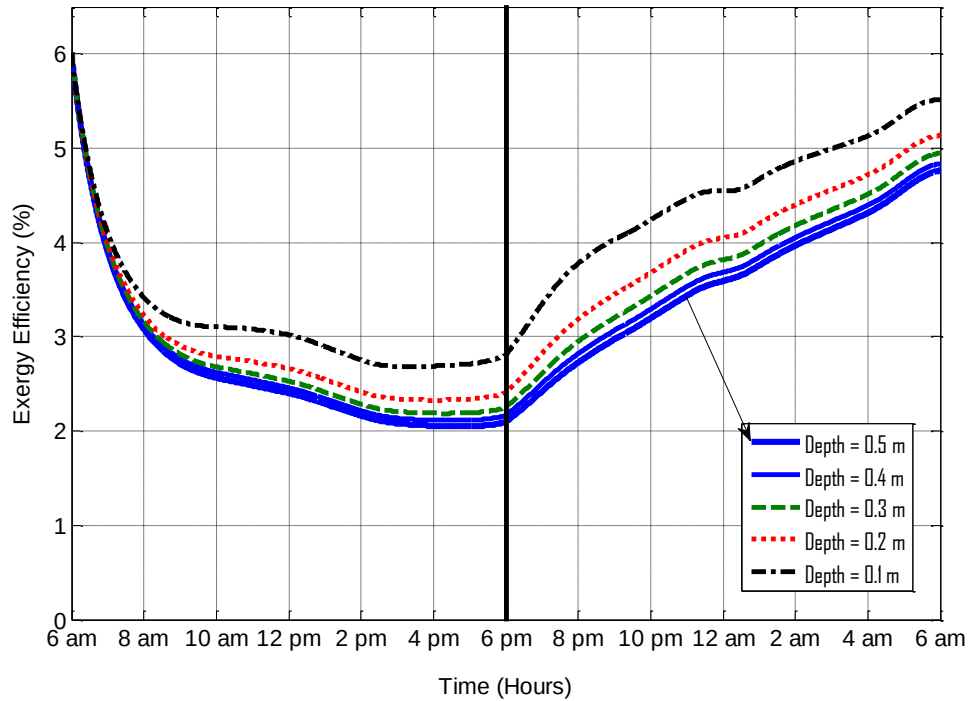


FIG. 4-52 Effect of depth on fresh water chamber exergy efficiency

4.4.3 Temperature of cooling water analysis

The temperature of the water used to cool the fresh water chamber is studied in this section. The temperature of 28 and 26 °C are used in the subsequent analysis.

FIG. 4-53 shows the effect of cooling water temperature on fresh water temperature, the freshwater temperature is decreased when decreasing the cooling water temperature, the maximum fresh water temperature for 28 and 26 °C cooling water temperature is 28.63 and 26.69 °C respectively.

The saline water temperature (shown in FIG. 4-54) decreases slightly with decreasing the cooling water temperature, the minor changes are attributed to the evaporation rate, as the temperature difference between the two chambers is increased, the evaporation rate increases, which results in more loss in energy (latent heat) from the saline water chamber, which drives the saline water temperature down.

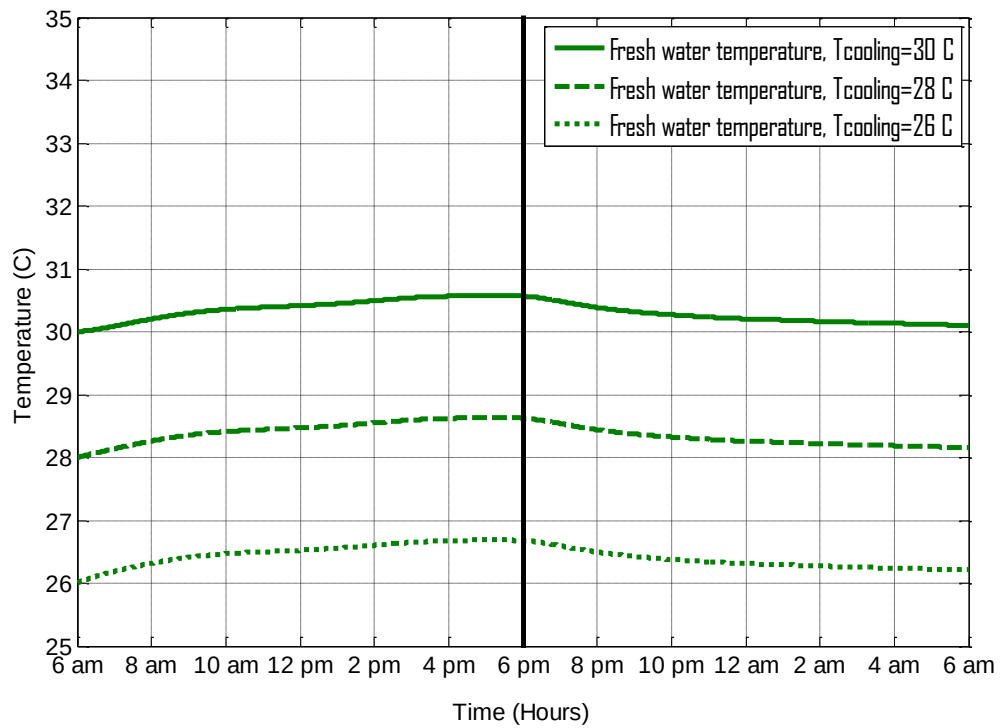


FIG. 4-53 Effect of cooling water temperature on fresh water temperature

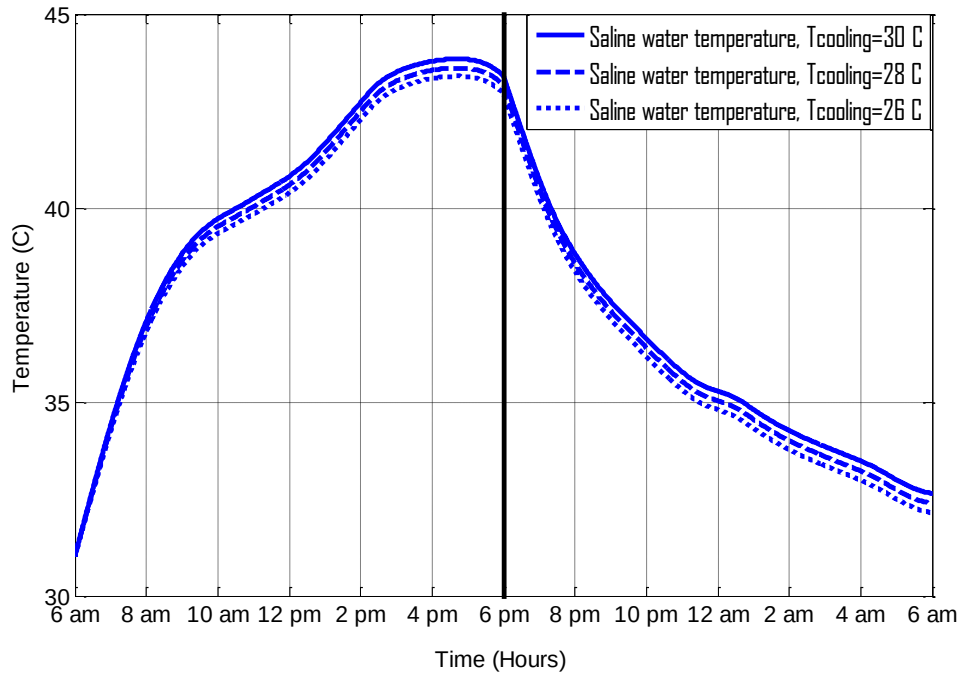


FIG. 4-54 Effect of cooling water temperature on saline water temperature

The effect of decreasing the cooling temperature on vapor pressure of saline and fresh water is similar to that of it on the temperature shown in FIG. 4-53 and FIG. 4-54. In FIG. 4-55 the effect of cooling water temperature on vapor pressure on fresh water is shown, the fresh water vapor pressure decreases as a result of its temperature decrease, and the saline water vapor pressure also decreases slightly (shown in FIG. 4- 56). The maximum vapor pressure of fresh water for 28 and 26 °C cooling water temperature is 3872 and 3458 Pa respectively.

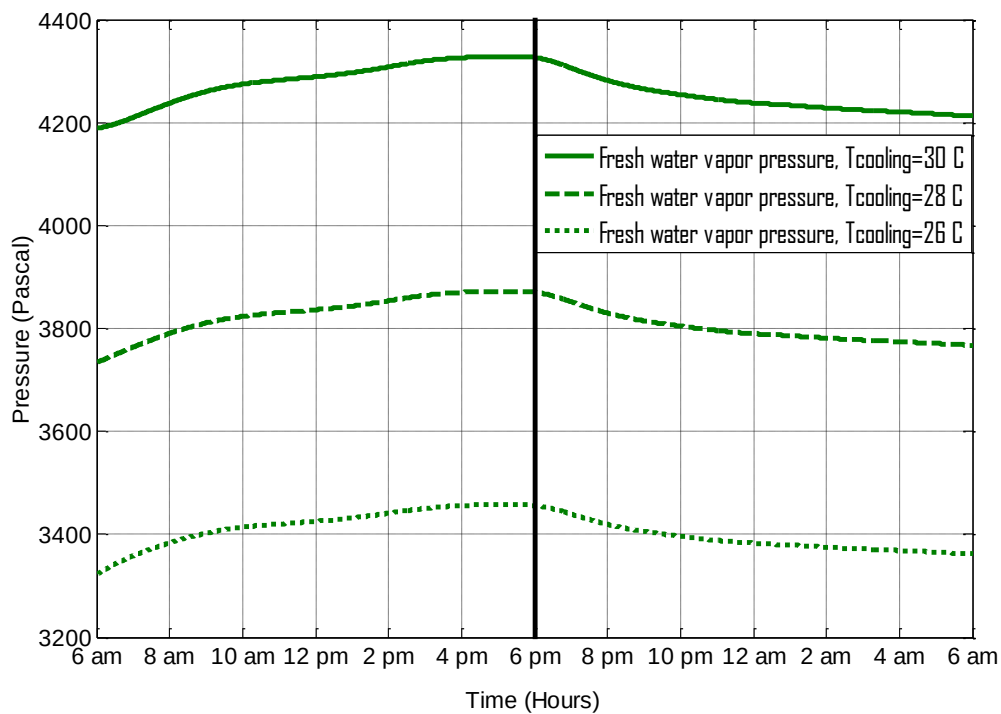


FIG. 4-55 Effect of cooling water temperature on vapor pressure of fresh water

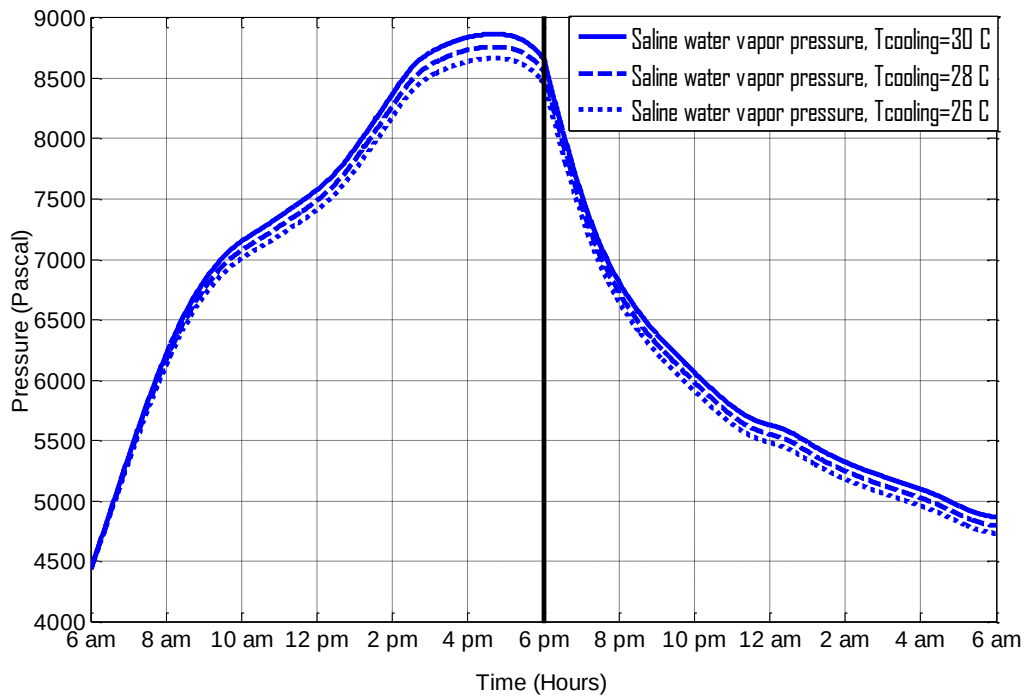


FIG. 4- 56 Effect of cooling water temperature on vapor pressure of saline water

FIG. 4-57 shows the effect of cooling water temperature on evaporation rate, as expected the rate increases with decreasing the cooling water temperature as a result of increasing the temperature difference between the saline and fresh water chambers. The maximum evaporation rate for 28 and 26 °C cooling water temperature is 0.0459 and 0.0491 kg/hr respectively.

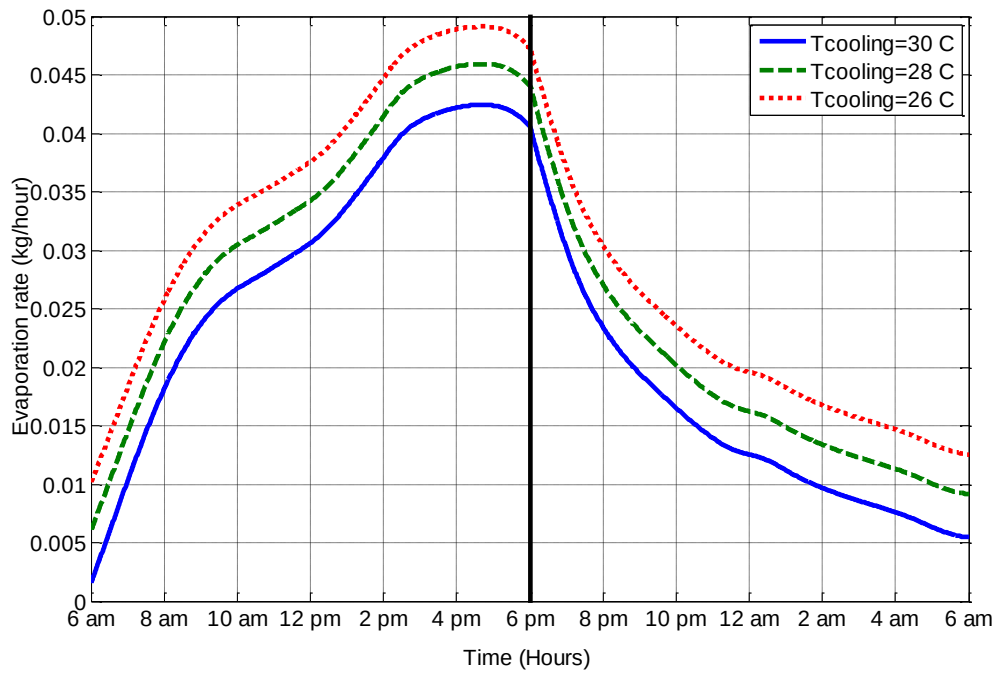


FIG. 4-57 Effect of cooling water temperature on evaporation rate

The effect of cooling water temperature on fresh water production is shown in FIG. 4-58, the amount produced for 24 hours of run time increases with decreasing the cooling water temperature as a result of the increased evaporation rates. The maximum amount of fresh water collected for 28 and 26 °C cooling water temperature is 0.629 and 0.710 kg.

