Simulation of a Thermal Desalination System

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SIMULATION OF A THERMAL DESALINATION SYSTEM

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Author's Declaration

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1. Muhammad Ali (ME-17087)
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    - Modeling and Simulation of Single-Effect System
2. Hammad Tahir (ME-17074)
    - Modeling of Multi-Effect System (8 and 10 Effects)
    - Results and Analysis
3. Muhammad Sameer Ali Khan (ME-17082)
    - Modeling of Multi-Effect System (12 and 14 Effects)
    - Results and Analysis
4. Mohammad Mowahhad Ullah (ME-17127)
    - Validation of Model
    - Industrial Research

ABSTRACT

Desalination technology offers the sustainable solution of providing freshwater supply to the water-scarce coastal areas such as the region from Karachi and Gwadar cities situated in Pakistan. Reverse osmosis (RO) desalination is an energy-efficient technology. However, recent advances such as the integration of adsorption/absorption vapor compression systems and the development of new antiscalants for the multi-effect desalination (MED) technology have made it a competitive choice. The MED unit's current top brine temperature (TBT) is 65 °C (because of salt precipitation in the evaporators), for which 8 – 10 falling film evaporators can be installed. But with the progress in antiscalants, the TBT can be stretched to 85 °C that reflects the incorporation of more evaporators and hence more freshwater productivity. For this purpose, a mathematical model of the MED unit is developed in Engineering Equation Solver (EES), and the performance of the MED unit is assessed at higher TBT. The mathematical model is validated with the empirical model available in the literature and with the commercial desalination plant located in Qatar. It is found that the performance ratio of the MED unit with TBT of 80 °C is 22.8% higher than that of 65 °C TBT. Furthermore, the specific heat transfer area is 18% higher, and the cooling water requirement is 76% lesser for the MED unit with TBT = 80 °C as compared to the MED unit with TBT = 65 °C.

EXECUTIVE SUMMARY

Desalination is the process of extracting brine from salty water to make it suitable for drinking domestic, and industrial purposes. However, the process is deemed energy extensive with high waste (brine) rejection and initial capital cost. Nevertheless, desalination is merely an option, not a solution for the prevalent water crisis in the world. Therefore, there is a need to make this process as energy efficient as it could be until the world finds a better alternative to solve the rising water demand.

A detailed study of the thermal desalination system has been presented in the project by employing a parallel feed system that requires the least pump work and most of the flow happens naturally. The energy efficiency of the process has been maximized by employing series of preheaters and a heat recovery box to extract the energy back from the distillate and brine. Flashing of brine and distillate has also been employed to further increase the yield. Thermal vapor compression is additionally used to enable the system to be used as a cogeneration plant. By employing these techniques, most of the heat has been utilized carefully to maximize the output.

The results of changing some of the characteristic parameters have also been observed and a detailed study has been provided regarding the choice of optimum temperature, number of evaporators, steam pressure, heat transfer area, etc. It has been found that the parallel/crossflow eight effects multi-effect thermal vapor compression system with a brine boiling temperature of 65°C in the first evaporator and a motive steam pressure of 1500KPa tends to give the maximum performance.

In the end, validation of Ras Laffan, Qatar desalination plant has been carried out to substantiate the accuracy of the modeling equations. Further study of more advanced MED systems has also been presented which are not very energy efficient at the moment, but with the advent of modern antiscalant, the research presented in the project will be used to make them commercially viable.

ACKNOWLEDGMENTS

We would like to immensely expand our words of gratitude for our Final Year Project Advisor Dr. Muhammad Shakaib, this project has become possible due to his utmost support and guidance. We deeply acknowledge his disinterested guidance and teaching that made this research possible. We were able to learn a lot because of his continual advice and the excellent research mindset that he transferred to us. His advice on exploring the latest research on the topic was specifically helpful in incorporating the ingenious features in our model that significantly improved the performance of our model.

We owe special thanks to Dr. Furqan Tahir for being a perfect mentor and taking out time from his tough schedule to help us become familiar with the techniques being practically employed in the industry. Due to his brilliance, we were able to validate our model with an already installed plant.

Last but not the least, we are thankful to Automotive Department for providing us with the software Engineering Equation Solver which has been used throughout the project.

DEDICATION

We would like to dedicate this project to the entire research community who are striving hard to find ingenious ways to solve the water crisis from the world.

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LIST OF ABBREVIATIONS

MED	Multi Effect Desalination
MEB	Multi Effect Boiling
MSF	Multi Stage Flash
TVC	Thermal Vapor Compression
TBT	Top Brine Temperature
PR	Performance Ratio
GOR	Gain Ratio
MVC	Mechanical Vapor Compression
HDH	Humidification-Dehumidification Desalination
Frz	Freezing
RO	Reverse Osmosis
FO	Forward Osmosis
ED	Electro-Dyalysis
NF	Nano Filtration
I.Ex	Ion-Exchange Desalination
G.Hyd	Gas Hydrate
LLE	Liquid-Liquid Extraction
Ads	Adsorption Technology
SD	Solar Distillation

LIST OF SYMBOLS

SYMBOLS

$\boldsymbol{F}$	Flow rate of feed to each effect ($\frac{kg}{s}$)
$\boldsymbol{D}$	Flow rate of distillate from each effect ($\frac{kg}{s}$)
$\boldsymbol{B}$	Flow rate of brine from each effect ($\frac{kg}{s}$)
$\boldsymbol{X}$	Salt concentration ($\boldsymbol{ppm}$)
$\boldsymbol{T}$	Temperature in each effect (°$\boldsymbol{C}$)
$\boldsymbol{Q}$	Rate of heat transfer ($\frac{kJ}{s}$)
$\boldsymbol{hfg}$	Specific enthalpy of vaporization in each effect ($\frac{kJ}{kg}$)
$\boldsymbol{S}$	Flow rate of steam from each effect ($\frac{kg}{s}$)
$\boldsymbol{C_p}$	Specific heat capacity ($\frac{kJ}{kg-°C}$)
$\boldsymbol{Cw}$	Flow rate of cooling water ($\frac{kg}{s}$)
$\boldsymbol{BPE}$	Boiling Point Elevation (°$\boldsymbol{C}$)
$\boldsymbol{sA}$	Specific heat transfer area ($\frac{m^2-s}{kg}$)
$\boldsymbol{sCw}$	Specific rate of cooling water
$\boldsymbol{A}$	Heat transfer surface area ($\boldsymbol{m^2}$)
$\boldsymbol{U}$	Overall heat transfer coefficient ($\frac{kW}{m^2-C}$)
$\boldsymbol{LMTD}$	Logarithmic mean temperature difference (°$\boldsymbol{C}$)
$\boldsymbol{P}$	Pressure (kPa)
$\boldsymbol{x}$	Quantity of entrained vapors ($\frac{kg}{s}$)
$\boldsymbol{PCF}$	Pressure correction factor
$\boldsymbol{TCF}$	Temperature correction factor
$\boldsymbol{R_a}$	Entrainment ratio
$\boldsymbol{t}$	Temperature (°C)
$\boldsymbol{n}$	Number of effects

SUBSCRIPTS

$1,2,..,n$	Effect number
$\boldsymbol{f}$	Feed seawater/Brine flashing
$\boldsymbol{b}$	Rejected brine
$\boldsymbol{avg}$	Average
$\boldsymbol{s}$	Heating steam
$\boldsymbol{d}$	Distillate Flashing
$\boldsymbol{dd}$	Total distillate in flashing boxes.
$\boldsymbol{v}$	Vapor phase
$\boldsymbol{HR}$	Heat recovery box
$\boldsymbol{ff}$	Feed water
$\boldsymbol{r}$	Entrained vapor
$\boldsymbol{m}$	Motive steam
$\boldsymbol{sat}$	Saturated
$\boldsymbol{e}$	Evaporator
$\boldsymbol{c}$	Condenser
$\boldsymbol{p}$	Preheaters

UNITED NATIONS SUSTAINABLE DEVELOPMENT GOALS

The Sustainable Development Goals (SDGs) are the blueprint to achieve a better and more sustainable future for all. They address the global challenges we face, including poverty, inequality, climate change, environmental degradation, peace and justice. There is a total of 17 SDGs as mentioned below. Check the appropriate SDGs related to the project.

☐ No Poverty

☐ Zero Hunger

☐ Good Health and Well being

☐ Quality Education

☐ Gender Equality

☒ Clean Water and Sanitation

☐ Affordable and Clean Energy

☐ Decent Work and Economic Growth

☒ Industry, Innovation and Infrastructure

☐ Reduced Inequalities

☐ Sustainable Cities and Communities

☒ Responsible Consumption and Production

☐ Climate Action

☐ Life Below Water

☒ Life on Land

☐ Peace and Justice and Strong Institutions

☒ Partnerships to Achieve the Goals

Chapter 1

INTRODUCTION

1.1 OBJECTIVES:

Following are the objective of this project

- Present a simulation of a 6MIGD thermal desalination plant.
- Optimize the process to make it feasible from engineering perspective with maximum performance.
- Make the system specific to conditions of coastal areas of Pakistan.
- Introduce the effects on performance after the commercial availability of more advance antiscalant.

1.2 SCOPES:

Following are the scopes of this project

- Limiting the Installation, operational, and handling costs to keep the technique manageable and attractive from performance viewpoint.
- Restriction of TBT to keep the performance maximum by avoiding the formation of scale.
- Robust system that can be commercialized by incorporating more economic considerations.

1.3 SIGNIFICANCE AND MOTIVATION:

The rising demand and alarming low level of water has intrigued a necessity for Pakistan to search for a more robust alternative. Desalination, being a reliable and globally practiced method, may turn out as a most effective alternate. The process is considered to be energy extensive with high initial investment, however, this is in fact low if we weigh the merits and reliability in the analysis and then compare it with the other methods to solve the water scarcity problems.

With this project our aim is to study this technique and make it more vigorous with tendency to absorb back the most of the energy supplied to the system and increase the yield ingeniously. This technique is a great method to meet the demand of Pakistan and the abundance of raw material, which is in fact salty water, marks the technique as a viable solution.

1.4 WATER COMPOSITION:

Water, also known as the universal solvent, is a compound made up of hydrogen and oxygen, and is the most abundant and vital genesis to sustain life on the 'Blue Planet'. It exists in mainly three states which comprises solid, liquid, and gaseous forms. The thermodynamic stability of water at various temperatures is what distinguishes and sets apart this gem from its other earthly contenders. Undeniably, the resourcefulness of water as a liquescent is a requisite for all breathing organisms [1].

Although planet Earth is made up of 71 percent of water, the majority of this fraction is inaccessible for human consumption. Around 97.25 percent of this segment is exploited by the oceans, while the other 2.05 percent is covered by various snowy chattels such as glaciers and polar ice caps. Hence, what we're left with is a minor portion that is actually termed as 'consumable'. This somewhat negligible amount survives in the form of lakes, rivers, and groundwater. For that reason, it cannot be denied how exquisite freshwater to mankind is [2], [3].

With the rising demand for freshwater, the need for various innovatory water purification techniques arises. It can be exaggerated by the fact that purer water is required for industrial purposes than human consumption. Likewise, Industrial boilers sustained at high pressure require water at purity levels of around 99.999998%. Hence, if transparency levels of this altitude need to be achieved then something must be done. Meanwhile, seawater which contains an exhilarating quantity of dissolved salts must be desalinated in order to be consumable by humans [2], [3].

1.4.1. FRESH WATER COMPOSITION:

Often referred to as the water planet, the Earth's total hoard of water is around 332.5×10^6 mi^3 of aquatic, from which 96 percent is salty. Of entire freshwater, above 68 percent is sealed in snowy elements such as glaciers and polar ice caps. Further 30 percent of this portion is buried under the earth. A major chunk of freshwater used by individuals is obtained from rivers, however, they comprise only 0.0001 of the remaining one percent of the entire water. The salinity of freshwater is typically <500 milligrams of salt per liter.

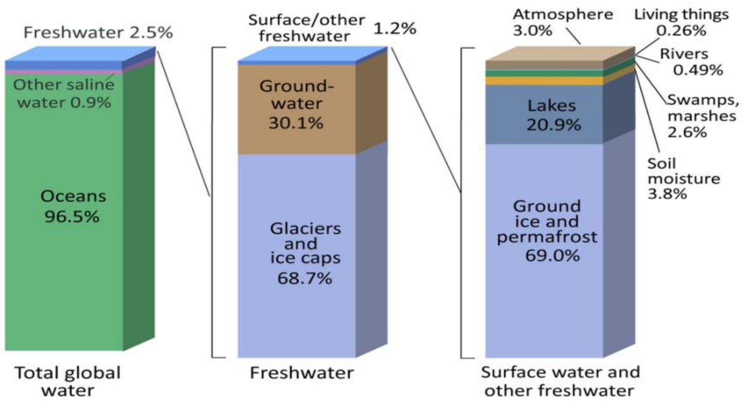


Figure 1.1 Composition of Earth`s water

Water source	Water volume, in cubic miles	Water volume, in cubic kilometers	Percent of freshwater	Percent of total water
Oceans, Seas, & Bays	321,000,000	1,338,000,000	--	96.54
Ice caps, Glaciers, & Permanent Snow	5,773,000	24,064,000	68.7	1.74
Groundwater	5,614,000	23,400,000	--	1.69
Fresh	*2,526,000*	*10,530,000*	*30.1*	*0.76*
Saline	*3,088,000*	*12,870,000*	--	*0.93*
Soil Moisture	3,959	16,500	0.05	0.001
Ground Ice & Permafrost	71,970	300,000	0.86	0.022
Lakes	42,320	176,400	--	0.013
Fresh	*21,830*	*91,000*	*0.26*	*0.007*
Saline	*20,490*	*85,400*	--	*0.006*
Atmosphere	3,095	12,900	0.04	0.001
Swamp Water	2,752	11,470	0.03	0.0008
Rivers	509	2,120	0.006	0.0002
Biological Water	269	1,120	0.003	0.0001

Table 1.1 World`s Fresh Water Resources

1.5 TYPES OF WATER:

Sea Water:

The liquid inhabiting an ocean or occupying a sea is termed Seawater. It comprises 96.5 percent of water mixed with 2.5 percent salts, and a minor amount of some additional ingredients that consist of dissolved minerals and biological constituents, particulates, and several atmospheric gases [4].

Brackish Water:

Brackish water is stated to be the type of water that is prominently more salty than freshwater but not as salty as seawater. This salinity is usually defined in a certain range and not as an exact amount. Furthermore, it can vary due to the effects of the environment.

Brine:

Brine is a highly saturated salt-water solution mainly used for culinary and food processing purposes, for removal of ice from streets and equipment in cold stroked countries and in some of the hi-tech development processes. Unfortunately, it is produced as a by-product of all distillation plants and sometimes various industrial processes also produce it as by-product. Brine is highly dangerous for local marine environment if discharged in sea, hence the need to dispose of it appropriately and apply wastewater treatment preserves.

Wastewater:

Any kind of water that is formerly used in households, industries, businesses, or wherever is termed as wastewater. This kind of water must be treated before it is discharged into the environment or some other source of water in order to maintain the purity of these sources [5].

S.NO.	STATUS OF SALINITY	SALINITY (mg/l)	USES
1.	Fresh	Less than 500	For irrigation and drinking water
2.	Marginal	500 to 1,000	Mostle for irrigigation, detrimental impacts on ecosystems became evident.
3.	Brackish	1,000 to 2,000	For irrigation of certain crops, suitable for the majority of cattle
4.	Saline	2,000 to 10,000	Adaptable to the majority of livestock
5.	Highly Saline	10,000 to 35,000	Highly saline groundwater,Certain animals have a limited usage.
6.	Brine	More than 35,000	Sea water, Certain mining and processing applications exist.

Table 1.2 Classifications of salinity according to salt concentration

1.6 PROPERTIES OF WATER:

1.6.1. PHYSICAL PROPERTIES:

The appearance of water is mainly what defines the physical properties of water. It generally comprises color, taste, temperature, turbidity, and odor. To be adequate for use as drinkable, water must be free from any kind of these impurities.

Water molecules have strong hydrogen bonds ensuing unusual properties in the fluid form. These hydrogen bonds are also responsible for the high melting and boiling points of water. In contrast to other liquids, water has a high value of thermal conductivity, surface tension, specific heat, dipole moment, etc. These properties distinguish it from its contenders. Being a solvent, water plays an essential part in metabolism and helps in the transportation of ions and molecules required for the process. It also helps to regulate the body temperature due to its high latent heat of vaporization [6].

Selected physical properties of water	
molar mass	18.0151 grams per mole
melting point	0.00 °C
boiling point	100.00 °C
maximum density (at 3.98 °C)	1.0000 grams per cubic centimetre
density (25 °C)	0.99701 grams per cubic centimetre
vapour pressure (25 °C)	23.75 torr
heat of fusion (0 °C)	6.010 kilojoules per mole
heat of vaporization (100 °C)	40.65 kilojoules per mole
heat of formation (25 °C)	−285.85 kilojoules per mole
entropy of vaporization (25 °C)	118.8 joules per °C mole
viscosity	0.8903 centipoise
surface tension (25 °C)	71.97 dynes per centimeter

Table 1.3 Key physical properties of water

It stays highly crucial to observe the contamination of water by evaluating its physical condition and quality. The corporeal features of water are frequently corroborated by:

- Color – Water which is pure is infinitely colorless. Any tinted variant means it is polluted and may contain biological constituents. The maximum criterion for color acceptance of safe drinking water is 15 TCU (True Color Unit).
- Taste and odor – Unpolluted water is eternally tasteless and fragrance-free. The Slight discrepancy in smell and taste could stipulate water contamination.
- Turbidity – Purity of water means it must be vibrant and does not captivate radiance. Signs of turbidity can illustrate external affluence in water.
- Temperature – Although the temperature of water isn't used to directly evaluate whether it can be used for drinking purpose or not, still, it is an imperious factor to determine physically the water quality in natural systems like lakes and rivers.

- Solids – When unclean water is filtered out by any means, the leftover solid particles are termed as TDS (Total Dissolved Solids). This amount of TDS must not increase by 300 milligrams/liter to ensure the well-being of breathing organisms and the purity of industrial goods [6].

1.6.2. CHEMICAL PROPERTIES:

Water has an exclusive ability to undergo various types of chemical reactions. Most importantly, it can perform as an acid (proton donor) as well as a base (proton acceptor). Owing to this unique feature, it also possesses the properties of amphoteric substances.