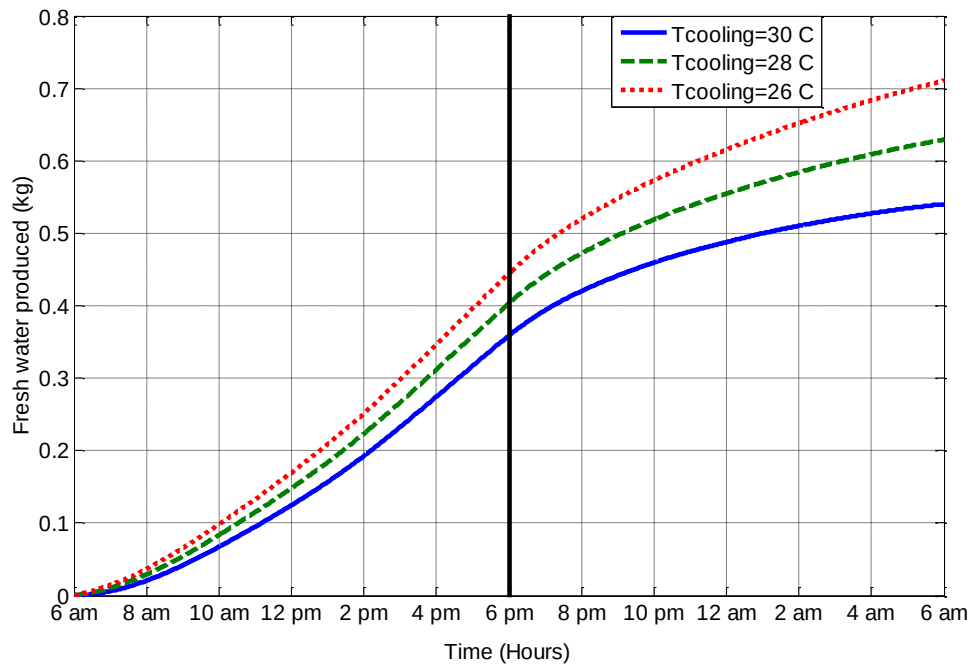


FIG. 4-58 Effect of cooling water temperature on fresh water production

Increasing the cooling load (by decreasing the cooling water temperature) results in increased fresh water production and increase in salts concentration. FIG. 4-59 shows the effect of cooling water temperature on salts concentration. The salts concentration increases slightly with decreasing the cooling water temperature, at the end of 24 hours run time, the salts concentration for 28 and 26 °C cooling water temperature is 3.59 and 3.60% respectively.

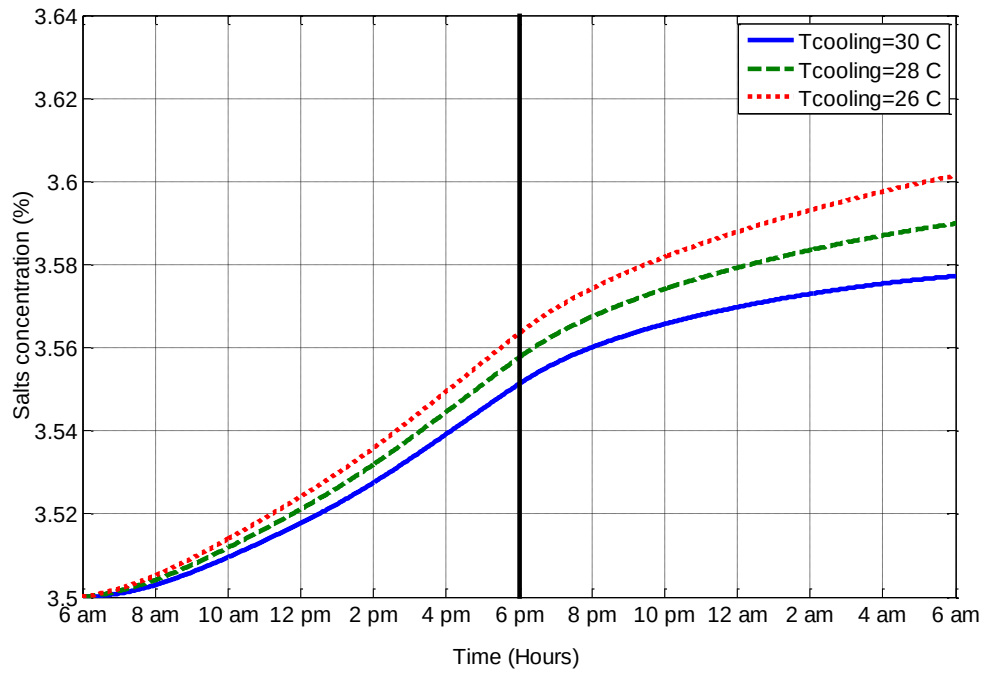


FIG. 4-59 Effect of cooling water temperature on salts concentration

The increase in production of fresh water results in a moderate increase in the thermal efficiency of the saline water chamber as seen in FIG. 4-60, where the output of the saline water chamber increases while the energy input (solar irradiance and surrounding) remains constant. The maximum efficiency for 28 and 26 °C cooling water temperature is 47.68 and 50.28% respectively.

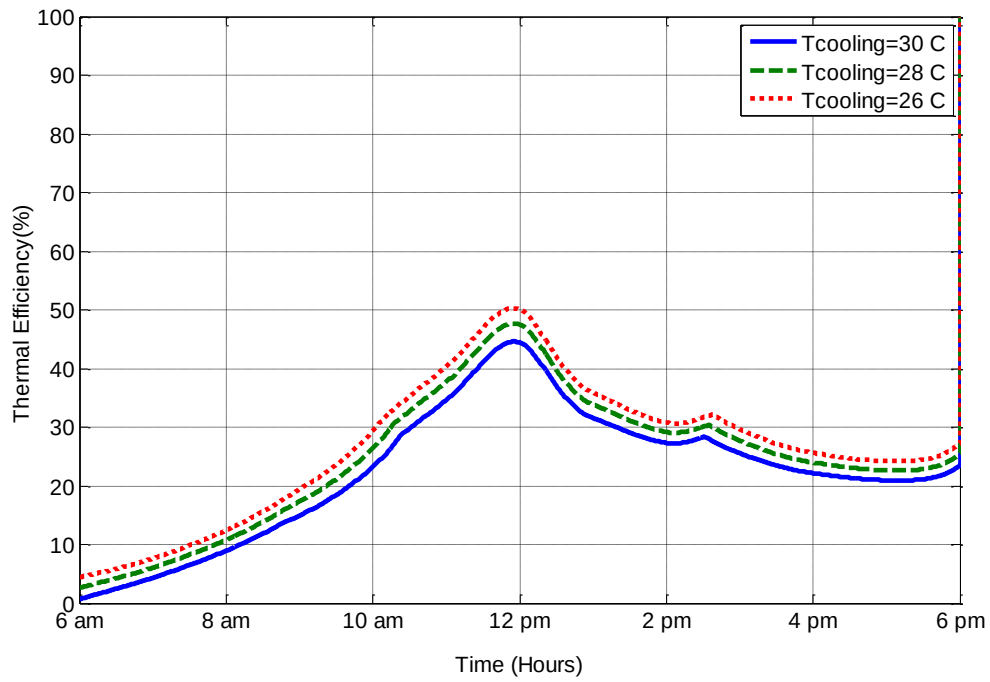


FIG. 4-60 Effect of cooling water temperature on thermal efficiency

The effect of cooling water temperature on exergy efficiency of saline water chamber is shown in FIG. 4-61, it is clear that decreasing the temperature of the cooling water increases the exergy efficiency, a result driven by an increase in vapor produced. The maximum exergy efficiency for 28 and 26 °C cooling water temperature is 5.985 and 6.485% respectively.

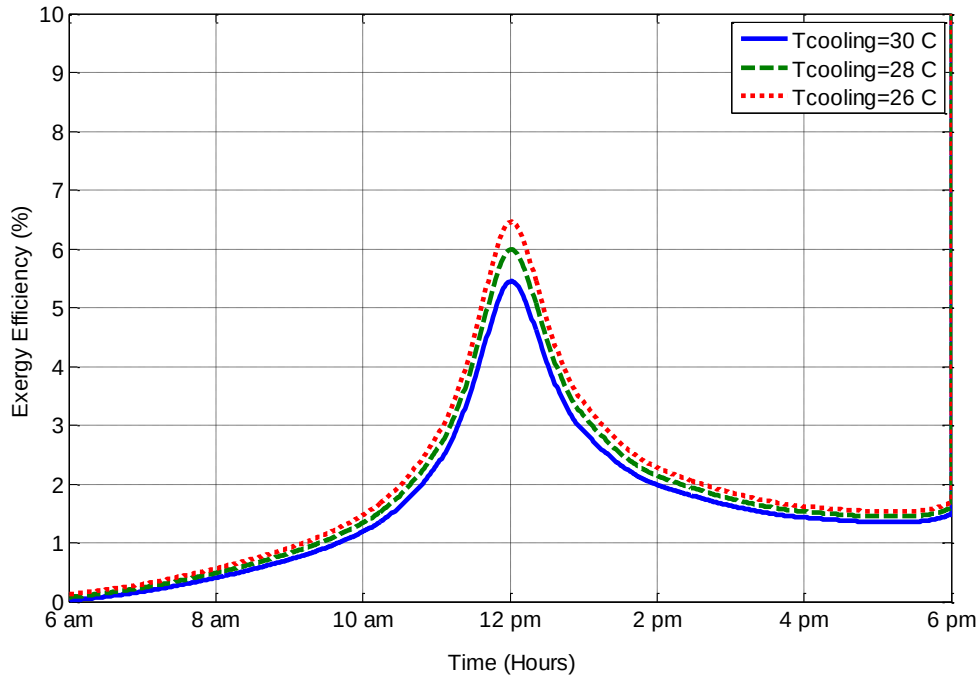


FIG. 4-61 Effect of cooling water temperature on exergy efficiency of saline water chamber

The increase of exergy efficiency of saline water chamber is met by a decrease of exergy efficiency of fresh water chamber. FIG. 4-62 shows a slight decrease of the exergy of fresh water with decreasing the temperature of cooling water, the reason of the decrease is the incremental increase of vapor production that its exergy is destroyed in the fresh water chamber. The minimum exergy efficiency of fresh water chamber during sunshine time for 28 and 26 °C cooling water temperature is 1.99 and 1.96% respectively.

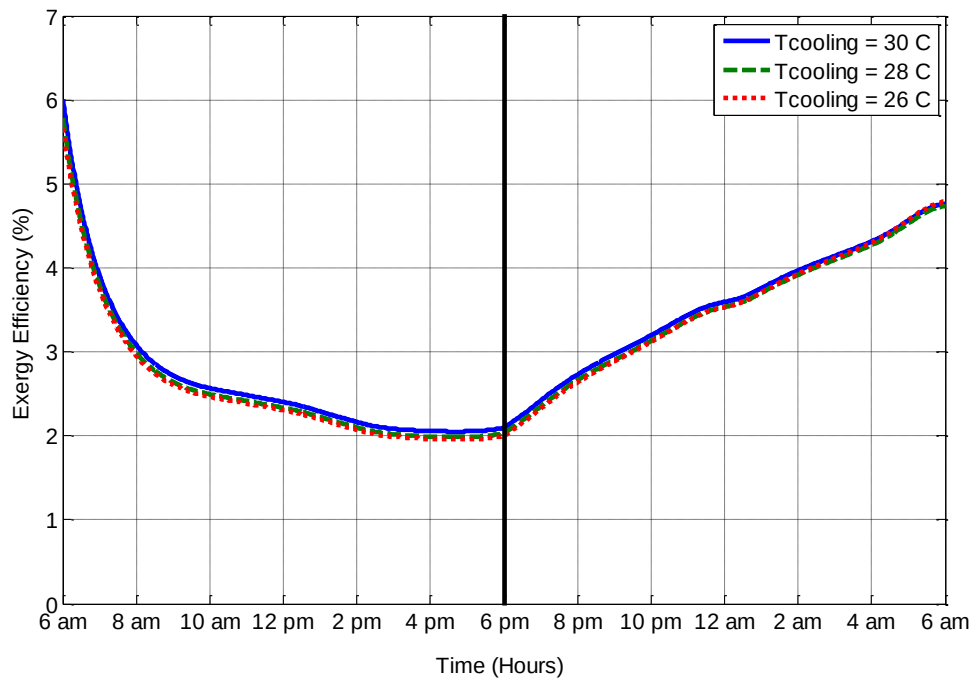


FIG. 4-62 Effect of cooling water temperature on exergy efficiency of fresh water chamber

4.4.4 Brine withdrawal analysis

Previously in section 4.4.2 , the salinity of water inside the saline water chamber increased when the depth of water decreased, at 0.1 m of saline water depth, the salts concentration was at its maximum. To control the salinity of the water, the brine is to be withdrawn from a secondary pipe. The withdrawal rates of brine to be studied in this section are 0.0001, 0.0005, 0.001, and 0.002 m³/hr.

FIG. 4-63 shows the effect of brine withdrawal rate on saline water temperature. It is clear that the temperature of saline water decreases when the withdrawal rate increases, as brine is removed from the saline water chamber, the energy is also removed since the brine carries heat with it, which drives the temperature down. The maximum temperature of saline water for 0.0001, 0.0005, 0.001, and 0.002 m³/hr is

38.73, 37.9, 37.05, and 35.79 °C respectively. The fresh water temperature (shown in FIG. 4-64) experiences a slight decrease with increasing the brine withdrawal rate, the slight decrease is suggested from the lower vapor temperature reaching the fresh water chamber.

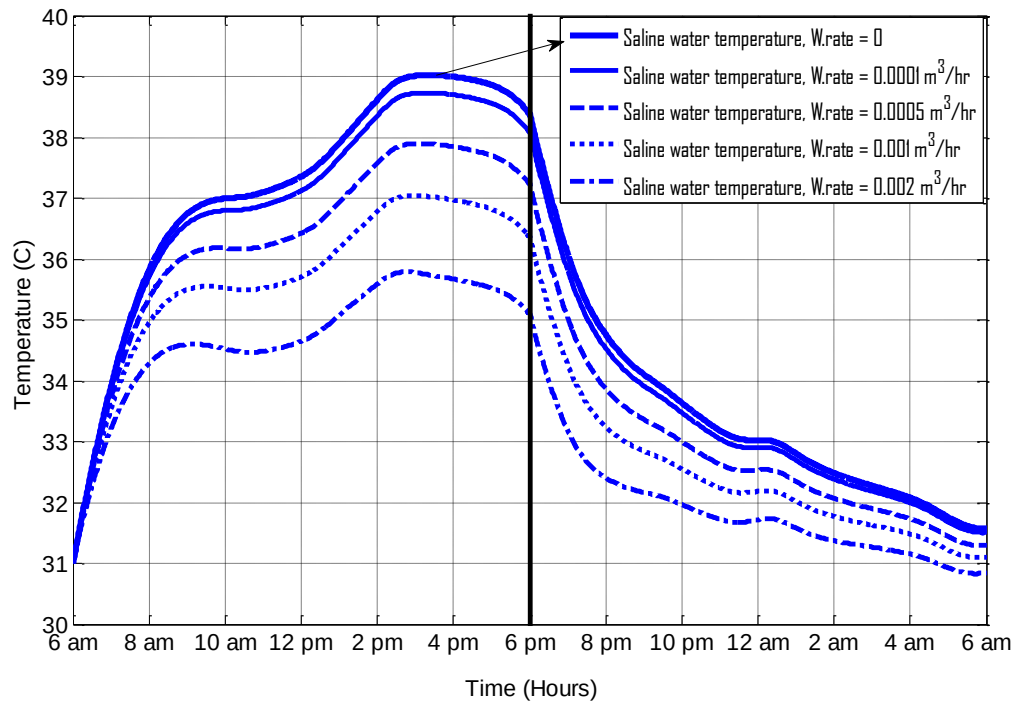


FIG. 4-63 Effect of brine withdrawal rate on saline water temperature

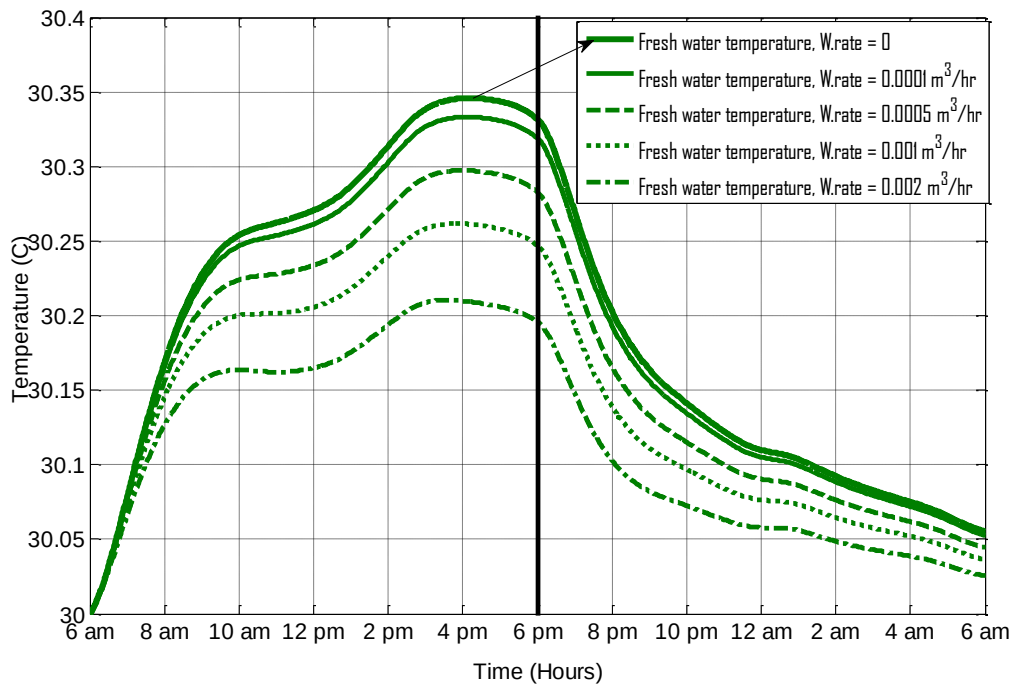


FIG. 4-64 Effect of brine withdrawal rate on fresh water temperature

The effect of brine withdrawal rate on vapor pressure of saline water is shown in FIG. 4-65, the saline water vapor pressure decreases with increasing the withdrawal rates, as a direct result of decreasing the temperature. The maximum vapor pressure of saline water for 0.0001, 0.0005, 0.001, and 0.002 m^3/hr is 6784, 6488, 6198, and 5788 Pa respectively. The fresh water vapor pressures (shown in FIG. 4-66) experience slight decrease corresponding to the slight decrease of its temperature.

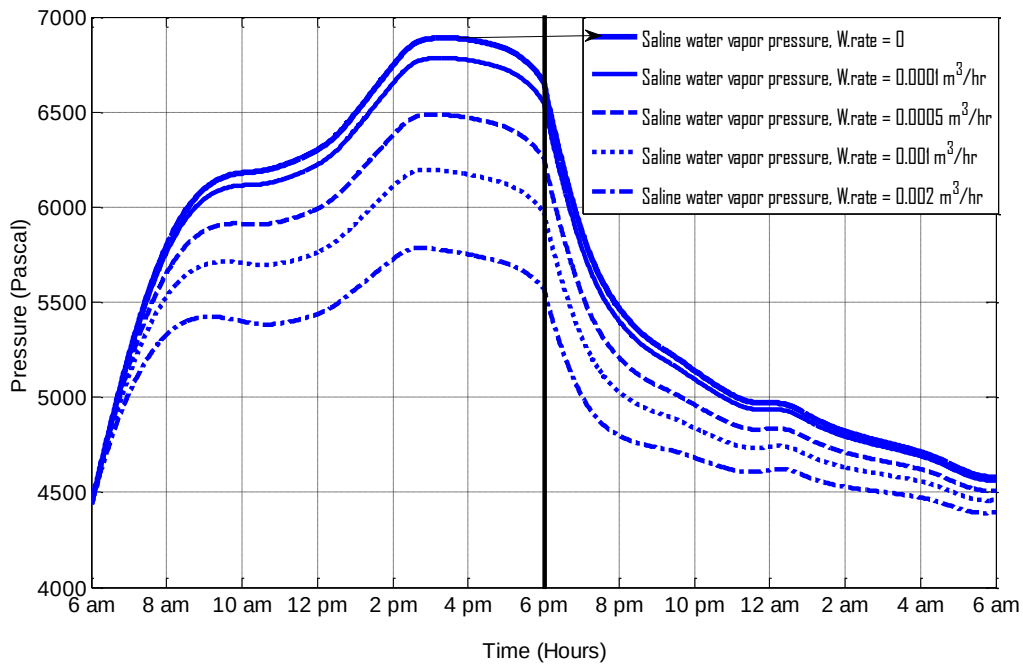


FIG. 4-65 Effect of brine withdrawal rate on vapor pressure of saline water

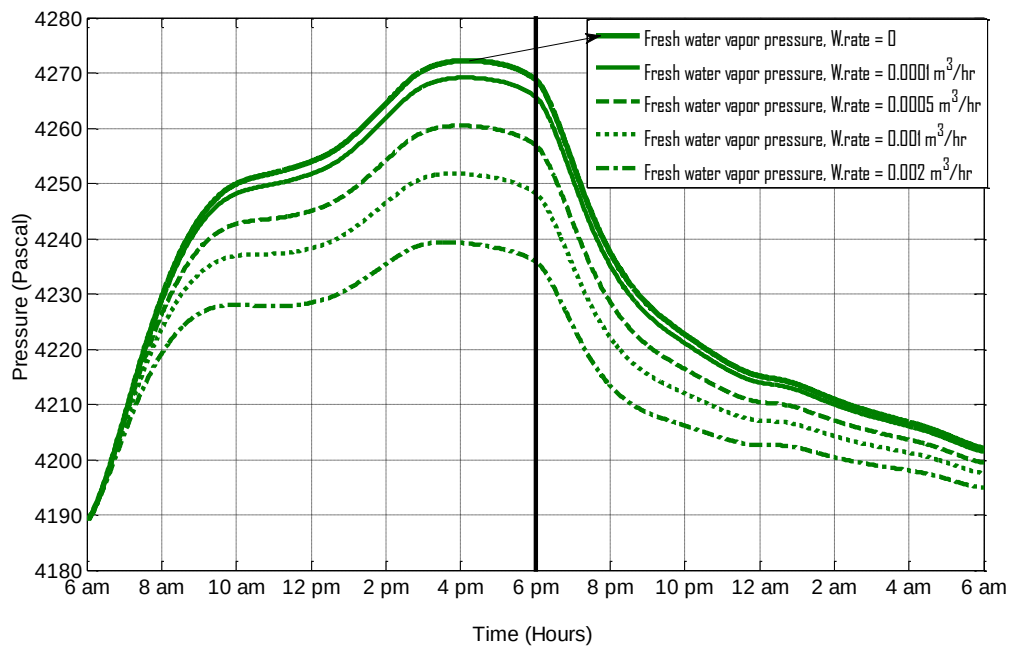


FIG. 4-66 Effect of brine withdrawal rate on vapor pressure of fresh water

The effect of brine withdrawal rate on evaporation rate is shown in FIG. 4-67. Increasing the withdrawal rate decreases the evaporation rate, a decrease driven by the temperature of saline water decrease. The maximum evaporation rate for 0.0001,

0.0005, 0.001, and 0.002 m³/hr is 0.023, 0.021, 0.018, and 0.014 kg/hr respectively. As a result of lower evaporation rates with higher withdrawal rates, the amount of fresh water produced at the end of the day becomes less. FIG. 4-68 shows the effect of brine withdrawal rate on fresh water production, for 0.0001, 0.0005, 0.001, and 0.002 m³/hr withdrawal rates, the amount of fresh water produced is 0.302, 0.264, 0.228, and 0.176 kg respectively.

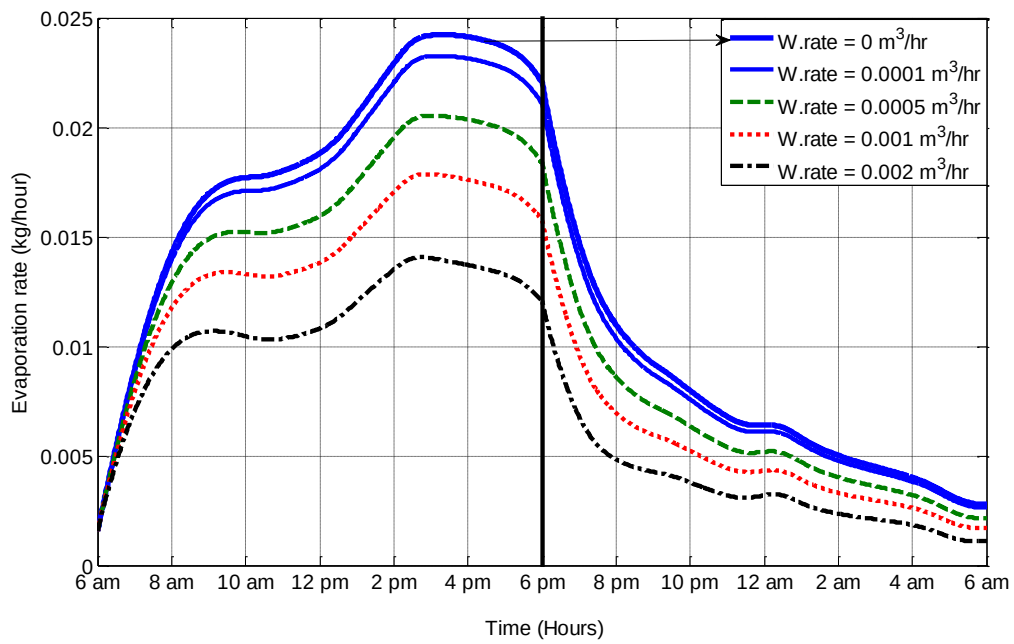


FIG. 4-67 Effect of brine withdrawal rate on evaporation rate

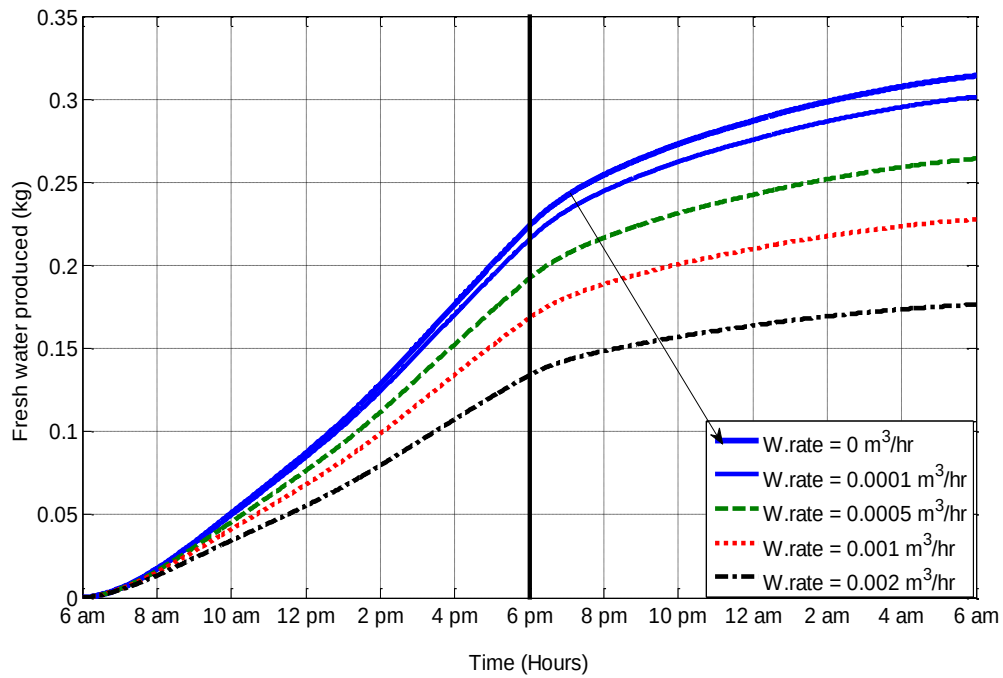


FIG. 4-68 Effect of brine withdrawal rate on fresh water production

FIG. 4-69 shows the effect of brine withdrawal rates on salts concentration. It is clearly seen that the salts concentration decreases with increasing withdrawal rates. For 0.0001 and 0.0005 m³/hr withdrawal rates, the salts concentration decreased, but still accumulated extra amount at the end of the day, only after increasing the rate beyond 0.001 m³/hr the concentration came down to the value of 3.5%, which is the sea water salts concentration. The salts concentration pattern after 0.0005 m³/hr follow the evaporation rate pattern, when evaporation rate increases the amount of salt increase inside the saline water chamber, when the evaporation rate decreases the salts concentration will decrease as well because the brine removal process dominates the amount of mass leaving the chamber.

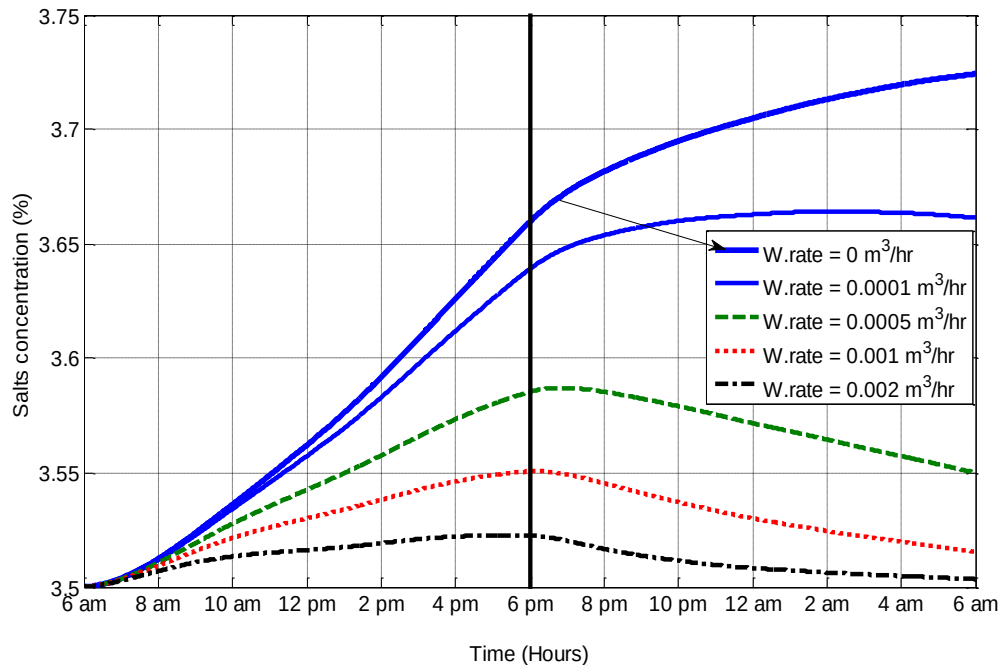


FIG. 4-69 Effect of brine withdrawal rates on salts concentration

The salts concentration for 0.0001, 0.0005, 0.001, and 0.002 m³/hr withdrawal rates is 3.661, 3.550, 3.516, and 3.503% respectively.

As a result of the decrease of fresh water production, the thermal efficiency drops dramatically, since lower output (water vapor) is produced for the same amount of heat supplied (solar irradiance), additionally, heat is lost when brine is removed. In FIG. 4-70 the maximum thermal efficiency for 0.0001, 0.0005, 0.001, and 0.002 m³/hr withdrawal rates is 59.43, 28.11, 16.73, and 8.36% respectively.

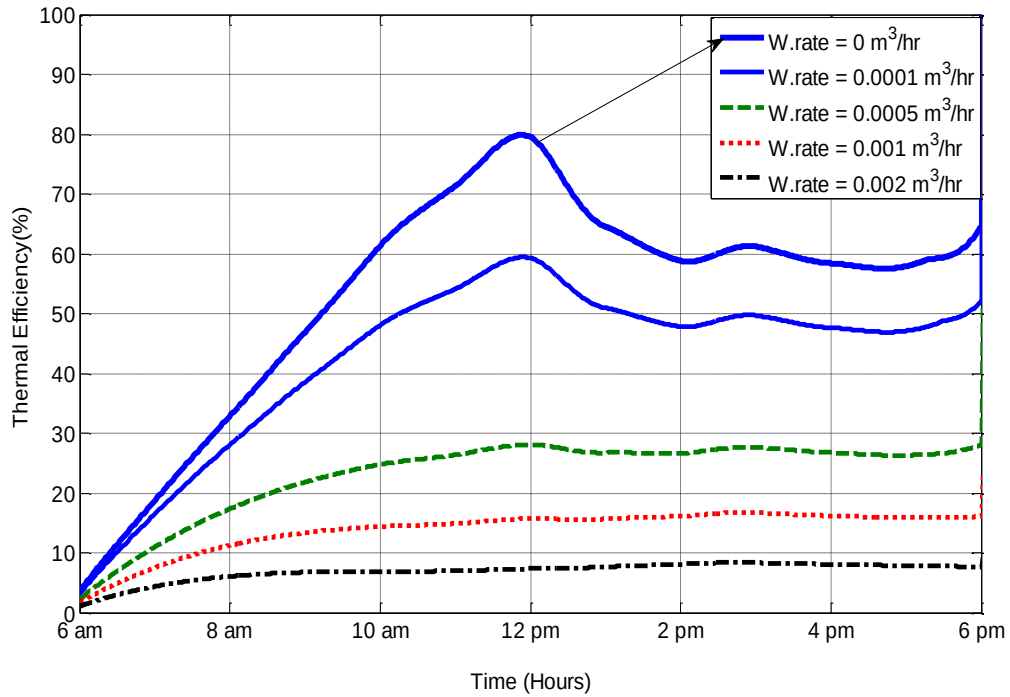


FIG. 4-70 Effect of brine withdrawal rate on thermal efficiency

The effect of brine withdrawal rate on exergy efficiency of saline water chamber is shown in FIG. 4-71, as the withdrawal rate increases the exergy efficiency decreases, since less vapor production results in less exergy produced from the saline water chamber, hence lowering the exergy efficiency. Additionally, the brine's exergy leaving the chamber decreases the exergy efficiency as well. The maximum exergy efficiency for 0.0001, 0.0005, 0.001, and 0.002 m³/hr withdrawal rates is 12.23, 10.09, 8.14, and 5.68% respectively.