Significant chemical characteristics of water implicate gauging factors such as dissolved oxygen and pH:

- PH – Measured between 0-14, pH of water is used to discern if it is acidic or alkaline in nature. A logarithmic scale is used for assessment purposes.
- Dissolved oxygen – Since the level of oxygen dissolved in water determines the presence of living organisms in it, therefore, it is an important constraint when evaluating water purity and quality. This level must be within specified frontiers [7].

neutral solution	$[H^+] = [OH^-]$	$pH = 7$
acidic solution	$[H^+] > [OH^-]$	$pH < 7$
basic solution	$[OH^-] > [H^+]$	$pH > 7$

Table 1.4 pH of solution

1.7 DRINK WATER STANDARD:

The World Health Organization:

There have been certain guidelines established for drinking water quality by the World Health Organization (WHO), these guidelines are universal and followed whenever water safety is concerned and standards need to be set. The rules proposed in Geneva In the year 1993 are the latest observed guidelines.

WHO believes in the nonstop revision of its guidelines after every few years. However, it is to be noted that some substances still have a minor set of definite guidelines. Thanks to its insignificant data availability to determine its various consequences on living organisms, making it impractical to set a standard frontier. Moreover, some elements are rare and insolvable so their proportion in water is negligible enough to cause any harmful effects. Thus, making it unrealistic to study these elements [8].

The European Union:

On the standard of water envisioned for human consumption, the EU has also issued certain directives such as the 98/83/EC with the most recent improvements in October 2015. This set of guidelines concerns water quality and hygiene which is used for human intake, safeguarding their well-being from any kind of adversarial consequences. Besides, they also guarantee an uncontaminated and non-toxic water supply. The European Union have also established certain criteria for the water properties that is used for drinking purposes, water supplied by tanks and storage, water bottles or basins, and water used by various food-processing corporations [9].

1.8 WATER SITUATION IN PAKISTAN:

Pakistan has been a rich country when we talk about the natural resources it possesses. However, scarcity of water has been a very alarming situation for the country in recent times. As stated by the United Nations Development Program (UNDP) and Pakistan Council of Research for Water Resources (PCRWR), water will grow into a scarce entity by 2025 and will reach its lowest level of 700 cubic meters' availability per capita. It must be noted that the surface water availability for the country in 1951 was around 5260 cubic meters per capita.

The main culprit of water scarcity in Pakistan has always been the agricultural sector which consumes a large chunk of the country's water database. Cash crops which are grown massively on the opportunity cost of domestic crops for export purposes soak an infinite amount of this valuable resource.

Apart from the agricultural issues, there have been many political factors that led towards the current deteriorating situation in terms of the water crisis. There have been no future plans or management to cope up with the water scarcity problem since the government doesn't see this as a problem in itself [10].

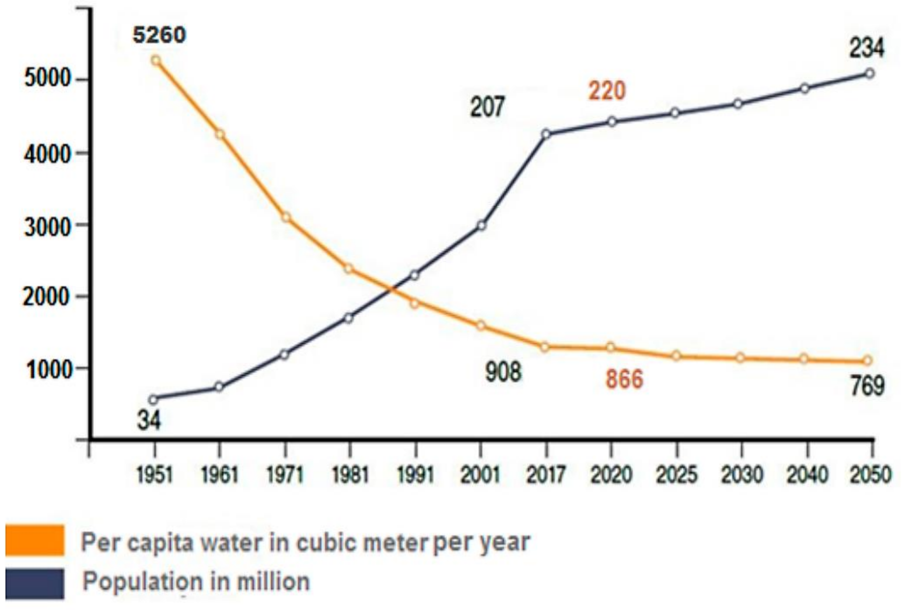


Figure 1.2 per capita water in Pakistan

Tarbela and Mangla dams are the two major dams in the country and since 1960 there have been no new dams built to mediocre the water conditions of the world's most water intensive economy. According to the International Monetary Firm (IMF), Pakistan ranks 3rd among countries facing water shortages. It touched the 'Water Stress Line' as early as 1990 and passed the 'Water Scarcity Line' in 2005. Research on the country's storage capacity stated that Pakistan has the ability to store water for only 30 days. India, on the other hand, can store it for 190 days, and the USA tops the list by a generous amount of 900 days. Moreover, groundwater extraction is also disturbingly high. According to recent data, 61 cubic kilometers of water have been extracted, which is more than the 'sustainable limit'. If the current trend continues and conditions remain preserving, then there might be a drought-like condition in the proximate future.

Water wastage in Pakistan has been a major factor contributing to the worse situation of the country. A large amount of freshwater is wasted every year in the form of used water from homes, agriculture, and industries. This water becomes polluted and is drained into the rivers and ocean. Consequently, the water quality in the country is also very poor and unhealthy. Currently, only 56 percent of the population has access to safe drinking water. There is also a severe distribution of water within the urban and rural segments, with almost 70 percent of the rural population deprived of clean water. Furthermore, bacterial contaminants have risen in the last 15 years causing numerous deaths and diseases due to unhygienic water availability [11].

The climate of Pakistan has also played a major role in the country's low water resource accumulation. Drastic climate changes have significantly reduced the amount of rainfall received by the coastal regions of Sindh and Balochistan and have increased the amount of rainfall received in other regions of the country, especially Punjab, causing floods and spillage of the dams and reservoirs [12].

1.9 SOLUTIONS TO OVERCOME CURRENT SITUATION:

In reference to the above-stated problems, a quick response must be initiated in order to save the few drops of supply that are left. There are numerous methods to overcome the water crisis of Pakistan.

- Development of waste-water treatment facilities in order to recycle the polluted water excreted from industries and households.
- Construction of small and large dams and reservoirs to store excess water during periods of heavy rainfall.
- National water conservation plan- to efficiently design, control and manage water resources and provide controlled irrigation for agricultural purposes.
- Utilization of modern irrigation techniques for farmers.
- Employment of modern water purifying techniques such as desalination, reverse osmosis, filtration, and chlorination [13].

Chapter 2

DESALINATION

2.1. WHY DESALINATION?

Planet Earth, often been referred to as the blue planet, owing to its major water dominant surface, has been facing severe water dilemmas for the past several decades, caused by its exponential inhabitants' growth, climate changes, pooled with colossal industrial requirements, has created drastic water scarcity amongst the human race. The Gulf Cooperation Council (GCC) countries such as Saudi Arabia, Kuwait, UAE, Oman, Qatar, and Bahrain who have little to no surface water availability in the form of lakes and rivers have to rely on their groundwater resources, which have also become saline due to the countries' oceanic parameters and some precarious levels of extractions [14][15]. From 2010 to 2035, the GCC nations' estimated water availability per capita as shown in **Table 2.1**

The superior nature of freshwater being exquisite to mankind is what makes desalination of seawater a go-to choice for the generations to come. The practice of desalination includes the elimination of salt from saline water by various techniques in order to make it consumable by individuals. Seawater desalination techniques can repair the lack of freshwater availability, lessen groundwater depletion and help maintain the traditional water cycle [14][15].

The desalination process comprises two distinguished parts with reference to the salt concentration of water. The one with low salt aggregate is termed freshwater, while the other with an extraordinary volume of salt is called the brine concentrate. According to the World Health Organization (WHO), the tolerable limit for drinking water salinity is 500-1000 ppm. Seawater, on the other hand, entails water ranging from 35000-45000 ppm of dissolved salts [15].

COUNTRY OF GCC	POPULATION IN 2010 (THOUSAND)	WATER AVAILABLE IN 2010 (m^3/cap)	EXPECTED POPULATION IN 2035 (THOUSAND)	WATER AVAILABLE IN 2035 (m^3/cap)
Kuwait	2 737	7.3	4 328	4.6 ±1
Qatar	1 759	33	2 451	21.6±2
Bahrain	1 262	91.9	1 711	67.8±3
U.A.E.	7 512	20	11 042	13.6±2
KSA	27 448	87.4	40 444	59.3±2
Oman	2 803	503	4 922	300±10

Table 2.1 Expected water availability in Gulf countries

2.1.1. ADVANTAGES OF DESALINATION:

Besides eradicating salt from seawater, desalination plays a vital role in providing pure, uncontaminated, and drinkable water to homes, workshops, and metropolises. Similarly, it has numerous additional rewards.

- Provides a substantial amount of freshwater at locations where climate and water conditions are hostile.
- Eases groundwater consumption at areas where surface water is limited
- Aids in sustaining the water cycle by preserving earth water which causes a greater amount of precipitations.
- Any environmental influences caused by desalination can be manageable in long term.