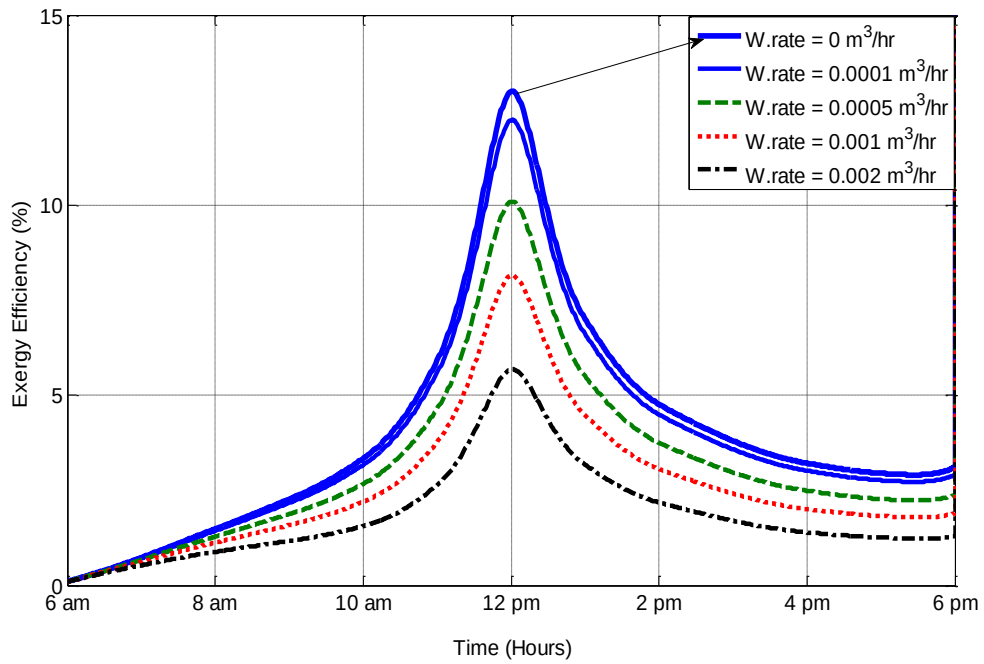


FIG. 4-71 Effect of brine withdrawal rate on exergy efficiency of saline water chamber

Unlike the saline water chamber, the fresh water chamber exergy efficiency increases when the withdrawal rates increase driven by the lower amounts of vapor exergy entering the fresh water chamber, which results in less destruction which leads to increase in exergy efficiency. From FIG. 4-72 the minimum exergy efficiency of fresh water chamber for 0.0001, 0.0005, 0.001, and 0.002 m³/hr withdrawal rates is 2.74, 2.90, 3.09, and 3.43% respectively.

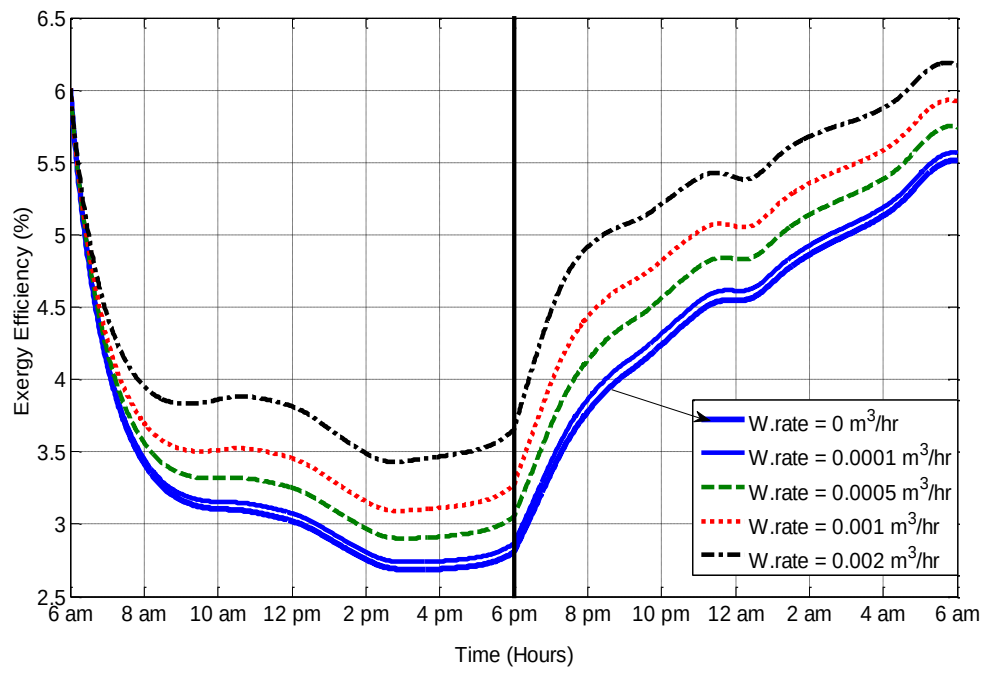


FIG. 4-72 Effect of brine withdrawal rate on exergy efficiency of fresh water chamber

CHAPTER 5

ECONOMIC ANALYSIS

The desalination unit economical characteristic is studied, and the price of 1 kg of fresh water produced is found. The unit is manufactured by assembling different parts; some of them are bought from the market (on the shelf) and others are made in house. The unit is manufactured at the University of Bahrain, and the cost of 1 kg of fresh water is based on theoretical yields of the system.

The initial cost of the unit consists of the capital cost of the unit and the labor cost for installing it. TABLE 5 shows the units parts and their cost.

TABLE 5 Cost of NVD system parts

Part Name	Quantity	Cost of Part (BD)	Cost of Manufacturing (BD)
Inverse U tube	1	75	50
1 m ² evaporator	1	75	50
Plastic Pipe (30 meters)	1	60	0
Valves	12	12	0
Tanks	2	20	0
Fresh Water (375 liters)	1	1.875	0
Vacuum Pump	1	50	0
Water Pump	1	20	0
Sea Water Piping System (40 meters plastic)	1	40	0
Condenser (Cylinder)	1	30	0
Gaskets		10	0
Special Glue	1	10	0
Pressure Sensor (Manometer)	1	50	0
Controller	1	50	0
Total Cost		603.875	

The labor cost in Bahrain is assumed to be 3 BD/hr, TABLE 6 shows the labor cost of the NVD system.

TABLE 6 Labor cost of the NVD system

Work Type	Hours	NO. of Labors	Man hours
Inverse U tube: Cutting, Welding, and Painting	16	2	32
Construction and Plumbing	8	2	16
Electrical Connections	5	1	5
Total	53		
Labor Cost (BD)	159		

The system has operation and maintenance cost, the operation cost is shown in TABLE 7, which is the electricity cost needed to operate the vacuum and water pumps, the commercial cost of kWatt/hr is 0.016 BD. The system requires two visits per year to maintain it, the cost of maintenance is 50 BD.

TABLE 7 Operational Cost (BD)

Pump	KWatt	Hours	KWatt/Hr
Vacuum Pump	0.7	2	1.4
Water Pump	0.5	24	12
Total Cost per year	0.214		

To find the cost of 1 kg of fresh water produced by the desalination unit, a cash flow diagram must be constructed, since the time affects the value of money. This diagram includes the initial cost (capital and installation costs) and the yearly operation and maintenance costs, to have a payback period the cash flow must have revenue, in this case it's the cost of water produced by the system. FIG. 5-1 shows the cash flow diagram.

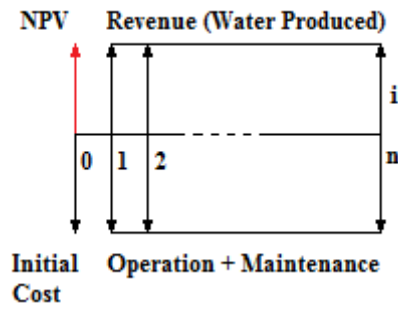


FIG. 5-1 Cash flow diagram

Solving the net present value of the cash flow shown in FIG. 5-1 yields the following equation (Blank & Tarquin, 2002):

$$\text{Net Present Value (NPV)} = (\text{Annual Revenue} - \text{Annual Operation Cost} - \text{Annual Maintenance Cost}) \frac{(1+i)^n - 1}{i(1+i)^n} - \text{Initial Cost} \quad (5.1)$$

Where:

i : Annual interest rate (%).

n : Desalination unit life time (years).

The system is assumed to have 20 years life time, and it has no salvage value. TABLE 8 shows the cost of 1 kg of fresh water for different interest rates; three areas of evaporator are studied, for each scenario the yearly yield of fresh water increases and the system initial cost increases too.

TABLE 8 Cost of 1 kg of fresh water (BD)

Interest Rate (%) Evaporator Area (m ²)	6	8	10
1	0.166	0.169	0.171
2	0.141	0.143	0.145
3	0.135	0.137	0.139

From TABLE 8, it can be seen that as the area increases the cost decreases, this is due to the increase in production when increasing the evaporator area, while increasing the interest rate increases the cost of the water produced. The values shown above cannot compete with Bahrain's cost of fresh water produced, but the advantage of the system lies in its impact on environment since it relies on the solar irradiance as its main source of energy, and not depending on fossil fuel which produces considerable amounts of pollutants.

The yearly production of the system varies along the year from a maximum (on a hot day) to a minimum (on a cold day), at any given day the amount produced cannot exceed the upper and lower bounds, the annual amount accumulated was calculated from those limits, hence it is an approximate value.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

After studying the natural vacuum desalination system theoretically, a number of remarks can be concluded:

1. The NVD system with a 0.125m radius of saline water chamber (evaporator) using 30 °C of cooling water temperature operating in hot conditions can produce up to 0.54 kg of fresh water, maximum thermal efficiency and exergy efficiency of the saline water chamber are 44.58 and 5.44% respectively.
2. The NVD system with a 0.125m radius of saline water chamber (evaporator) using 11 °C of cooling water temperature operating in cold conditions can produce up to 0.149 kg of fresh water, maximum thermal efficiency and exergy efficiency of the saline water chamber are 9.98 and 0.375 % respectively.
3. The system has the potential to produce up to 3.60 kg/day if the saline water chamber surface area increased to 1 m², which is 21.11% more than a conventional solar still.
4. The system's output increases with increasing the area of the evaporation surface (saline water chamber radius), increasing the area beyond 2 m² has little effect on the output. Increasing the area from 0.05 to 3 m² decreases the maximum thermal efficiency from 44.58 to 17.56%, and the maximum exergy efficiency of the saline water chamber decreases from 5.44 to 1.68%.
5. Decreasing the depth of saline water from 0.5 to 0.1m decreases the output from 0.54 to 0.313 kg, and the salts concentration increases from 3.521 to 3.724%. Maximum thermal efficiency increases from 44.58 to 79.85% and the maximum exergy efficiency of saline water chamber increases from 5.44 to 12.97%.

6. Decreasing the cooling water temperature 4 °C (from 30 to 26 °C) increases the output of the system from 0.54 to 0.710 kg.
7. Generally, withdrawing brine from the saline water chamber results in a decrease in salts concentration. Using 0.001 m³/hr withdrawal rate stabilizes the concentration near seawater salt percentage, and decreases fresh water production from 0.313 to 0.228 kg (for 0.1 m saline water depth).
8. The theoretical results of the NVD system were compared to a previous study performed (Veeragnaneswar & Nermalakhandan, 2007). The production rate of the current NVD unit was 3.6 kg/m².Day compared to 4.9 kg/m².Day for Veeragnaneswar's unit (Veeragnaneswar & Nermalakhandan, 2007) . The maximum efficiency of the current configuration is 27.71% for 1 m² of surface area of evaporation compared to Veeragnaneswar's maximum efficiency which is near 80%.
9. The cost of 1 kg of fresh water produced for the current NVD system with 20 years life time is 0.166, 0.169, and 0.171 BD for 6, 8, and 10% interest rates, respectively. Thus it is not feasible as an alternative to the conventional desalination plants operating in Bahrain.

The system's performance can be enhanced using a modified and compact design. FIG. 6-1 shows the conical NVD system, the design shown in FIG. 6-1 is more compact and consumes less space, the amount of fresh water output, thermal and exergy efficiency can increase by utilizing a conical solar collector, the water inside the solar collector is heated via the solar irradiance and enters the saline water chamber through a heat exchanger, the hot water will heat the saline water and become the main source of supplied heat. The vapor produced is condensed when it contacts the cold conical cover, which is cooled using a spiral condenser. A thermal insulation separates the conical solar collector and the spiral condenser to reduce heat transferred between them.

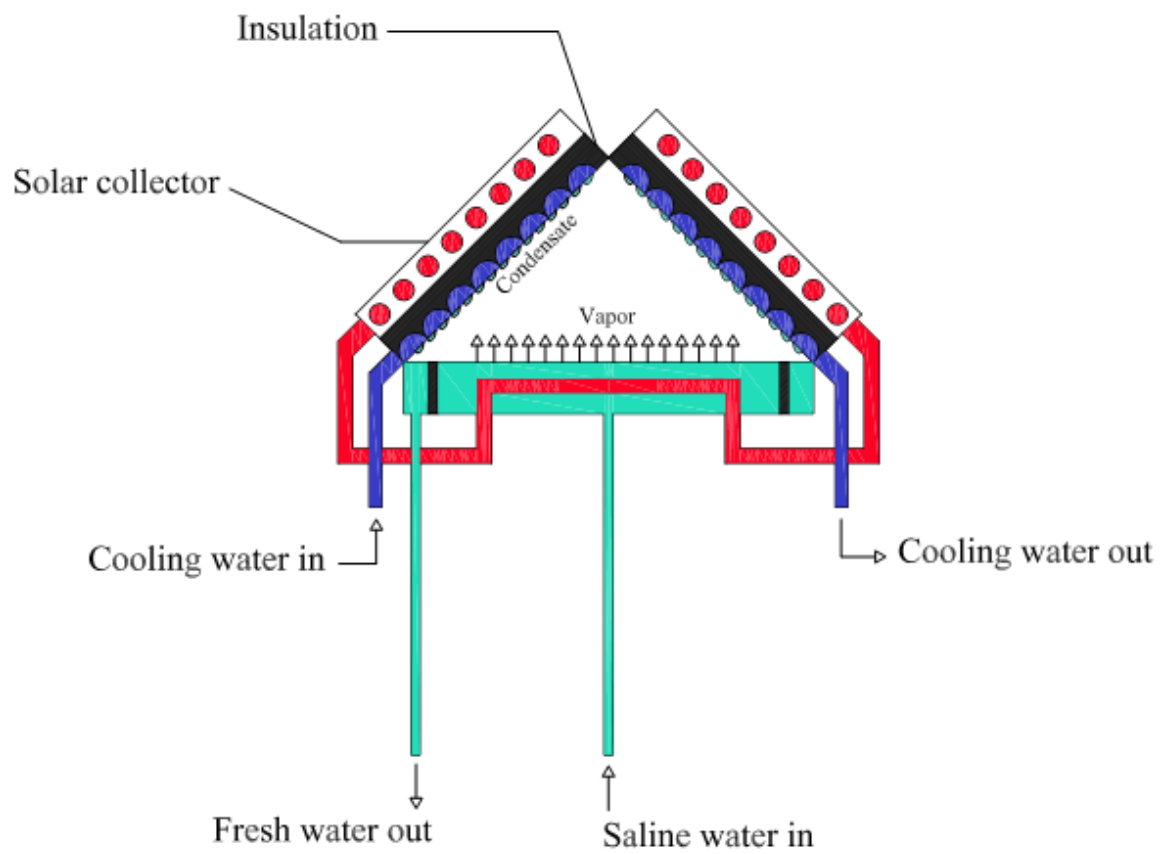


FIG. 6-1 Conical NVD system

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APPENDIX (A)