- Scarcity of freshwater causes its price to upsurge dramatically, ensuing cost of desalination implicitly acceptable in that case.
- Ecological cost of the high rate of freshwater withdrawal is excessive, ascertaining desalination a more creditable preference.
- Desalination techniques can be utilized when no other substitutes to acquire freshwater are available [15]–[17].

2.1.2. DRAWBACKS OF DESALINATION:

Desalination looks like a textbook solution for freshwater deficiencies in recent times. However, researchers have already warned the community about its significant environmental impacts and the high cost of production of pure water for consumption. In the same manner, it has some other concerns.

- It can cost millions of dollars to build and drive a plant working on desalination principles.
- The energy requirements to smoothly function a desalination plant are aggressively high.
- Not economically viable in remote locations where availability of fossil fuels and uninterrupted electric supply is a major hindrance.
- Desalination of seawater can have disastrous effects on the environment. Disposal of brine into the oceans is a threat to marine life and ecosystems.
- The burning of fossil fuels to run plants can cause the greenhouse effect and hence leads to global warming and depletion of ozone [15]–[17].

2.2. PAKISTAN`S SEAWATER DESALINATION NEEDS:

Desalination is a natural process to produce fresh water for human necessities. The technique of removing salt from seawater dates long way before mankind. The energy from the sun causes ocean water to evaporate, forming clouds. These clouds pour freshwater at high altitude regions which subsequently deposits in the form of rivers and glaciers.

Along with several extended glacier collections upstream, Pakistan has 5 major river systems, with Indus being the dominant supplier of fresh water, while its tributaries consist of Ravi, Chenab, Jhelum and Sutlej. These river systems mainly flow through the Punjab region and diminish as they reach towards the lower parts of Sindh, compelling such parts of the country to remain water-depressed.

Pakistan has always been known as an agricultural country ever since it gained independence in 1947, and since then its population has been growing vigorously, reaching 226.0 million in 2021, according to the United Nations. It has been further uncovered that 21.7 million of this amount doesn't have access to safe drinking water, with over 19,400 offspring under 5 dying from diarrhea each year [18].

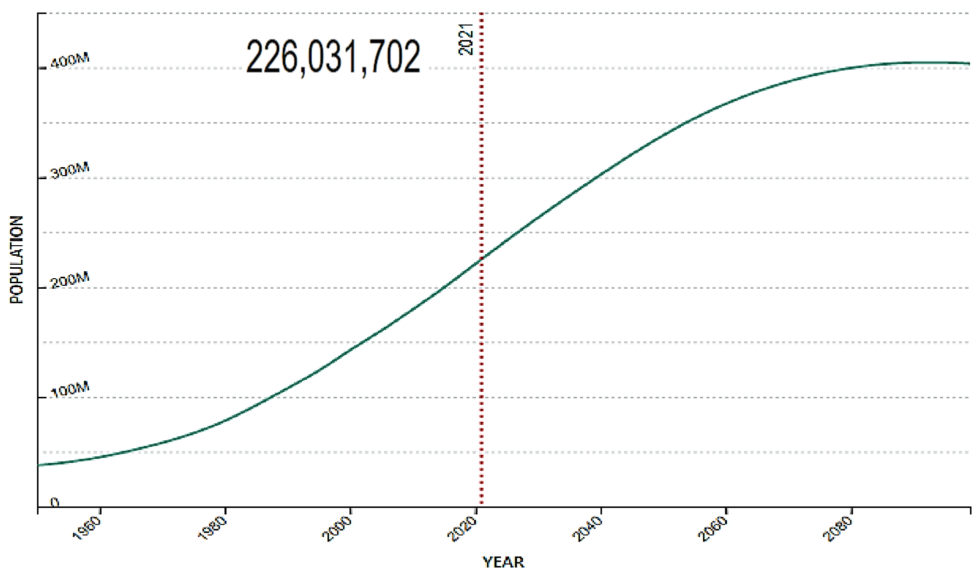


Figure 2.1 Population of Pakistan

The major ratio of Pakistan's freshwater is utilized to produce cash crops for export purposes as well as to fulfill local burdens. Therefore, a very minor amount is left for metropolitan and drinking purposes. Water deficiencies mainly occur in Pakistan's coastal areas which include the big cities of Karachi and Hyderabad. With more than 30 million people residing in these states alone, their water requirements have to be met on a routine basis. Balochistan, on the other hand, has no major natural river system and no canal system, while it also doesn't get a lot of rain due to its natural climate. Consequently, its water necessities must also be addressed as well.

Pakistan has a lengthy range of coastal belts. Extending beyond 1046km, it provides access to a cumbersome amount of oceanic resources. Desalination of this salty water can overcome Pakistan's major agrarian and civic water requirements. Solar desalination is a highly viable option in hot and arid areas of Sindh and Balochistan. Moreover, partial desalination and magnetic treatment can be used in areas where groundwater is saline, usually near the coast.

The excessive utilization of freshwater resources by China, Afghanistan, and India in the upstream region has begun to cause greater impacts on the availability of freshwater for Pakistan. This water usage by its neighbors will prospectively upsurge soon, worsening the current situation of the country. Hence, appreciating the need for seawater desalination even further.

With all the variables favoring desalination as an answer for Pakistan's current water situation, the major interruption for its installation is the colossal cost that it sustains. Since Pakistan is a developing country, it doesn't have the capital and resources required to inaugurate such projects.

However, significant attempts have been made to introduce desalination technology and overcome the water discrepancy. A large sum of Rs 430 million has been spent by the government of Sindh to construct a seawater RO plant, which has the ability to satisfy the water demand of 0.2 million people in the Manora district. Around 40% of the project work has been concluded so far. The plant has the capacity to bring down the TDS value to an acceptable range of 500mg/l.

Meanwhile, schemes are also in motion to inaugurate a new distillation facility for the inhabitants of Karachi's Clifton and Defense Housing Authority areas which are faced with unfriendly water problems and shortages. Besides, the government with joint efforts with China has planned to construct a desalination plant for Gwadar city. A grant of around Rs 2 Billion has been allocated to provide 1.2 Million Gallons per Day of water to its inhabitants.

2.3. DESALINATION PROCESSES:

Ancient human societies have been using unpretentious heating to evaporate and collect water systems since the primeval eras. Antiquated organizations used this system on the ships to meet the consumption requirement while on the expedition. In today's modern civilization, desalination methods have become much more advanced and efficient. Desalination methods can be broadly classified into 2 categories,

1. Thermal Type
2. Membrane Type

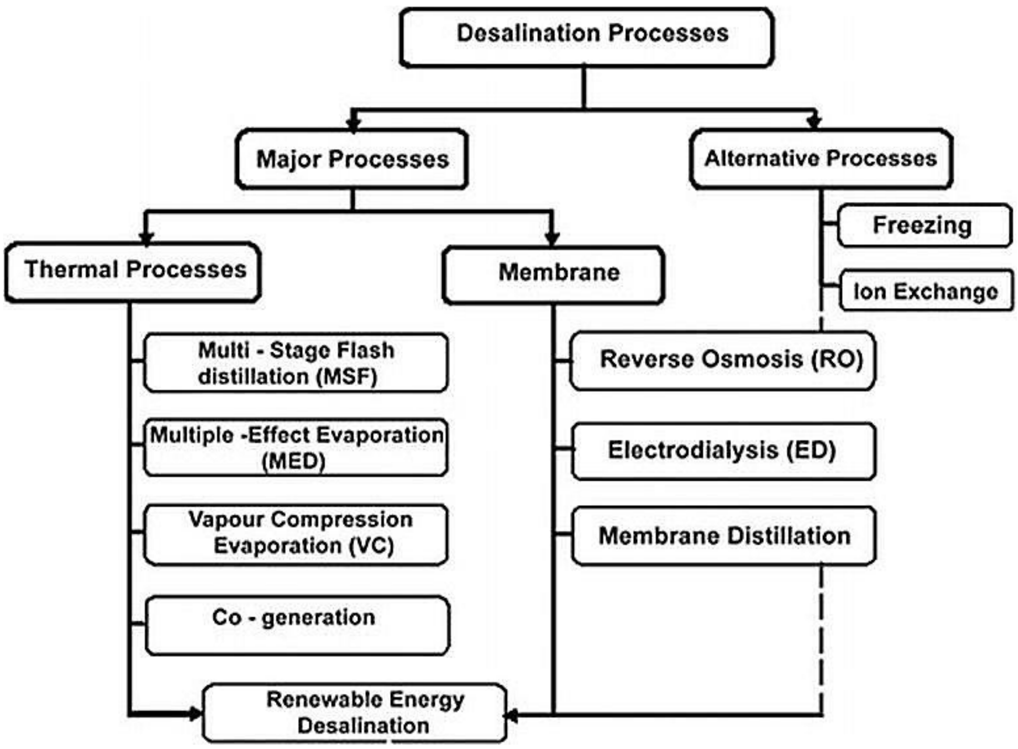


Figure 2.2 Categorization of water desalination systems

2.4. <u>THERMAL TYPE DESALINATION:</u>

As the name suggests this type of desalination is driven by heat energy. Seawater is heated to evaporate pure water, which is then collected to meet different requirements. Due to advancements in technology, we have developed different methods as compared to just heating the water to evaporate, namely;

2.4.1. MULTI EFFECT DISTILLATION:

In this arrangement, two or more effects are employed. Each effect is essentially a shell & tube heat exchanger with some extra arrangements. The pressure of each effect is maintained below the atmospheric pressure to enhance evaporation.