AQUIFERS AND TREATMENT CENTERS IN BAHRAIN

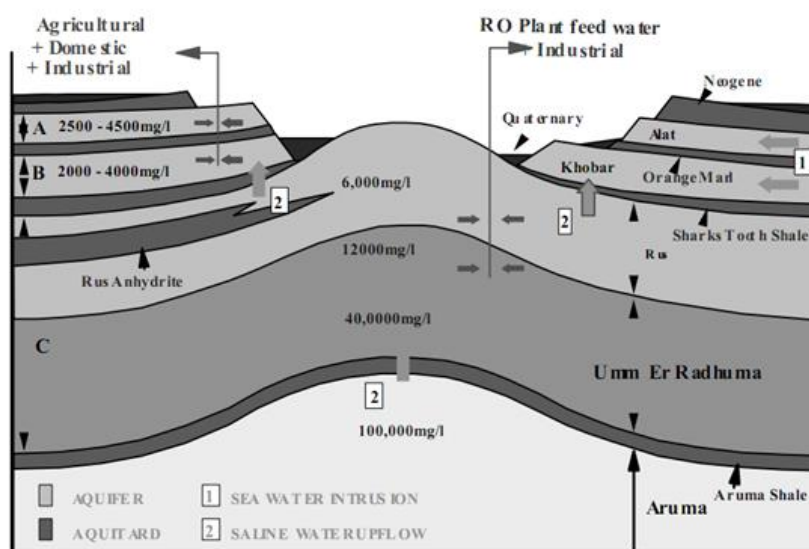


FIG. A- 1 Schematic illustration of the aquifers system, adapted from (Khater, 1999)

TABLE A- 1 Treatment Centers in Bahrain, adapted from (Khater, 1999)

Area	Population served	Capacity m ³ /day	Operational date	
Nuwaidrat	6460	1760	1980	Anaerobic bond
Tubli	45000	124000	1982	Activated sludge
Asker	1250	288	1982	Activated sludge
Demistan	650	130	1985	Activated sludge
North Sitra	25000	5800	1985	Activated sludge
Sukhair	1679	504	1986	Activated sludge
Jaw	1500	408	1988	Activated sludge
Hasra			1988	Biological Contact
West Alba	3000	900	1994	Activated sludge
Jeddah	100	25	1997	Activated sludge
West Riffa		250	1999	Activated sludge

APPENDIX (B)

HEAT TRANSFER CONVECTION COEFFICIENTS

Heat transfer convection coefficient for surrounding air around the saline water chamber:

$$Re = \frac{2 r_{e,out} V_{air}}{v_{air}} \quad (b.1)$$

Where:

Re : Reynolds number (dimensionless)

V_{air} : Speed of air (m/s)

v_{air} : Kinematic viscosity of air (m²/s)

$$\overline{Nu} = Z Re^w Pr_{air}^{0.37} \left(\frac{Pr_{air}}{Pr_{wall-air}} \right)^{1/4} \quad (b.2)$$

Where:

$\overline{Nu}$: Average nusselt number (dimensionless)

Z : Constant (dimensionless)

w : Constant (dimensionless)

Pr_{air} : Prandtl number of air (dimensionless)

$Pr_{wall-air}$: Prandtl number of air at saline water chamber wall-air interface temperature (dimensionless)

Depending on Re , Z and m shown in equation b.2 can take a different value, TABLE B- 1 shows the different values of Z and w for different ranges of Re :

TABLE B- 1 Z and m values for different ranges of Re

Re	Z	w
1-40	0.75	0.4
40-1000	0.51	0.5
$10^3 - 2 \times 10^5$	0.26	0.6
$2 \times 10^5 - 10^6$	0.076	0.7

$$h_{air} = \frac{\overline{Nu} k_{air}}{2 r_{e,out}} \quad (b.3)$$

Where:

k_{air} : Thermal conductivity of air (Watt/m.°C)

Internal heat transfer convection coefficient for saline water:

$$Gr = \frac{g \beta (T_{saline-wall} - T_s) d_e^3}{\nu_{saline}^2} \quad (b.4)$$

Where:

Gr : Grashof number (dimensionless)

g : Gravitational acceleration (m/s²)

β : Thermal expansion coefficient of saline water (K⁻¹)

ν_{saline} : Kinematic viscosity of saline water (m²/s)

$$Ra = Gr Pr_{saline} \quad (b.5)$$

Where:

Ra : Raleigh number (dimensionless)

Pr_{saline} : Prandtl number of saline water (dimensionless)

$$\overline{Nu} = \left\{ 0.825 + \frac{0.387 Ra^{1/6}}{[1 + (0.492/Pr_{saline})^{9/16}]^{8/27}} \right\}^2 \quad (b.6)$$

$$h_{saline} = \frac{\overline{Nu} k_{saline}}{d_e} \quad (b.7)$$

Where:

k_{saline} : Thermal conductivity of saline water (Watt/m.°C)

Heat transfer convection coefficient for cooling water around the fresh water chamber:

$$D_h = (2 r_{c,out} - 2 r_{cooling}) \quad (b.8)$$

Where:

D_h : Hydraulic diameter (m)

$r_{cooling}$: Internal radius of the condenser (m)

$$Re = \frac{4 \dot{m}_{cooling}}{\pi D_h \mu} \quad (b.9)$$

Where:

$\dot{m}_{cooling}$: Mass flow rate of cooling water (kg/s)

μ : Viscosity of cooling water (N/m²)

$$\overline{Nu} = 0.023 Re^{4/5} Pr_{cooling}^{0.3} \quad (b.10)$$

Where:

$Pr_{cooling}$: Prandtl number of the cooling water (dimensionless)

$$h_{cooling} = \frac{\overline{Nu} k_{cooling}}{D_h} \quad (b.11)$$

Where:

$k_{cooling}$: Thermal conductivity of cooling water (Watt/m.°C)

APPENDIX (C)

SOLAR IRRADIANCE FOR DIFFERENT SALINE WATER

CHAMBER AREAS

The solar irradiance is calculated using SOLIDWORKS 2013. The saline water chamber is drawn (shown in FIG. C-1) and a group of parameters and conditions are defined. FIG. C-2 shows the initial mesh window, the mesh is created automatically and the value of the mesh is set to 3. FIG. C-3 shows the calculation control options window, the maximum physical time is set to 43200 seconds, which represents 12 hours of day light.

The final step is to define radiation conditions. FIG. C-4 shows the general settings window, the solar radiation is defined by location and time, the location is defined by latitude value of Bahrain which is 26° 09' north. The time is 26th of July (for a hot weather case) and the simulation starts at 6 am. The weather is assumed to be clear (cloudiness is set to 0) and the saline water chamber stands vertically (angle is set to 0 rad).

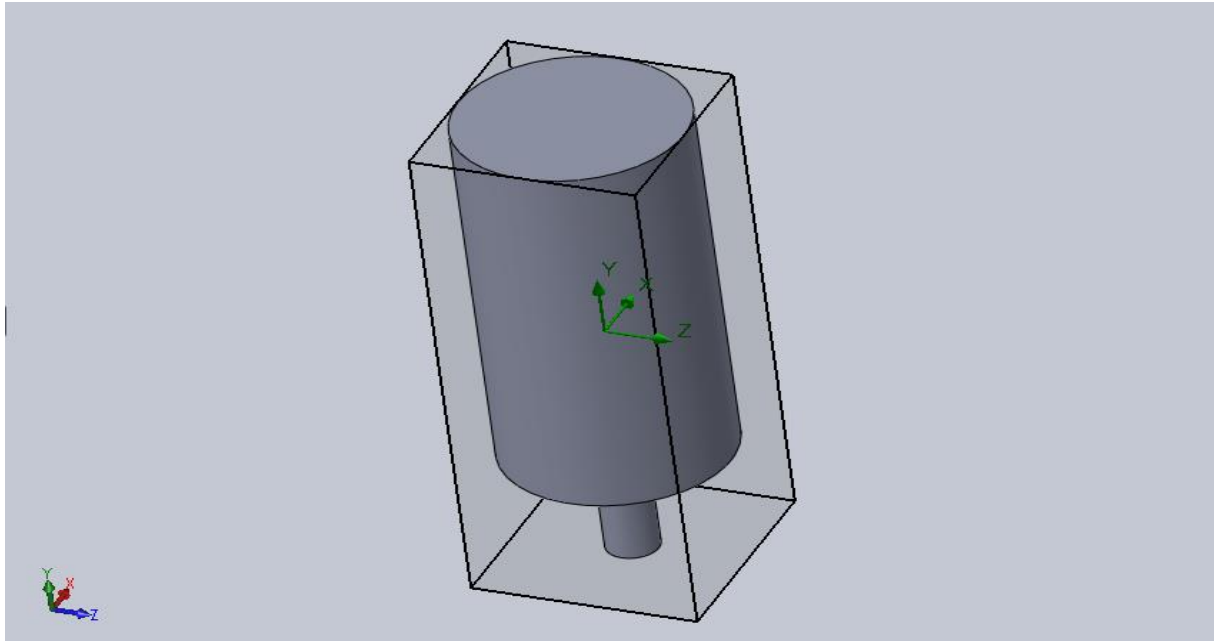


FIG. C-1 Saline Water Chamber

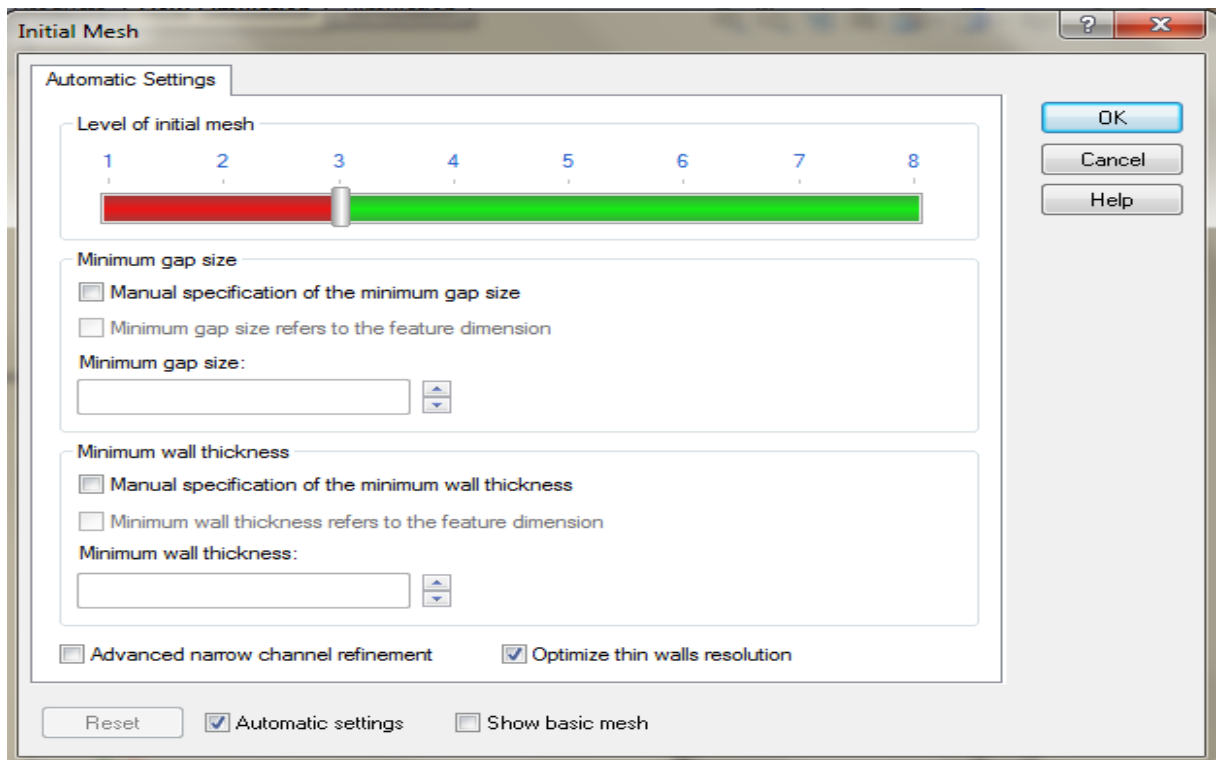


FIG. C-2 Initial Mesh

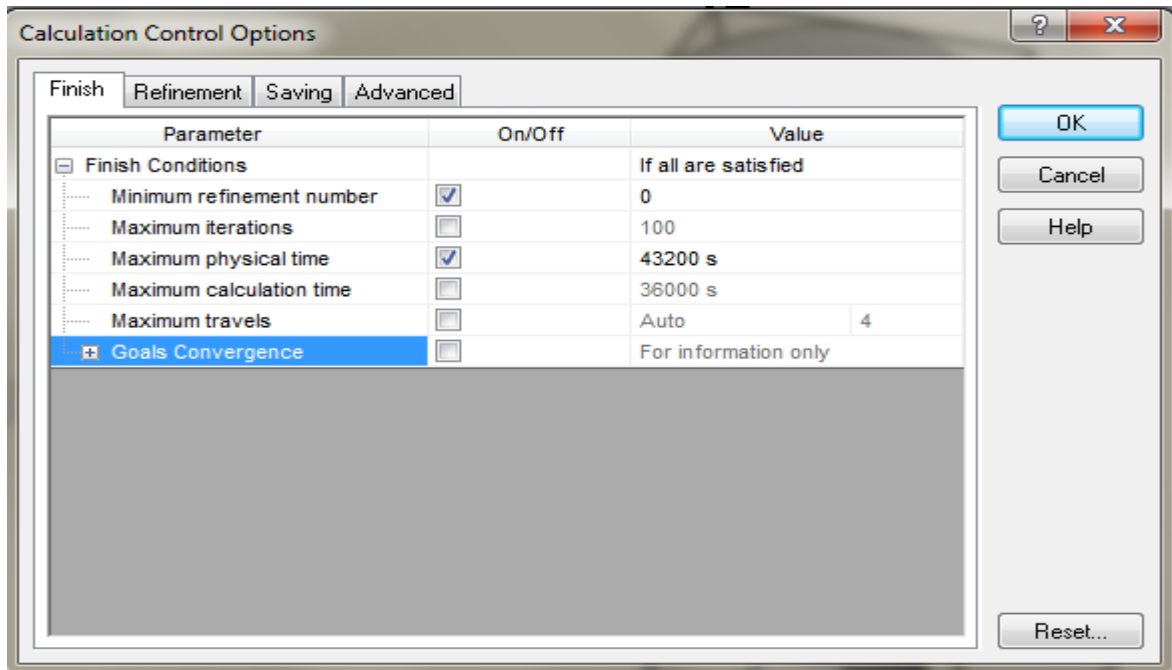


FIG. C-3 Calculation Control Options

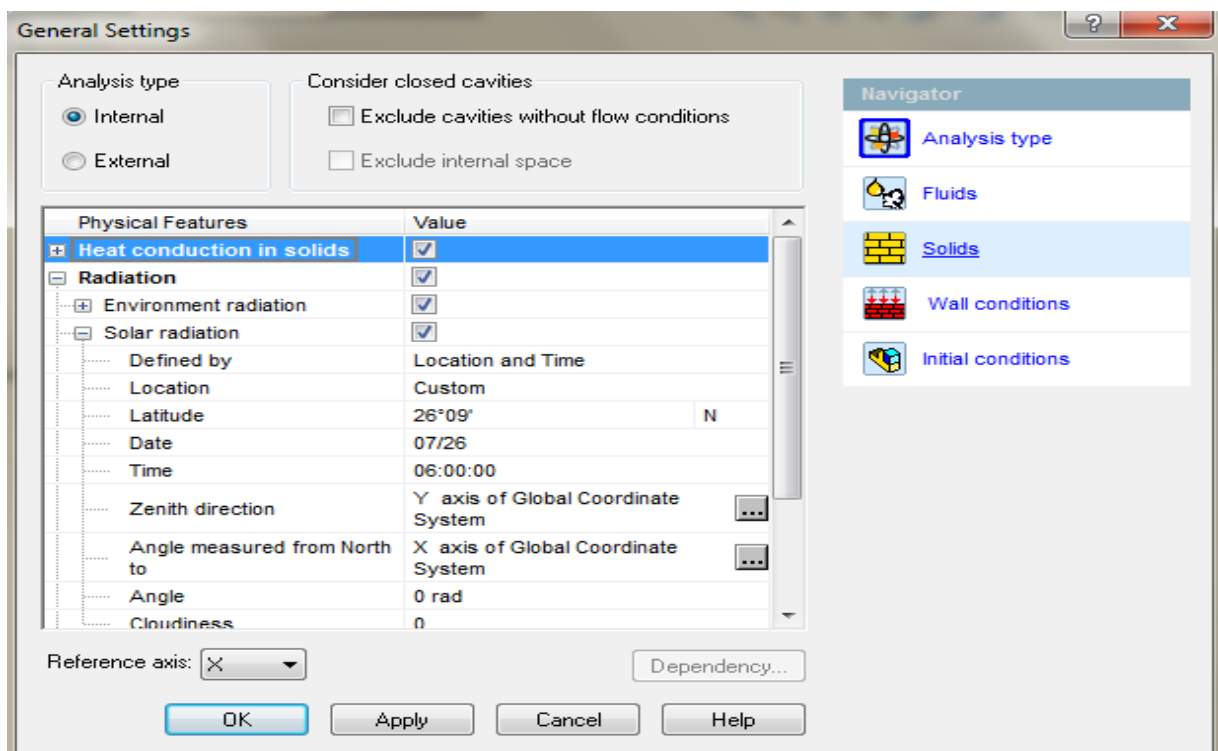


FIG. C-4 General Settings

FIG. C-5 shows the result of the simulation of solar energy, per unit area, falling on the saline water chamber during a hot weather. FIG. C-6 shows the solar irradiance falling on the saline water chamber for 1, 2, and 3 m² evaporation surface area.

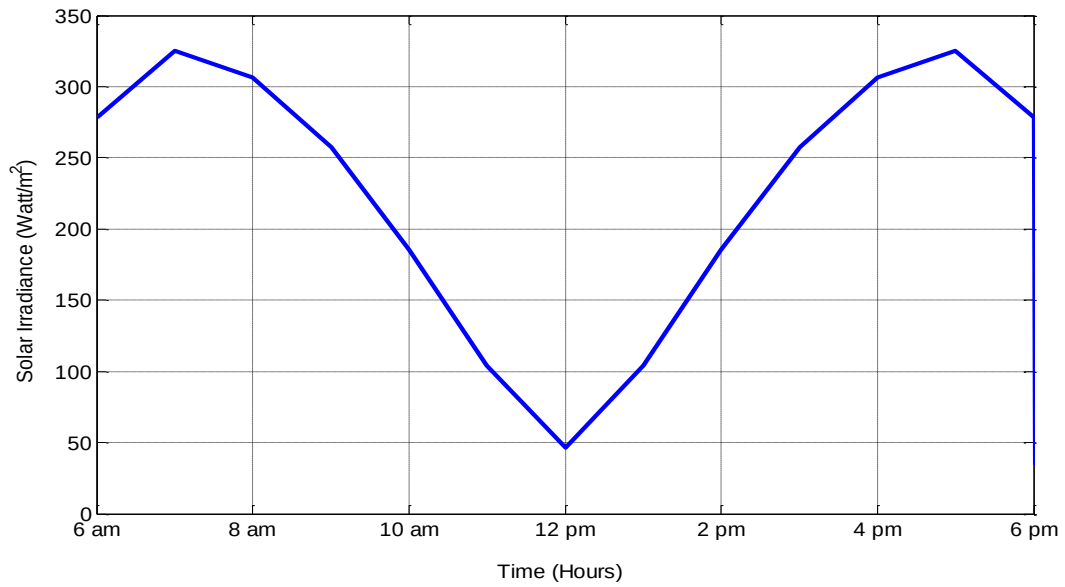


FIG. C-5 Solar irradiance per unit area for a hot weather

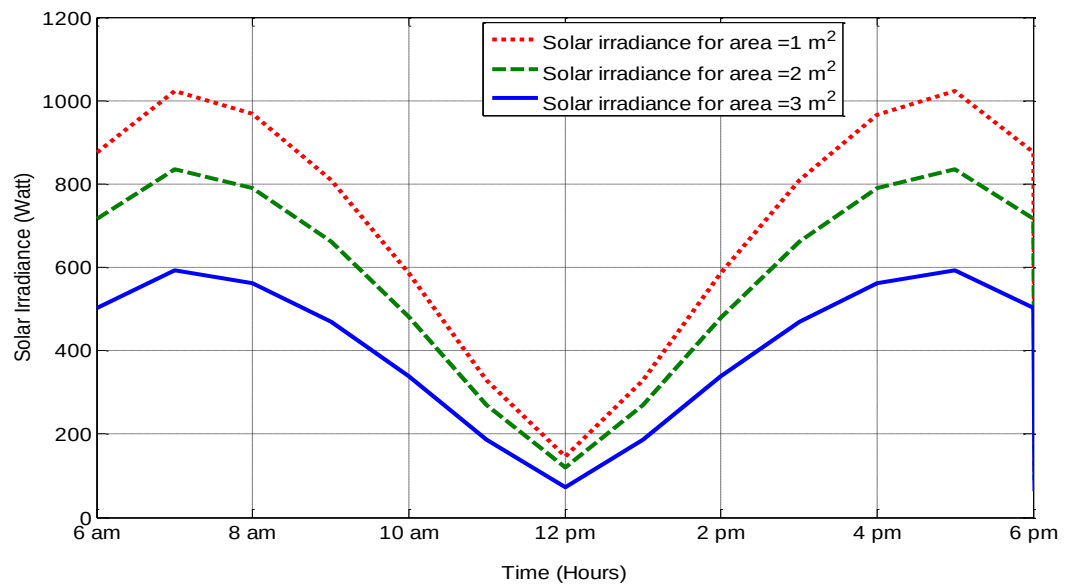


FIG. C-6 Solar irradiance for various surface areas of evaporation for hot weather

APPENDIX (D)

MATLAB CODE

The following subroutine is the main portion of the MATLAB code that was developed to find the required variables of the NVD system.

```
clear all
clc

%Hot Conditions
[t,T]=runkut4(@TempevaCC3,0,[31 30 3.5], 86400,60); % [y(1) y(2) y(3)]
t=t/3600;
Ts=T(:,1);
Tf=T(:,2);
S= T(:,3);
Tcooling=30; % Celcius
hwatercooling=185; % Watt/m^2.K
Vair=7; % m/s
th=0.005; % m, thickness of the pipe
k=15; % W/m.k
alfa= 0.5; % dimensionless
de=0.5; % meter
dc=0.5; % meter
re=0.125; % meter
r2=re+th; % meter
rc=0.125; % meter
rcout=rc + th; % meter, outside radius of the condensor

plot(t,Ts,t,Tf);grid; xlabel ('Time (Hours)'); ylabel ('Temperature
(C)'); legend ('Saline water temperature','Fresh water temperature')
```

```

figure
plot(t,S);grid; xlabel ('Time (Hours)');ylabel ('Salts concentration
(%)')
F=1 - (0.0054*S);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
alfam = (0*(1e-7)+1*(1e-6)); %
Bt=5e-4; % Thermal expansion coefficient (1/C) %
Bc=8e-3; % Solute concentration expansion coefficient (1/%)%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

As = 3.14 * (re^2); % m^2, evaporation chamber surface area
Ac = 3.14 * (rc^2); % m^2, condensation chamber surface area
Aeva = 2*3.14*re*de; % m^2, external surface area evaporator
Acon = 2*3.14*rc*dc; % m^2, fresh water chamber surface area

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
RAWsteel=8000; % Kg/m^3
Csteel = 420; %j/Kg.C
Volumesteel= (de*3.14*((re+th)^2)) - (de*3.14*(re^2)); % m^3
Msteel=Volumesteel * RAWsteel; % Kg
Volumesteelc= (dc*3.14*((rc+th)^2)) - (dc*3.14*(rc^2)); % m^3
Msteelc=Volumesteelc * RAWsteel; % Kg

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Ps = (exp(63.042 - ((7139.6)./(Ts+273)) - (6.2558*log(Ts+273))))*100;
Pf = (exp(63.042 - ((7139.6)./(Tf+273)) - (6.2558*log(Tf+273))))*100;
me = 3600*alfam*As*((F.*Ps)./sqrt(Ts+273)) - (Pf./sqrt(Tf+273));
%Kg/hr
hl = (3146 - 2.36*(Ts+273))*1000; % j/Kg, Latent heat
tt=0:60:86400;
tt=tt';

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Cps=zeros(1441,1);
Cpf=zeros(1441,1);
Cin=zeros(1441,1);
CBout=zeros(1441,1);
RAWs=zeros(1441,1);
RAWf=zeros(1441,1);
RAWsin=zeros(1441,1);
for i=1:1441
    Cps(i) = SW_SpcHeat(Ts(i),'C',S(i),'%'); %j/Kg.C specific heat of
    saline water
    Cpf(i) = SW_SpcHeat(Tf(i),'C',0,'%'); %j/Kg.C specific heat of
    fresh water
    Cin(i) = SW_SpcHeat(Ts(i),'C',3.5,'%'); % j/Kg.C, specific heat of
    feed water
    CBout(i) = SW_SpcHeat(Ts(i),'C',S(i),'%');% j/Kg.C, specific heat
    of brine water
    RAWs(i) =1026*(1 - Bt*((Ts(i) + 273)-298) + Bc*(S(i)-3.5)); %
    Kg/m^3, Saline water density
    RAWf(i) =SW_Density(Tf(i),'C',0,'%'); % Kg/m^3, fresh water
    density
    RAWsin(i)=SW_Density(Ts(i),'C',3.5,'%'); % Kg/m^3, brine water
    density
end

MassCon=(3.14*rc*rc*dc)*RAWf; % Kg
MassEva=(3.14*re*re*de)*RAWs; % Kg

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
I=zeros(1441,1);

for i=1:1441;
    I(i)=I1(tt(i));
end

Tsur=zeros(1441,1);

```

```

for i=1:1441;
    Tsur(i)=AmbientTemp(tt(i));
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

figure
ME=zeros(1441,1);
for i=1:1441
    ME(i)=sum(0.0167*me(1:i));
end
ME;
plot(t,ME);grid;xlabel ('Time (Hours)'); ylabel('Fresh water produced
(kg)')
figure
plot(t,me);grid; xlabel ('Time (Hours)'); ylabel ('Evaporation rate
(kg/hour)')
figure
plot(t,Ps,t,Pf);grid; xlabel ('Time (Hours)'); ylabel ('Pressure
(Pascal)'); legend ('Saline water pressure','Fresh water pressure')
figure
plot(t,Ts,t,Tsur);grid; xlabel ('Time (Hours)'); ylabel ('Temperature
(C)'); legend ('Saline water temperature','Surrounding temperature')

```

The following subroutine shows the set of differential equation to be solved simultaneously.

```

%Hot Conditions
function Tempeval=TempevaCC3(t,y)
% t      :time
% y(1)  :Saline water chamber temperature
% y(2)  :Fresh water chamber temperature
% y(3)  :solute concentration percentage
Tempeval=zeros(1,3);

```

```

Vair=7; % m/s
E=0.5; %emissivity of steel
sigma=5.6703e-8;
Tcooling=30; % Celcius
hwatercooling=185; % W/m^2.C
Tsur=AmbientTemp(t);
re=0.125; % meter, radius of the evaporator
rc=0.125; % meter, radius of the condensor
de=0.5; % meter, depth of water in the evaporation chamber
dc=0.5; % meter, depth of water in the condensation chamber
th=0.005; % m, thickness of the pipe
k=15; % W/m.K, thermal conductivity of the pipe (steel)
Cps = SW_SpcHeat(y(1),'C',y(3),'%'); %j/Kg.C
Cpf = SW_SpcHeat(y(2),'C',0,'%'); %j/Kg.C
Qaux=0*0.01*0.2*(60-y(1)); %Watts
F=1 - (0.0054*y(3));% Salinty percentage
Cin= SW_SpcHeat(y(1),'C',3.5,'%'); % j/Kg.C, specific heat of feed
water
alfa= 0.5; % dimensionless
Bt=5e-4; % Thermal expansion coefficient (1/C)
Bc=8e-3; % Solute concentration expansion coefficient (1/%)
r2=re + th; % meter, outside radius of the pipe
rcout=rc + th; % meter, outside radius of the condensor
mout= 0/(60*60);% Kg/s, brine water flow rate
CBout = SW_SpcHeat(y(1),'C',y(3),'%');% j/Kg.C, specific heat of brine
water
RAWf =SW_Density(y(2),'C',0,'%'); %j/Kg.C; % Kg/m^3, water density
RAWs =1026*(1 - Bt*((y(1) + 273)-298) + Bc*(y(3)-3.5)); % Kg/m^3,
Saline water density
RAWsin=SW_Density(y(1),'C',3.5,'%');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
alfam = (0*(1e-7)+1*(1e-6)); % Kg.K^0.5/m^2.Pa.s %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Aeva = 2*3.14*re*de; % m^2, internal surface area evaporator
Acon = 2*3.14*rc*dc; % m^2, internal surface area evaporator
As = 3.14 * (re^2); % m^2, evaporation chamber surface area

```

```

Ac = 3.14 * (rc^2); % m^2, condensation chamber surface area
Ps = (exp(63.042 - (7139.6/(y(1)+273)) - (6.2558*log(y(1)+273))))*100;
% Pa, Vapor pressure of evaporation chamber
Pf = (exp(63.042 - (7139.6/(y(2)+273)) - (6.2558*log(y(2)+273))))*100;
% Pa, Vapor pressure of condensation chamber
ve = alfa*(As/RAWf)*(((F*Ps)/sqrt(y(1)+273)) - (Pf/sqrt(y(2)+273)));
% m^3/s, evaporation rate
hl = (3146 - 2.36*(y(1)+273))*1000; % j/Kg, Latent heat
Qe = RAWf * ve * hl; % Watt, Evaporation energy output
MassEva= RAWs * As * de; % Kg, mass of salin water in evaporation
chamber
MassCon= RAWf * Ac * dc; % Kg, mass of fresh water in evaporation
chamber
min=(RAWsin*ve); % Kg/s, feed of salin water flow rate

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%x(1)=T1 and x(2)=T2

func=@(x) [(alfa*I1(t))+(2*pi*r2*de*(hairforced(Tsur,x(2),Vair,r2))*(T
sur-x(2))) - ((2*pi*de*k*(x(2) - x(1)))/(log(r2/re)))];...
((2*pi*de*k*(x(2) - x(1)))/(log(r2/re))) -
(2*pi*re*de*(hwaterfree(y(1),x(1),de,y(3)))*(x(1)-y(1)))]);

a=zeros(2,1);
a=newtonRaphson2(func,[Tsur;Tsur]);

Tinterfacein=a(1);
Tinterfaceout=a(2);

```

```

% z(1)=T3 and z(2)=T4

func2=@(z) ([ (2*pi*rc*dc* (hwaterfree(y(2),z(1),dc,0))*(y(2) - z(1))) -
((2*pi*dc*k*(z(1) - z(2)))/(log(rcout/rc))) ;...
((2*pi*dc*k*(z(1) - z(2)))/(log(rcout/rc))) -
(2*pi*rcout*dc*hwatercooling*(z(2) - Tcooling)) ]);

a2=zeros(2,1);

a2=newtonRaphson2(func2,[Tcooling;Tcooling]);

Tinterfaceinc=a2(1);
Tinterfaceoutc=a2(2);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tempeval(1)=(min*Cin*y(1)) + Qaux - (mout*CBout*y(1)) - Qe +
((hwaterfree(y(1),Tinterfacein,de,y(3)))*Aeva*(Tinterfacein - y(1)))
)/(MassEva*Cps); %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tempeval(2)=( Qe - (RAWf*ve*Cpf*y(2)) - (2*pi*rc*dc*
(hwaterfree(y(2),Tinterfaceinc,dc,0))*(y(2) - Tinterfaceinc))
)/(MassCon*Cpf); %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

Tempeval (3)=((min*3.5) - (mout*y(3)))/(MassEva); %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
end

```

The following subroutines find the heat convection coefficients.