Steam at high temperature is supplied in the tubes of the first effect, where saline water is sprayed from the top. A part of this evaporates and goes into the tubes of the following effect, while the rest of the saline water is collected in the bottom of the first effect. This Saline water is then sent to the first effect where it is sprayed again from the top.
This process is continued until the last effect. The brine from the latter effect is ultimately blown down.

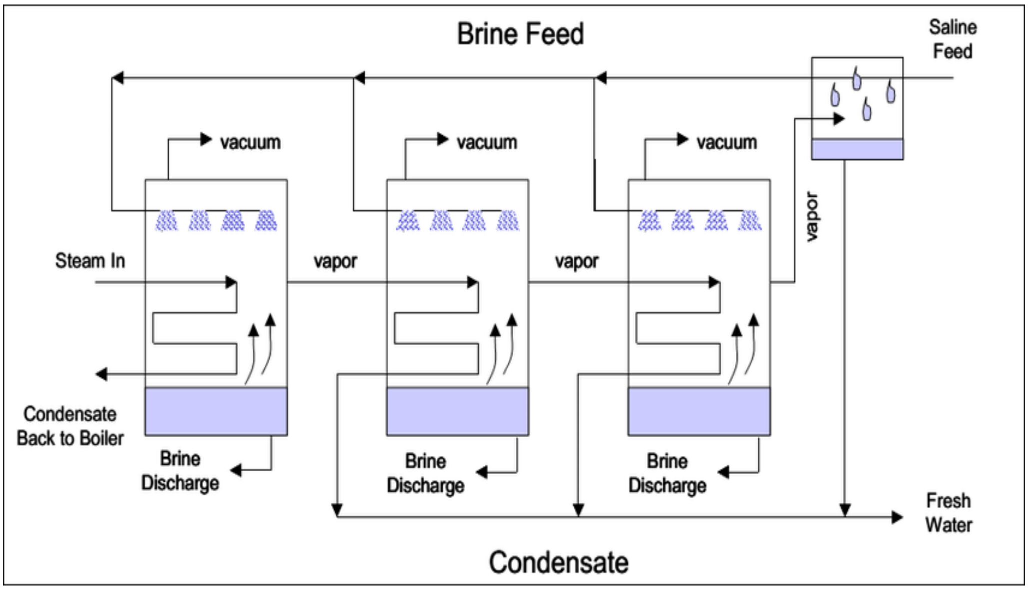


Figure 2.3 Schematic Diagram of MED

2.4.1.1. CONFIGURATIONS OF MED:

Accumulation of more evaporators in Multi Effect Distillation can last until ‘n’ number of effects. A container is used underneath to collect the vapor generated from the last ‘n’ effect. This type of arrangement of desalination is known as the ‘n’ effect assembly. In this style of assembly, the outdoor steam is condensed in the first effect bearing the utmost temperature. The temperature variance declines as the number of effects escalate. The forward, backward, and parallel feed arrangements are the most popular types of layouts of MED [19].

FORWARD FEED:

The forward feed assembly of MED is the most commonly used arrangement because of its ability to provide low saltwater at the peak temperature of the first effect. Here, the supply water ‘F’ is guided to the first effect of the peak temperature.

Consequently, a selected portion of the supply water ‘D_1’ evaporates while the residual brine ‘B_1’ enters as feed ‘F2’ in the succeeding effect. Likewise, the brine exiting the second effect ‘B2’ arrives in the third effect ‘F3’. The development continues till the final effect is reached. In this type of assembly, the supply of water and vapor that enters the effects runs in the same direction [19].

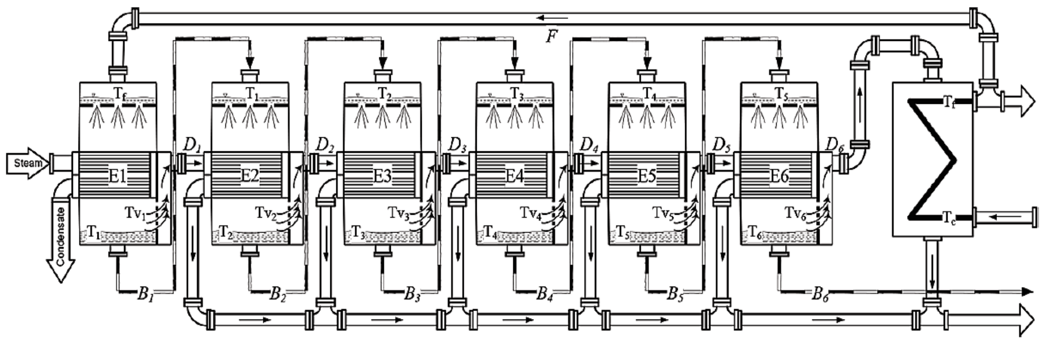


Figure 2.4 Schematic of Forward Feed MED

BACKWARD FEED:

In the backward feed assembly of MED system, the supply water ‘F’ is steered to the last effect at the least temperature from the condenser. In this conformation, the brine from the final effect ‘n’ is guided as a supply to the ‘n-1’ effect. This progression lingers until the elementary effect is reached. The highly saturated saline water attained from this first stage is gusted down in the ocean. Correspondingly, the course of flow of the supply water and vapor are contradictory to each other when entering the system.

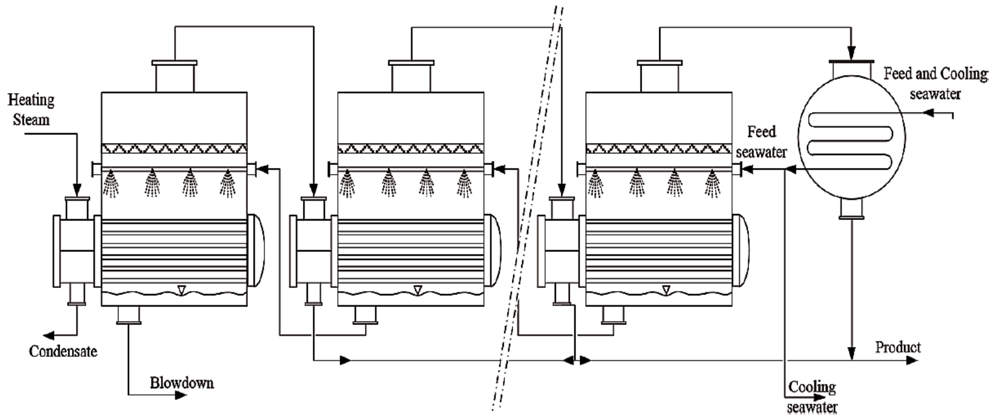


Figure 2.5 Schematic of Backward Feed MED

PARALLEL FEED:

In the parallel feed arrangement of a Multi-Effect distillation system, the supply water ‘F’ is virtually homogenously alienated and circulated to each of the effects after leaving the condenser [19].

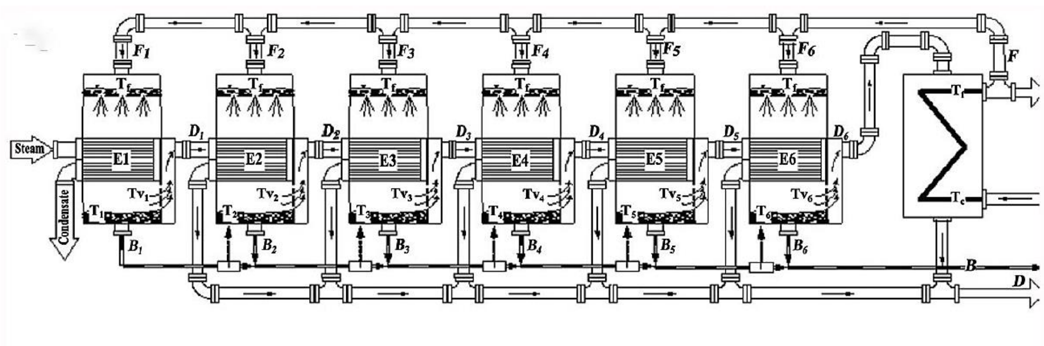


Figure 2.6 Schematic of Parallel Feed MED

2.4.2. MULTI STAGE FLASH:

In the Multi-Stage Flash system, brine is sprayed over tubes carrying hot steam. Meanwhile, the pressure of the first effect is retained just enough to make the water evaporate. The hot brine is then sent to the subsequent effect, where the pressure is maintained at a lesser value to trigger the flashing of brine. This process is illustrated in the schematic diagram [19].

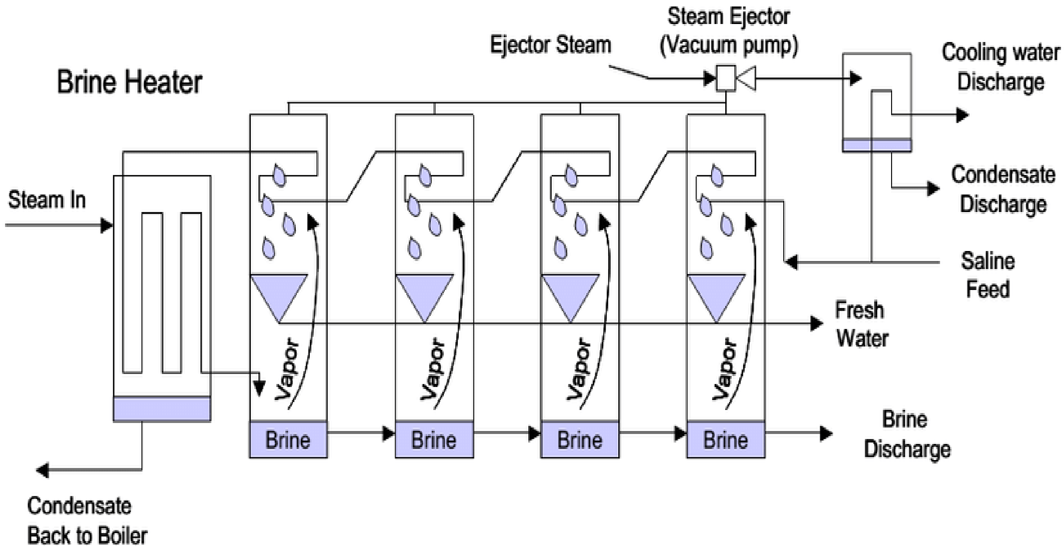


Figure 2.1 Schematic of Multi Stage Flash

2.4.3. THERMAL VAPOR COMPRESSION:

Compression of vapor is a customary technique used by the desalination industry to facilitate the vapor-liquid evolution state of water.

A Multi effect Distillation system usually employs a Thermal Vapor Compression unit to improve productivities. This type of plant can exploit the kinetic energy and enthalpy of the drive steam simply by exercising a steam jet ejector. Similarly, it can improve the efficiencies of the plant twice by its preceding value [20].

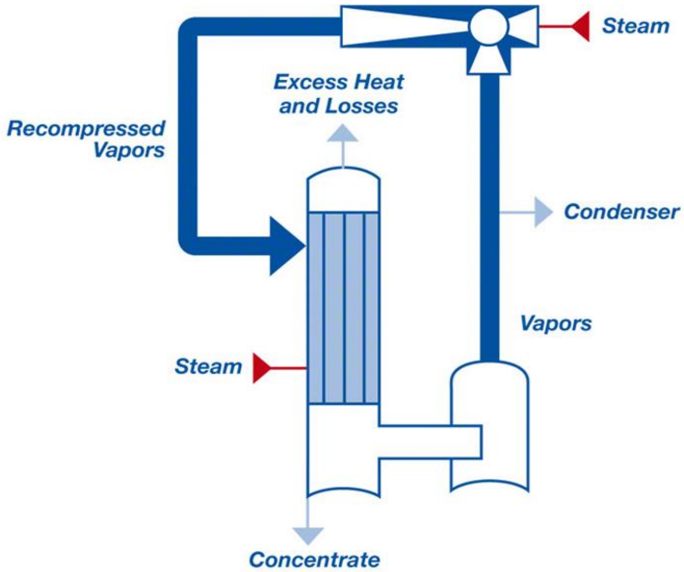


Figure 2.8 Schematic of Thermal Vapor Compression

2.4.4. MECHANICAL VAPOR COMPRESSION:

Somewhat similar to TVC, Mechanical Vapor Compression is also employed for vapor extraction inside the chamber. When compressed, the vapor raises its pressure and temperature. This temperature rise can be used for heat transfer between the pressurized vapor and the salty water in the compartment, and to produce vapor by commissioning a heat exchanger.

The Mechanical Vapor Compression process also requires electricity to function. Consequently, a discrete desalination module can be mounted to satisfy freshwater demand of about 100-3000 cubic meters per day [14], [21].

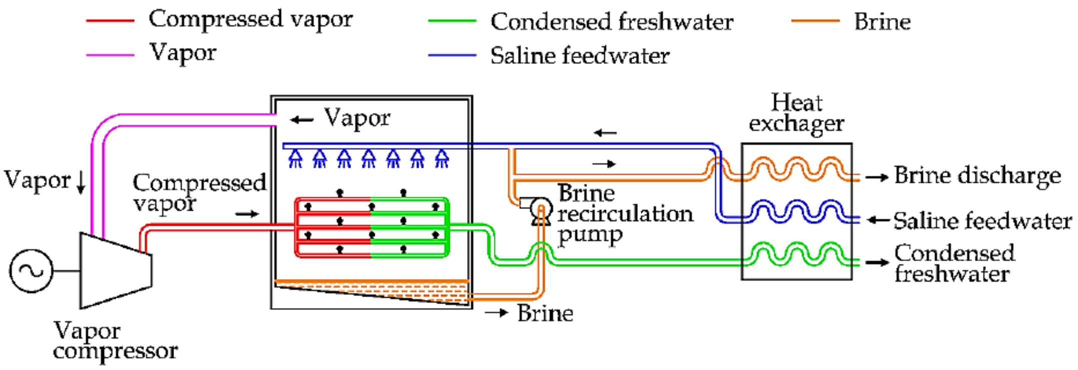


Figure 2.9 Schematic of Mechanical Vapor Compression

2.5. MEMBRANE TYPE DESALINATION:

2.5.1. REVERSE OSMOSIS:

Whenever two different concentrated solutions are naturally or artificially separated by a semi-permeable membrane, the solvent from the more diluted solution will flow instinctively to the more concentrated one.

In reality, this flow can be countered if a considerable pressure (Δp) is applied in the reverse direction to the membrane. When the value of this applied pressure is precisely the same as the solvent flow, it is termed as Osmotic pressure. When Δp exceeds the osmotic pressure, the solvent movement is inverted in the reverse direction. By utilizing this practice, any solvent can be extricated from a concentrated solution, which in our case is seawater.

The Reverse Osmosis desalination technique generally requires the use of mechanical or electrical energy for pump operations. These pumps are used to escalate the saline water pressure at the semi-permeable membrane frontage [14], [21].

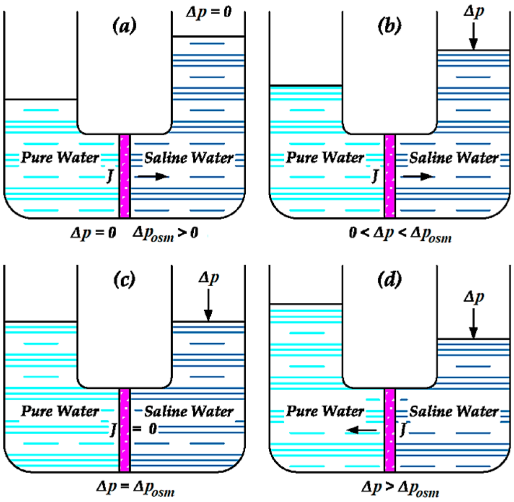


Figure 2.10 Osmosis features with respect to applied pressure

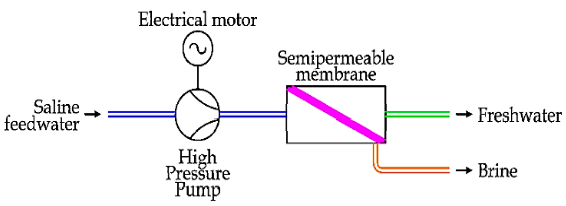


Figure 2.11 Schematic of simple Reverse Osmosis

2.6. COMPARISON OF DESALINATION SYSTEMS:

The consideration of a highly functional desalination system involves the salinity and supremacy of desalinated water required. Moreover, it encompasses the utilization of energy, price tag, and costing, as well as its effects on the environment. The salinity of water involves seawater, brackish and pure water. Seawater contains salinity in the range greater than 3500 ppm of dissolved salts, while brackish water lies in the range of 1000-25000 ppm. Pure water has a salinity lesser than 1000 ppm of dissolved salts. It has been established that 'Multistage Flash' and 'Adsorption Desalination' techniques can convert the highest ranks of saltwater into the purest forms.

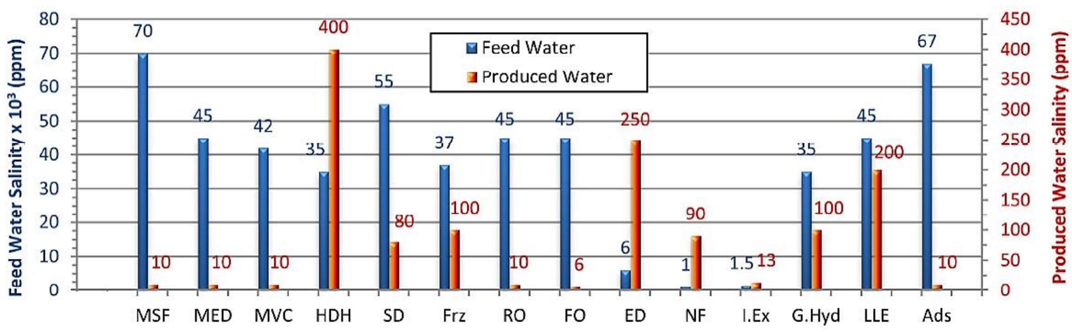


Figure 2.12 Salinity of feed and produced water of various systems

Similarly, studies have also found that Solar Desalination, Ion Exchange, Gas Hydrate and Adsorption desalination practices require the least amount of energy in the form of electrical or thermal power. These energy requirements are usually less than 2killowatt hour per meter cube.