For surrounding air:

```

function H=hairforced(Tsur,T2,Vair,r2)

Re=(2*r2*Vair)/airProp2(Tsur+273,'ny');

if Re <=1 && Re >=40
    C=0.75;
    m=0.4;
end

if Re <=1000 && Re >40
    C=0.51;
    m=0.5;
end

if Re <=200000 && Re >1000
    C=0.26 ;
    m=0.6;
end

if Re <=1000000 && Re >200000
    C=0.076 ;
    m=0.7;
end

```

```

Nu =
(C*(Re^m)*((airProp2(Tsur+273,'Pr'))^0.37)*(((airProp2(Tsur+273,'Pr'))
/(airProp2(T2+273,'Pr')))^0.25));

H=Nu* ((airProp2(Tsur+273,'k'))/(2*r2));
end

```

For saline water:

```

function H=hwaterfree(Ts,Tl,l,S)
g=9.81; % m/s^2
Tfilm=(Ts + Tl)/2; % Celcius
Beta=1/(Tfilm+273); % 1/K
kvis=SW_Kviscosity(Tfilm,'C',S,'%'); % m^2/s
Gr= (g*Beta*(abs(Ts-Tl))*(l^3))/(kvis^2); % Dimensionless
Prf= SW_Prandtl(Tfilm,'C',S,'%'); % Dimensionless
kthf= SW_Conductivity(Tfilm,'C',S,'%'); % W/m.K
Ra=Gr*Prf;

Nufree = (0.825 + ((0.387*(Ra^(1/6)))/((1 +
((0.492/Prf)^(9/16))^(8/27))))^2;
H = (Nufree*kthf)/l;
end

```

For cooling water:

```

Mu= SW_Viscosity(11,'C',3.5,'%'); % N.s/m^2
Pr= SW_Prandtl(11,'C',3.5,'%'); % Dimensionless
Re=(4*2)/(pi*0.24*(Mu)); % Dimensionless
kth= SW_Conductivity(11,'C',3.5,'%'); % W/m.K
Nu=0.023*(Re^(4/5))*(Pr^0.3);
hwatere=Nu*(kth/0.24)

```

The following subroutines are used to find the solar irradiance for different sizes of saline water chamber:

For surface area of evaporation=0.0491 m²

```
function Output=I1(t) % Solar Irradiance for summer time (26 July),
radius=0.125 meter

time=[0 1 2 3 4 5 6 7 8 9 10 11 12 12.0167 13 14 15 16 17 18 19 20 21
22 23 24]*3600; % time in seconds
irradiance=[113.47 132.58 124.77 105.06 75.66 42.47 18.85 42.46 75.64
105.05 124.76 132.58 113.48 0 0 0 0 0 0 0 0 0 0 0 0]; % solar
irradiance in Watts

I=pchip(time,irradiance);
Output=ppval(I,t);
end
```

```
function Output=I1w(t) % Solar Irradiance for winter time (10
January), radius=0.125 meter

time=[0 0.7653 0.7657 1 2 3 4 5 6 7 8 9 10 11 11.2350 11.2353 12 13 14
15 16 17 18 19 20 21 22 23 24]*3600; % time in seconds
irradiance=[0 0 41.31 80 127.55 132.35 126.29 118.98 116.03 118.98
126.29 132.35 127.55 80.04 41.31 0 0 0 0 0 0 0 0 0 0 0 0 0]; % solar
irradiance in Watts

I=pchip(time,irradiance);
Output=ppval(I,t);
end
```

For surface area of evaporation=1 m²

```
function Output=I2(t) % Solar Irradiance for summer time (26 July),
radius=0.5643 meter
```

```

time=[0 1 2 3 4 5 6 7 8 9 10 11 12 12.0167 13 14 15 16 17 18 19 20 21
22 23 24]*3600; % time in seconds
irradiance=[502.74 592.34 560.92 469.34 338.96 187.06 73.35 186.90
338.84 469.19 560.85 592.35 502.74 0 0 0 0 0 0 0 0 0 0 0 0]; % solar
irradiance in Watts

I=pchip(time,irradiance);
Output=ppval(I,t);
end

```

For surface area of evaporation=2 m²

```

function Output=I3(t) % Solar Irradiance for summer time (26 July),
radius=0.7981 meter

time=[0 1 2 3 4 5 6 7 8 9 10 11 12 12.0167 13 14 15 16 17 18 19 20 21
22 23 24]*3600; % time in seconds
irradiance=[716.14 836.24 790.70 662.16 480.17 269.47 118.99 269.13
479.30 661.77 790.46 836.29 716.14 0 0 0 0 0 0 0 0 0 0 0 0]; % solar
irradiance in Watts

I=pchip(time,irradiance);
Output=ppval(I,t);
end

```

For surface area of evaporation=3 m²

```

function Output=I4(t) % Solar Irradiance for summer time (26 July),
radius=0.9775 meter

time=[0 1 2 3 4 5 6 7 8 9 10 11 12 12.0167 13 14 15 16 17 18 19 20 21
22 23 24]*3600; % time in seconds
irradiance=[875.68 1023.02 967.15 809.89 586.91 329.35 146.03 329.26
586.85 809.83 967.11 1023.02 875.68 0 0 0 0 0 0 0 0 0 0 0 0]; %
solar irradiance in Watts

```

```

I=pchip(time,irradiance);
Output=ppval(I,t);
end

```

Solar intensity for surface area of evaporation = 0.05 m²

```

function Output=I1flux(t) % Solar Intensity for summer time (26
July), radius=0.125 meter

time=[0 1 2 3 4 5 6 7 8 9 10 11 12 12.0167 13 14 15 16 17 18 19 20 21
22 23 24]*3600; % time in seconds
irradiance=[278.46 325.33 306.17 257.80 185.66 104.22 46.25 104.19
185.62 257.77 306.15 325.33 278.46 0 0 0 0 0 0 0 0 0 0 0 0]; % solar
irradiance in Watt/m^2

I=pchip(time,irradiance);
Output=ppval(I,t);
end

```

Ambient temperature for hot conditions:

```

function Output=AmbientTemp(t) % Ambient Temperature for summer time
(26 July)

time=[0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
24]*3600; % time in seconds

Temperature=[35.9 37.8 38.7 38.9 39.5 41.7 43.8 44.9 44.7 42.2 40.8
39.7 37.7 35.4 35.9 35.9 34.9 34.4 35.3 33.6 33.5 33.3 32.8 31.8
32.7]; % Ambient Temperature, Celcius

T=pchip(time,Temperature);
Output=ppval(T,t);
end

```

Ambient temperature for cold conditions:

```
function Output=AmbientTempw(t) % Ambient Temperature for winter time
(10 January)

time=[0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
24]*3600; % time in seconds

Temperature=[10.6 11.0 12.6 15.1 16.3 17.0 17.2 17.1 17.0 17.0 16.6
16.2 15.8 15.4 15.2 15.1 14.8 14.5 15.0 15.1 15.5 15.6 15.3 15.4
15.4];% Ambient Temperature, Celcius

T=pchip(time, Temperature);
Output=ppval(T,t);
end
```

APPENDIX (E)

WATER AND AIR PROPERTIES

The properties of air are calculated using the following subroutine:

```
function varargout=airProp2(T, prop)
%-----
% Interpolates thermodynamic air properties
% Temp. range: 100-2500 K
% According to Eckert & Drake, Analysis of Heat
% and Mass Transfer, p. 780
%
% Values are in SI-units:
%
%   col-#   prop.   units
%   -----
%   1       T       K
%   2       rho     kg/m^3
%   3       cp      J/(kg K)
%   4       mu      kg/ms
%   5       nu      m^2/s
%   6       k       W/(m K)
%   7       alpha   m^2/s
%   8       Pr      -
%
% Example 1:   out=airProp2(296, 'ny')
% Example 2:
%   [cp, nu]=airProp2([333 444],{'cp' 'ny'})
%-----
% (c)2004 by Stefan Billig
%-----
% Last Change: 04-Jun-2004
%-----
```

```

% check # of input arguments
if ~isequal(nargin,2)
    error('airProp2 requires 2 input arguments!')
    return
    % check temperature request
elseif find(T<100) | ~isnumeric(T)
    error('Valid temperature range: 100 <= T[K] <= 2500')
    return
end
% get table
load propTabAir2
% if multi property request
if iscell(prop)
    % scan along cells
    for idx=1:length(prop)
        % identify property column
        col=find(strcmp(propInfo,prop(idx)));
        if isempty(col)
            disp(['Property "' char(prop(idx)) '" not recognized!'])
        else
            % create output
            varargout{idx}=interp1(airTab(:,1),airTab(:,col),T);
        end
    end
end
% single property request
else
    % identify property column
    col=find(strcmp(propInfo,prop));
    if isempty(col)
        disp(['Property "' prop '" not recognized!'])
    else
        % create output
        varargout{1}=interp1(airTab(:,1),airTab(:,col),T);
    end
end
end

```

The properties of saline water are calculated using the following subroutine:

```
function cp = SW_SpcHeat(T,uT,S,uS)
    % SW_SpcHeat    Specific heat at constant pressure of seawater

%=====
%=====
% USAGE:  cp = SW_SpcHeat(T,uT,S,uS)
%
% DESCRIPTION:
%   Specific heat of seawater at 0.1 MPa given by [1]
%
% INPUT:
%   T  = temperature
%   uT = temperature unit
%       'C' : [degree Celsius] (ITS-90)
%       'K' : [Kelvin]
%       'F' : [degree Fahrenheit]
%       'R' : [Rankine]
%   S  = salinity
%   uS = salinity unit
%       'ppt': [g/kg] (reference-composition salinity)
%       'ppm': [mg/kg] (in parts per million)
%       'w'  : [kg/kg] (mass fraction)
%       '%'  : [kg/kg] (in parts per hundred)
%
%   Note: T and S must have the same dimensions
%
% OUTPUT:
%   cp = specific heat [J/kg-K]
%
%   Note: cp will have the same dimensions as T and S
%
% VALIDITY: 0 < T < 180 C; 0 < S < 180 g/kg;
%
% ACCURACY: 0.28%
%
% REVISION HISTORY:
%   2009-12-18: Mostafa H. Sharqawy (mhamed@mit.edu), MIT
```

```

%           - Initial version
%   2012-06-06: Karan H. Mistry (mistry@mit.edu), MIT
%           - Allow T,S input in various units
%           - Allow T,S to be matrices of any size
%
% DISCLAIMER:
%   This software is provided "as is" without warranty of any
kind.
%   See the file sw_copy.m for conditions of use and licence.
%
% REFERENCES:
%   [1] D. T. Jamieson, J. S. Tudhope, R. Morris, and G.
Cartwright,
%       Physical properties of sea water solutions: heat capacity,
%       Desalination, 7(1), 23-30, 1969.

%=====
====

%% CHECK INPUT ARGUMENTS

% CHECK THAT S&T HAVE SAME SHAPE
if ~isequal(size(S),size(T))
    error('check_stp: S & T must have same dimensions');
end

% CONVERT TEMPERATURE INPUT TO °C
switch lower(uT)
    case 'c'
    case 'k'
        T = T - 273.15;
    case 'f'
        T = 5/9*(T-32);
    case 'r'
        T = 5/9*(T-491.67);
    otherwise
        error('Not a recognized temperature unit. Please use
''C'', ''K'', ''F'', or ''R''');

```

```

end

% CONVERT SALINITY TO PPT
switch lower(uS)
    case 'ppt'
    case 'ppm'
        S = S/1000;
    case 'w'
        S = S*1000;
    case '%'
        S = S*10;
    otherwise
        error('Not a recognized salinity unit. Please use ''ppt'',
''ppm'', ''w'', or ''%''');
end

% CHECK THAT S & T ARE WITHIN THE FUNCTION RANGE
if ~isequal((T<0)+(T>180),zeros(size(T)))
    warning('Temperature is out of range for specific heat
function 0<T<180 C');
end

if ~isequal((S<0)+(S>180),zeros(size(S)))
    warning('Salinity is out of range for specific heat function
0<S<180 g/kg');
end

%% BEGIN

T = 1.00024*T;      %convert from T_90 to T_68
S = S / 1.00472;    %convert from S to S_P

A = 4206.8 - 6.6197*S + 1.2288E-2*S.^2;
B = -1.1262 + 5.4178E-2*S - 2.2719E-4*S.^2;
C = 1.2026E-2 - 5.3566E-4*S + 1.8906E-6*S.^2;
D = 6.8777E-7 + 1.517E-6 *S - 4.4268E-9*S.^2;

```

```

        cp = A + B.*T + C.*T.^2 + D.*T.^3;

end

function rho = SW_Density(T,uT,S,uS)
    % SW_Density    Density of seawater

%=====
=====
    % USAGE:   rho = SW_Density(T,uT,S,uS)
    %
    % DESCRIPTION:
    %   Density of seawater at atmospheric pressure (0.1 MPa) using
Eq. (8)
    %   given by [1] which best fit the data of [2] and [3]. The pure
water
    %   density equation is a best fit to the data of [4].
    %   Values at temperature higher than the normal boiling
temperature are
    %   calculated at the saturation pressure.
    %
    % INPUT:
    %   T   = temperature
    %   uT  = temperature unit
    %       'C' : [degree Celsius] (ITS-90)
    %       'K' : [Kelvin]
    %       'F' : [degree Fahrenheit]
    %       'R' : [Rankine]
    %   S   = salinity
    %   uS  = salinity unit
    %       'ppt': [g/kg] (reference-composition salinity)
    %       'ppm': [mg/kg] (in parts per million)
    %       'w'  : [kg/kg] (mass fraction)
    %       '%'  : [kg/kg] (in parts per hundred)
    %
    %   Note: T and S must have the same dimensions

```

```

%
% OUTPUT:
%   rho = density [kg/m^3]
%
%   Note: rho will have the same dimensions as T and S
%
% VALIDITY: 0 < T < 180 C; 0 < S < 160 g/kg;
%
% ACCURACY: 0.1%
%
% REVISION HISTORY:
%   2009-12-18: Mostafa H. Sharqawy (mhamed@mit.edu), MIT
%               - Initial version
%   2012-06-06: Karan H. Mistry (mistry@mit.edu), MIT
%               - Allow T,S input in various units
%               - Allow T,S to be matrices of any size
%
% DISCLAIMER:
%   This software is provided "as is" without warranty of any
kind.
%   See the file sw_copy.m for conditions of use and license.
%
% REFERENCES:
%   [1] M. H. Sharqawy, J. H. Lienhard V, and S. M. Zubair,
Desalination
%       and Water Treatment, 16, 354-380, 2010.
(http://web.mit.edu/seawater/)
%   [2] Isdale, and Morris, Desalination, 10(4), 329, 1972.
%   [3] Millero and Poisson, Deep-Sea Research, 28A (6), 625, 1981
%   [4] IAPWS release on the Thermodynamic properties of ordinary
water substance, 1996.

%=====
====

%% CHECK INPUT ARGUMENTS

% CHECK THAT S&T HAVE SAME SHAPE

```

```

if ~isequal(size(S),size(T))
    error('check_stp: S & T must have same dimensions');
end

% CONVERT TEMPERATURE INPUT TO °C
switch lower(uT)
    case 'c'
    case 'k'
        T = T - 273.15;
    case 'f'
        T = 5/9*(T-32);
    case 'r'
        T = 5/9*(T-491.67);
    otherwise
        error('Not a recognized temperature unit. Please use
''C'', ''K'', ''F'', or ''R'');
end

% CONVERT SALINITY TO PPT
switch lower(uS)
    case 'ppt'
    case 'ppm'
        S = S/1000;
    case 'w'
        S = S*1000;
    case '%'
        S = S*10;
    otherwise
        error('Not a recognized salinity unit. Please use ''ppt'',
''ppm'', ''w'', or ''%'');
end

% CHECK THAT S & T ARE WITHIN THE FUNCTION RANGE
if ~isequal((T<0)+(T>180),zeros(size(T)))
    warning('Temperature is out of range for density function 0 <
T < 180 C');
end

```

```

    if ~isequal((S<0)+(S>160),zeros(size(S)))
        warning('Salinity is out of range for density function 0 < S <
160 g/kg');
    end

    %% BEGIN

    s = S/1000;

    a = [
        9.9992293295E+02
        2.0341179217E-02
        -6.1624591598E-03
        2.2614664708E-05
        -4.6570659168E-08
    ];

    b = [
        8.0200240891E+02
        -2.0005183488E+00
        1.6771024982E-02
        -3.0600536746E-05
        -1.6132224742E-05
    ];

    rho_w = a(1) + a(2)*T + a(3)*T.^2 + a(4)*T.^3 + a(5)*T.^4;
    D_rho = b(1)*s + b(2)*s.*T + b(3)*s.*T.^2 + b(4)*s.*T.^3 +
b(5)*s^2.*T.^2;
    rho    = rho_w + D_rho;

end

function k = SW_Conductivity(T,uT,S,uS)