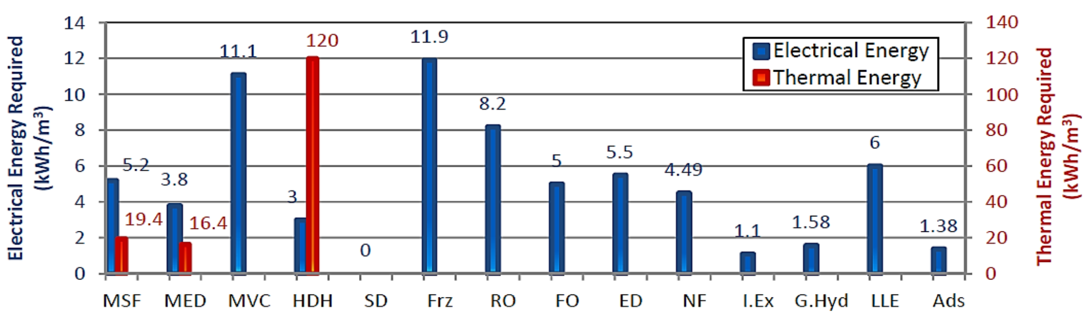


Figure 2.13 Energy required by various Desalination systems

Likewise, it has also been observed that the cost to run a desalination plant is the lowest for Adsorption, Freezing, and liquid-liquid extraction technologies, where the cost is less than 0.5 dollars per cubic meter [14].

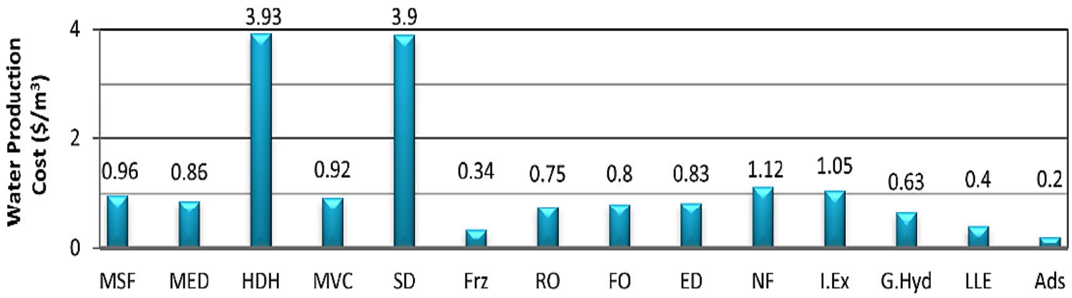


Figure 2.14 Drinking water cost for various systems

Technology	Average Capacity [10^3 m^3/day]	Input	Recovery Ratio	Water Quality [ppm]	Energy Consumption		Water Cost [$/$m^3$]
					Electrical [kWh/m^3]	Thermal [kJ/kg]	
MED	0.6–30	SW	0.25	10	1.5–2.5	230–390	0.52–1.5
TVC	10–35	SW	0.25	10	1.5–2.5	145–390	0.87–0.95
MSF	50–70	SW	0.22	10	4–6	190–390	0.56–1.75
MVC	0.1–3	SW		10	6–12	no	2.0–2.6
SWRO	1–320	SW	0.42	400–500	3–6	no	0.45–1.72
BWRO	Up to 98	BW	0.65	200–500	1.5–2.5	no	0.26–1.33
ED	Up to 145	BW	0.9	150–500	2.64–5.5	no	0.6–1.05

Table 2.2 Properties of modern Desalination plants

2.7. WORLDWIDE USE OF DESALINATION:

The worldwide usage of freshwater in recent times has been comprehensively superior to its regeneration rate. Groundwater resources are being exhausted and the surface water quality is worsening. Drinkable water is becoming rare, especially in regions where there was no such problem before. Globally, the one single-handed solution for all these problems is water treatment or desalination. This startling practice can provide excellent quality freshwater which can be utilized in homes, industries, and irrigation purposes.

The world's water crisis is expected to further deteriorate with the exponential population growth, hot and arid climatic conditions, and long periods of drought due to high temperatures caused by global warming. Lately, the regions of Latin America, Western and Central Europe have also been faced with acute freshwater shortages. The water concentration in these states has reached below 1500 cubic meters per year, which is United Nation's conventional least water existence level [22].

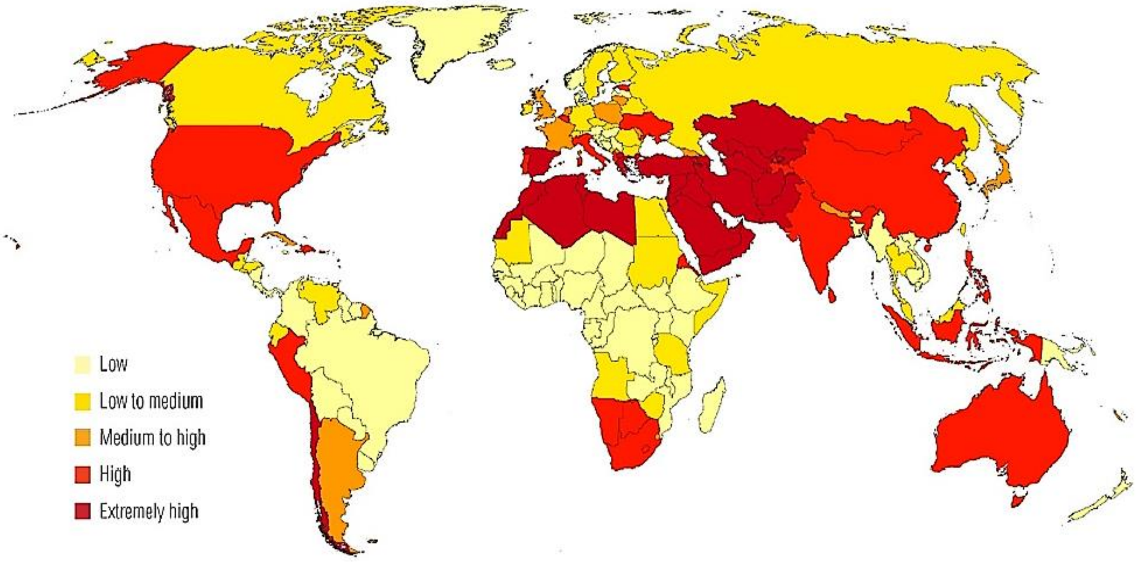


Figure 2.15 World's Water Stress Prediction by 2040

Desalination has been labeled as a 'partial' solution for the world's water scarcity crisis. The world is expected to observe a major growth of desalination plants in the coming 5-10 years. The North African and the Middle Eastern countries are the major heart of this expansion. Apart from these regions, desalination has paved its way towards some water-stressed areas of the USA, including California, and countries like Australia, Spain, and China. The freshwater supply in these countries falls way before the United Nation's water scarcity perimeter, which is about 350 gallons per day/person.

Currently, there are more than 20,000 desalination plants in about 177 countries, producing billions of gallons of freshwater daily. Around 57 percent of this estimate is in the Middle East, where the availability of fuel is not an issue.

Desalination technologies are usually limited to well-off countries having enough seawater access and a significant amount of fossil fuels. Due to the prodigious cost and energy consumption of such plants, many low GDP states find it difficult to afford this kind of luxury. The figure illustrates the various desalination technologies used worldwide. One can observe the dependency of the world on the seawater Reverse Osmosis technique for water desalination [23].

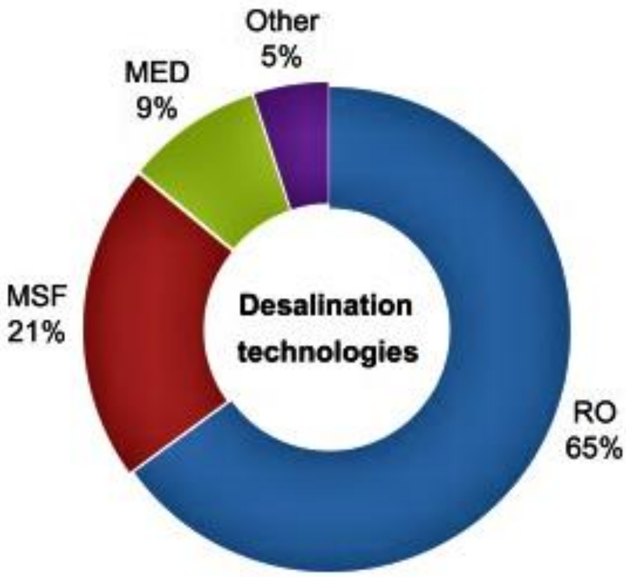


Figure 2.16 Worldwide employed Desalination Technologies

Seawater Desalination comes with its demerits. The global environmental costs of this unfailing method are unwarranted. Desalination plants universally produce a precarious amount of greenhouse gases while ingesting a large amount of energy. Furthermore, brine disposal is yet another issue since it is extremely salty and encompasses poisonous chemicals which are diffused in it during various treatment processes. Collective research on enhancing desalination systems by formulating robust and more proficient membranes is on the role globally. Likewise, more resourceful ways to deal with the amply concentrated unwanted brine, and to produce more freshwater per unit of energy, are always a part of the technologists’ schedule.

2.8. WORLD`S PROMINENT DESALINATION PLANTS:

Desalination technology has greatly improved in the last few decades. It was not long before, when the 'Rabigh 3' desalination project of the Kingdom of Saudi Arabia received the honor to be called one of the world's largest desalination plant, with having the competence to produce 600,000 cubic meters of freshwater daily. However, this plant presently looks inferior to the current desalination systems of the world which have the astonishing ability to produce enormous amounts of freshwater daily.