```

```

% SW_Conductivity      Thermal conductivity of seawater

%=====
====

% USAGE:   k = SW_Conductivity(T,uT,S,uS)
%
% DESCRIPTION:
%   Thermal conductivity of seawater at 0.1 MPa given by [1]
%   Values at temperature higher than the normal boiling
temperature
%   are calculated at the saturation pressure.
%
% INPUT:
%   T = temperature
%   uT = temperature unit
%       'C' : [degree Celsius] (ITS-90)
%       'K' : [Kelvin]
%       'F' : [degree Fahrenheit]
%       'R' : [Rankine]
%   S = salinity
%   uS = salinity unit
%       'ppt': [g/kg] (reference-composition salinity)
%       'ppm': [mg/kg] (in parts per million)
%       'w' : [kg/kg] (mass fraction)
%       '%' : [kg/kg] (in parts per hundred)
%
%   Note: T and S must have the same dimensions
%
% OUTPUT:
%   k = thermal conductivity [W/m K]
%
%   Note: k will have the same dimensions as T and S
%
% VALIDITY: 0 < T < 180 C; 0 < S < 160 g/kg
%
% ACCURACY: 3.0%
%
% REVISION HISTORY:

```

```

% 2009-12-18: Mostafa H. Sharqawy (mhamed@mit.edu), MIT
%           - Initial version
% 2012-06-06: Karan H. Mistry (mistry@mit.edu), MIT
%           - Allow T,S input in various units
%           - Allow T,S to be matrices of any size
%
% DISCLAIMER:
% This software is provided "as is" without warranty of any
kind.
% See the file sw_copy.m for conditions of use and licence.
%
% REFERENCES:
% [1] D. T. Jamieson, and J. S. Tudhope, Desalination, 8, 393-
401, 1970.

%=====
====

%% CHECK INPUT ARGUMENTS

% CHECK THAT S&T HAVE SAME SHAPE
if ~isequal(size(S),size(T))
    error('check_stp: S & T must have same dimensions');
end

% CONVERT TEMPERATURE INPUT TO °C
switch lower(uT)
    case 'c'
    case 'k'
        T = T - 273.15;
    case 'f'
        T = 5/9*(T-32);
    case 'r'
        T = 5/9*(T-491.67);
    otherwise
        error('Not a recognized temperature unit. Please use
''C'', ''K'', ''F'', or ''R'');
end

```

```

% CONVERT SALINITY TO PPT
switch lower(uS)
    case 'ppt'
    case 'ppm'
        S = S/1000;
    case 'w'
        S = S*1000;
    case '%'
        S = S*10;
    otherwise
        error('Not a recognized salinity unit. Please use ''ppt'',
''ppm'', ''w'', or ''%''');
end

% CHECK THAT S & T ARE WITHIN THE FUNCTION RANGE
if ~isequal((T<0)+(T>180),zeros(size(T)))
    warning('Temperature is out of range for thermal conductivity
function 0<T<180 C');
end

if ~isequal((S<0)+(S>160),zeros(size(S)))
    warning('Salinity is out of range for thermal conductivity
function 0<S<160 g/kg');
end

%% BEGIN

T = 1.00024*T;      %convert from T_90 to T_68
S = S / 1.00472;    %convert from S to S_P
k = 10.^(log10(240+0.0002*S)+0.434*(2.3-
(343.5+0.037*S)./(T+273.15)).*(1-(T+273.15)./(647.3+0.03*S)).^(1/3)-
3));

end

```

```

function Pr = SW_Prandtl(T,uT,S,uS)
    % SW_Prandtl    Prandtl number of seawater

%=====
%=====
    % USAGE:  Pr = SW_Prandtl(T,uT,S,uS)
    %
    % DESCRIPTION:
    %   Prandtl number of seawater at atmospheric pressure (0.1 MPa)
using
    %   specific heat, viscosity, and thermal conductivity
    correlations given in [1].
    %   Values at temperature higher than the normal boiling
temperature
    %   are calculated at the saturation pressure.
    %
    % INPUT:
    %   T   = temperature
    %   uT  = temperature unit
    %       'C' : [degree Celsius] (ITS-90)
    %       'K' : [Kelvin]
    %       'F' : [degree Fahrenheit]
    %       'R' : [Rankine]
    %   S   = salinity
    %   uS  = salinity unit
    %       'ppt': [g/kg] (reference-composition salinity)
    %       'ppm': [mg/kg] (in parts per million)
    %       'w'  : [kg/kg] (mass fraction)
    %       '%'  : [kg/kg] (in parts per hundred)
    %
    %   Note: T and S must have the same dimensions
    %
    % OUTPUT:
    %   Pr = Prandtl number [-]
    %
    %   Note: Pr will have the same dimensions as T and S
    %
    % VALIDITY: 0 < T < 180 C and 0 < S < 150 g/kg;

```

```

%
% ACCURACY: 3.4% (estimated at average value within the range)
%
% REVISION HISTORY:
%   2009-12-18: Mostafa H. Sharqawy (mhamed@mit.edu), MIT
%               - Initial version
%   2012-06-06: Karan H. Mistry (mistry@mit.edu), MIT
%               - Allow T,S input in various units
%               - Allow T,S to be matrices of any size
%
% DISCLAIMER:
%   This software is provided "as is" without warranty of any
kind.
%   See the file sw_copy.m for conditions of use and licence.
%
% REFERENCES:
%   [1] M. H. Sharqawy, J. H. Lienhard V, and S. M. Zubair,
Desalination
%       and Water Treatment, 16, 354-380, 2010.
(http://web.mit.edu/seawater/)

%=====
====

% RANGE CHECKING NOT REQUIRED SINCE OTHER PROPERTIES ARE CALLED

%% BEGIN

cp = SW_SpcHeat(T,uT,S,uS);
mu = SW_Viscosity(T,uT,S,uS);
k  = SW_Conductivity(T,uT,S,uS);
Pr = cp.*mu./k;

end

function mu = SW_Viscosity(T,uT,S,uS)
% SW_Viscosity    Dynamic viscosity of seawater

```

```

%=====
=====
% USAGE:  mu = SW_Viscosity(T,uT,S,uS)
%
% DESCRIPTION:
%   Dynamic viscosity of seawater at atmospheric pressure (0.1
MPa) using
%   Eq. (22) given in [1] which best fit the data of [2], [3] and
[4].
%   The pure water viscosity equation is a best fit to the data of
[5].
%   Values at temperature higher than the normal boiling
temperature
%   are calculated at the saturation pressure.
%
% INPUT:
%   T  = temperature
%   uT = temperature unit
%       'C'  : [degree Celsius] (ITS-90)
%       'K'  : [Kelvin]
%       'F'  : [degree Fahrenheit]
%       'R'  : [Rankine]
%   S  = salinity
%   uS = salinity unit
%       'ppt': [g/kg] (reference-composition salinity)
%       'ppm': [mg/kg] (in parts per million)
%       'w'  : [kg/kg] (mass fraction)
%       '%'  : [kg/kg] (in parts per hundred)
%
%   Note: T and S must have the same dimensions
%
% OUTPUT:
%   mu = dynamic viscosity [kg/m-s]
%
%   Note: mu will have the same dimensions as T and S
%
% VALIDITY: 0 < T < 180 C and 0 < S < 150 g/kg;

```

```

%
% ACCURACY: 1.5%
%
% REVISION HISTORY:
%   2009-12-18: Mostafa H. Sharqawy (mhamed@mit.edu), MIT
%               - Initial version
%   2012-06-06: Karan H. Mistry (mistry@mit.edu), MIT
%               - Allow T,S input in various units
%               - Allow T,S to be matrices of any size
%
% DISCLAIMER:
%   This software is provided "as is" without warranty of any
kind.
%   See the file sw_copy.m for conditions of use and licence.
%
% REFERENCES:
%   [1] M. H. Sharqawy, J. H. Lienhard V, and S. M. Zubair,
Desalination
%       and Water Treatment, 16, 354-380, 2010.
(http://web.mit.edu/seawater/)
%   [2] B. M. Fabuss, A. Korosi, and D. F. Othmer, J., Chem. Eng.
Data 14(2), 192, 1969.
%   [3] J. D. Isdale, C. M. Spence, and J. S. Tudhope,
Desalination, 10(4), 319 - 328, 1972
%   [4] F. J. Millero, The Sea, Vol. 5, 3 - 80, John Wiley, New
York, 1974
%   [5] IAPWS release on the viscosity of ordinary water substance
2008

%=====
====

%% CHECK INPUT ARGUMENTS

% CHECK THAT S&T HAVE SAME SHAPE
if ~isequal(size(S),size(T))
    error('check_stp: S & T must have same dimensions');
end

```

```

% CONVERT TEMPERATURE INPUT TO °C
switch lower(uT)
    case 'c'
    case 'k'
        T = T - 273.15;
    case 'f'
        T = 5/9*(T-32);
    case 'r'
        T = 5/9*(T-491.67);
    otherwise
        error('Not a recognized temperature unit. Please use
''C'', ''K'', ''F'', or ''R'');
end

% CONVERT SALINITY TO PPT
switch lower(uS)
    case 'ppt'
    case 'ppm'
        S = S/1000;
    case 'w'
        S = S*1000;
    case '%'
        S = S*10;
    otherwise
        error('Not a recognized salinity unit. Please use ''ppt'',
''ppm'', ''w'', or ''%'');
end

% CHECK THAT S & T ARE WITHIN THE FUNCTION RANGE
if ~isequal((T<0)+(T>180),zeros(size(T)))
    warning('Temperature is out of range for Viscosity function
0<T<180 C');
end

if ~isequal((S<0)+(S>150),zeros(size(S)))
    warning('Salinity is out of range for Viscosity function
0<S<150 g/kg');
end

```

```

end

%% BEGIN

S = S/1000;

a = [
    1.5700386464E-01
    6.4992620050E+01
   -9.1296496657E+01
    4.2844324477E-05
    1.5409136040E+00
    1.9981117208E-02
   -9.5203865864E-05
    7.9739318223E+00
   -7.5614568881E-02
    4.7237011074E-04
];

mu_w = a(4) + 1./(a(1)*(T+a(2)).^2+a(3));

A = a(5) + a(6) * T + a(7) * T.^2;
B = a(8) + a(9) * T + a(10)* T.^2;
mu = mu_w.*(1 + A.*S + B.*S.^2);
end

function nu = SW_Kviscosity(T,uT,S,uS)
    % SW_Kviscosity    Kinematic viscosity of seawater

    %=====
    %==
    % USAGE:  nu = SW_Kviscosity(T,uT,S,uS)
    %
    % DESCRIPTION:
    %    Kinematic viscosity of seawater at atmospheric pressure (0.1
    MPa) using

```

```

% dynamic viscosity and density correlations given in [1]
% Values at temperature higher than the normal boiling
temperature
% are calculated at the saturation pressure.
%
% INPUT:
% T = temperature
% uT = temperature unit
%      'C' : [degree Celsius] (ITS-90)
%      'K' : [Kelvin]
%      'F' : [degree Fahrenheit]
%      'R' : [Rankine]
% S = salinity
% uS = salinity unit
%      'ppt': [g/kg] (reference-composition salinity)
%      'ppm': [mg/kg] (in parts per million)
%      'w' : [kg/kg] (mass fraction)
%      '%' : [kg/kg] (in parts per hundred)
%
% Note: T and S must have the same dimensions
%
% OUTPUT:
% nu = specific kinematic viscosity [m^2/s]
%
% Note: nu will have the same dimensions as T and S
%
% VALIDITY: 0 < T < 180 C and 0 < S < 150 g/kg;
%
% ACCURACY: 1.5% (estimated at average value within the range)
%
% REVISION HISTORY:
% 2009-12-18: Mostafa H. Sharqawy (mhamed@mit.edu), MIT
%            - Initial version
% 2012-06-06: Karan H. Mistry (mistry@mit.edu), MIT
%            - Allow T,S input in various units
%            - Allow T,S to be matrices of any size
%
% DISCLAIMER:

```

```

% This software is provided "as is" without warranty of any
kind.
% See the file sw_copy.m for conditions of use and licence.
%
% REFERENCES:
% [1] M. H. Sharqawy, J. H. Lienhard V, and S. M. Zubair,
Desalination
% and Water Treatment, 16, 354-380, 2010.
(http://web.mit.edu/seawater/)

%=====
====

%% BEGIN

mu = SW_Viscosity(T,uT,S,uS);
rho = SW_Density(T,uT,S,uS);
nu = mu./rho;

end

function a = SW_Exergy(T,uT,S,uS,T0,S0)
% SW_Exergy Specific exergy of seawater, J/kg

%=====
====

% USAGE: a = SW_Exergy(T,uT,S,uS,T0,S0)
%
% DESCRIPTION:
% Specific exergy of seawater at atmospheric pressure (0.1 MPa)
using
% specific internal energy, specific entropy, and chemical
potential correlations given in [1].
% Values at temperature higher than the normal boiling
temperature
% are calculated at the saturation pressure.

```

```

%
% INPUT:
%   T = temperature
%   uT = temperature unit
%       'C' : [degree Celsius] (ITS-90)
%       'K' : [Kelvin]
%       'F' : [degree Fahrenheit]
%       'R' : [Rankine]
%   S = salinity
%   uS = salinity unit
%       'ppt': [g/kg] (reference-composition salinity)
%       'ppm': [mg/kg] (in parts per million)
%       'w' : [kg/kg] (mass fraction)
%       '%' : [kg/kg] (in parts per hundred)
%
%   Note: T and S must have the same dimensions
%   Note: T0 and S0 should have the same units given for T and S
(i.e. uT and uS)
%
% OUTPUT:
%   a = specific exergy [J/kg]
%
%   Note: af will have the same dimensions as T and S
%
% VALIDITY: 10 < T < 120 C, 0 < S < 120 g/kg
%
% ACCURACY: 0.5% (estimated at average value within the range)
%
% REVISION HISTORY:
%   2009-12-18: Mostafa H. Sharqawy (mhamed@mit.edu), MIT
%               - Initial version
%   2012-06-06: Karan H. Mistry (mistry@mit.edu), MIT
%               - Allow T,S input in various units
%               - Allow T,S to be matrices of any size
%
% DISCLAIMER:
%   This software is provided "as is" without warranty of any
kind.

```

```

% See the file sw_copy.m for conditions of use and licence.
%
% REFERENCES:
% [1] M. H. Sharqawy, J. H. Lienhard V, and S. M. Zubair,
Desalination
% and Water Treatment, 16, 354-380, 2010.
(http://web.mit.edu/seawater/)

%=====
====

%% CHECK INPUT ARGUMENTS

% CHECK THAT S&T HAVE SAME SHAPE
if ~isequal(size(S),size(T))
    error('check_stp: S & T must have same dimensions');
end

% CONVERT TEMPERATURE INPUT TO °C
switch lower(uT)
    case 'c'
    case 'k'
        T = T - 273.15;
        T0 = T0 - 273.15;
    case 'f'
        T = 5/9*(T-32);
        T0 = 5/9*(T0-32);
    case 'r'
        T = 5/9*(T-491.67);
        T0 = 5/9*(T0-491.67);
    otherwise
        error('Not a recognized temperature unit. Please use
''C'', ''K'', ''F'', or ''R''');
end

% CONVERT SALINITY TO PPT
switch lower(uS)
    case 'ppt'

```

```

        case 'ppm'
            S = S/1000;
            S0 = S0/1000;
        case 'w'
            S = S*1000;
            S0 = S0*1000;
        case '%'
            S = S*10;
            S0 = S0*10;
        otherwise
            error('Not a recognized salinity unit. Please use 'ppt',
                'ppm', 'w', or '%');
    end

% RANGE CHECKING NOT REQUIRED SINCE OTHER PROPERTIES ARE CALLED

%% BEGIN

u_sw      = SW_IntEnergy(T,'C',S,'ppt');
s_sw      = SW_Entropy(T,'C',S,'ppt');
u_sw_star = SW_IntEnergy(T0,'C',S,'ppt');
s_sw_star = SW_Entropy(T0,'C',S,'ppt');
mu_w_star = ChemPot_W(T0,'C',S,'ppt');
mu_s_star = ChemPot_S(T0,'C',S,'ppt');
mu_w_0    = ChemPot_W(T0,'C',S0,'ppt');
mu_s_0    = ChemPot_S(T0,'C',S0,'ppt');

a = (u_sw - u_sw_star) - (T0+273.15).*(s_sw-s_sw_star)...
    +(1-0.001*S).*(mu_w_star-mu_w_0)+0.001*S.*(mu_s_star-mu_s_0);

end

```