The world's largest desalination plants, along with the daily freshwater production capacity and type of technology utilized, are illustrated in the figure. 'Ras Al Khair' of Saudi Arabia, being a hybrid plant, leads the queue with an astonishing daily capacity of 1.036 million cubic meters [24].

S.NO	NAME	LOCATION	DESALINATION CAPACITY (m^3/day)	DESALINATION TECHNOLOGY
1.	Ras Al Khair	Saudi Arabia	1,036,000	MSF+RO
2.	Taweelah	U.A.E.	909,200	RO plant
3.	Shuaiba 3	Saudi Arabia	880,000	Thermal and RO plant
4.	Jubail Water and Power Company	Saudi Arabia	800,000	MED
5.	Umm Al Quwain	U.A.E.	682,900	RO plant
6.	DEWA Station M	Dubai	636,000	MSF
7.	Sorek	Israel	624,000	RO plant
8.	Jubail 3A IWP	Saudi Arabia	600,000	RO plant
9.	Fujairah 2	U.A.E.	591,000	MED+RO
10.	Sorek 2	Israel	570,000	RO plant

Table 2.3 World's top 10 desalination plants in 2021

Chapter 3
SIMPLE SYSTEMS

3.1. METHODOLOGY:

The simulation of the given model presented in the project has been carried out by the aid of Engineering Equation Solver (EES). This software has been F-Chart Software, LCC and is widely used in all sort of engineering applications. This software has tendency to perform solution of general-purpose equations including differential and integral equations, model complex processes and execute their analysis. EES is used in both industrial and academic sector for all sort of engineering purposes.

3.1.1. ADVANTAGES OF USING EES:

There are series of reasons to use this software to carry out the simulation, despite the availability of plenty of other options. First is its ease of use and user friendliness. EES is a compact size software, filled with all the necessary tools required for an engineering analysis. It does not require an extensive knowledge of programming and the syntax it uses is quite basic and intuitive. It is an iterative solver and does not require equations to be written in a particular format and in a particular sequence. Instead, it is capable of finding the unknown variables without the requirement of chronology. The runtime of calculation is very fast and EES compute the solution of all equations with in a fraction of second. Also, it is smart enough to guess the units of the properties it computes. It automatically performs unit consistency check and suggest user about any inconsistency in the unit which might miss the eye of the user. Similarly, it has many features that can be controlled using GUI which are extremely easy to use and save tons of time of the user.

Secondly, EES comes with nearly every useful built-in function required for a thermodynamic analysis. It possesses transport functions and thermodynamic properties of hundreds of fluids. Apart from that, it also has a library for solids and their properties including stresses, young’s modulus, heat transfer properties, etc. The properties from steam table, Mollie chart, psychometric charts come built-in with the software, which are very easy to call. Similarly, it comes with a pre-installed library of nearly all important engineering constants. These libraries can also be updated with a custom property that a user wants to add.

Thirdly, special care has been given to the tools required for a parametric study while assembling this software. EES uses spreadsheet like approach to perform the parametric study of observing the change on variables by changing other variables. It has exceptional optimization capabilities of single and multi-multi variable functions. The parametric calculations are too calculated quickly with the software. Apart from that, it has extraordinary plotting capabilities. It can plot 2-D and 3-D scatter and line plots. It can also plot bar plots of categorical variables. These plots come with a label, title, legend, or any other text you want to write. The size, style and colors of the marker and lines can also be tweaked according to the requirement of the user. It too comes with capabilities of performing curve fitting and regression analysis on the graphical values.

3.1.2. COMPUTATION OF VALUES:

EES is an iterative solver and uses Newton's method to solve the non-linear equations [25]. The newton's method can be given by:

$$x_{n+1} = x_n + \frac{f(x)}{f'(x)} \tag{3.1}$$

The process starts by first finding the residue ε of any equation at a randomly guessed value. Next, the derivative of the function is calculated. In EES, this derivative is represented by Jacobian Matrix. The rows of the matrix correspond to the derivate of the equations and the columns represent the variable whose respect the derivative has been computed. EES uses the techniques of numerical differentiation to compute these derivate. Next, the difference in the values of the variable Δx can be found by:

$$\Delta x = \frac{\varepsilon}{J} \tag{3.2}$$

Where Δx is the matrix of difference between all the variable whose value has to be computed. These guess values are then updated by the help of these differences.

$$x_{n+1} = x_n + \Delta x \tag{3.3}$$

This updated value is then again used to compute the updated value. This computation proceeds until this value stops to converge significantly.

3.2. SINGLE EFFECT BOILING:

The word single effect signifies the use of only one evaporator or boiling unit with just a solitary condenser or feed preheater. The single effect boiling system has a very basic configuration that accommodates its limited usage: such as in marine vessels, or numerous small-scale industries. On top of that, the amount of steam required to initiate the desalination process is greater than the output obtained. The resultant distillate is at an elevated temperature which is usually not desired. However, the exploration of the Single Effect model is essential to understand the more complex and efficient configurations.

3.2.1. PROCESS DESCRIPTION:

A mixture of feed water and cooling water (F + Cw) is delivered into the condenser's tube side, where the feed water temperature rises from T_{cw} to T_f, whereas the mass (Cw) is directed back. The flow rate of the cooling water (Cw) is used to drag away the surplus heat from the condenser. Here, the condenser serves the additional purpose of preheating the feed (F) before it enters the shell side of the evaporator. The feed (F) evaporates to produce the distillate (D) at T_c, and brine (B) at T_b by exchanging its heat with the steam (S) at T_s, which is either taken as a bleed from the turbine or a solar heater. The distillate is then introduced at the temperature (T_c) of the condenser from where it is cooled down to T_d by heating the incoming feed as shown in **Figure 3.1** .The vapor generated from the boiling process streams through the 'Knitted Wires Mist Separator' also titled as the demister. The core function of the demister is to free the vapor from the entrained brine droplets which can degrade the quality of the product water.

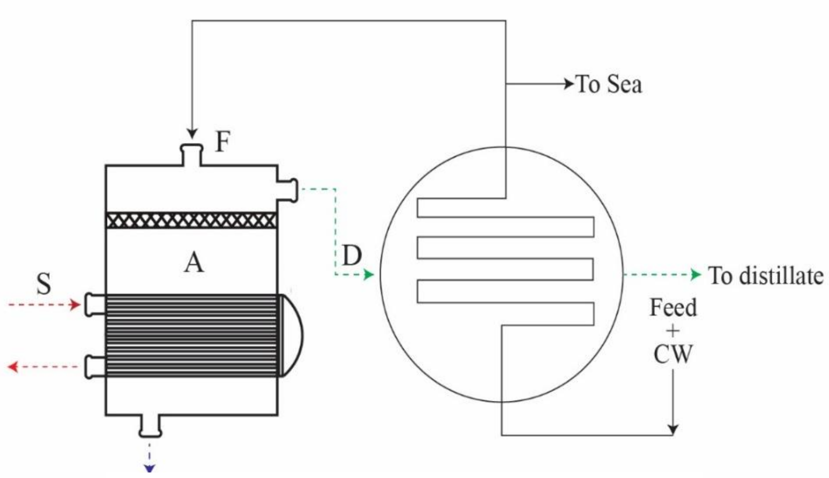


Figure 3.1 Schematic of a Single Effect Boiling system

3.2.2. PROCESS MODELING:

Before moving towards the process modeling, we need to make certain assumptions to make the process manageable and relatively simpler [19].

These comprise:

1. The product water obtained is free from any salt and contaminant.
2. The pressure loss across the demister is ignored.
3. The process is assumed to be free of any thermodynamic losses.
4. The resistance across tubes of the condenser is negligible.
5. The process is continuous and steady.

The mass balance of the given system can be given as

$$F = D + B \tag{3.4}$$

$$F . X_f = B . X_b \tag{3.5}$$

$$B = D . \left(\frac{X_f}{X_b - X_f} \right) \tag{3.6}$$

$$F = D . \left(\frac{X_b}{X_b - X_f} \right) \tag{3.7}$$

Here, F, B, and D represent the flow rate of Feed, Brine and Distillate.
The energy balance across the evaporator can be attained by summation of both the sensible heating and the latent heating of the vapors.

$$Q_e = F.C_p.\left(T_b - T_f\right) + D.hfg = S.hfg_s \tag{3.8}$$

Here, Q_e represents the evaporator's thermal load, C_p represents the specific heat at constant pressure and hfg is the latent heat of evaporation. 'S' supplies both the sensible and latent heat necessary for the stated amount of vapor to evaporate.

Similarly, the load on the condenser can be derived by the following relation

$$Q_c = (F + Cw).C_p.\left(T_f - T_{cw}\right) = D\ .hfg \tag{3.9}$$

Here, Q_c indicates the condenser's thermal load.
The overall energy balance can be combined as,

$$S.hfg_s = B.C_p.(T_b - T_{cw}) + D.C_p.(T_v - T_{cw}) + Cw.C_p\ (T_f - T_{cw}) \tag{3.10}$$

OR

$$S.hfg_s = B.C_p.\left(T_b - T_f\right) + D.C_p.\left(T_v - T_f\right) + D.hfg \tag{3.11}$$

Due to the presence of the salt in the water, the boiling temperature of water slightly increases by a factor known as the Boiling Point Elevation (BPE)

$$T_b = T_v + BPE \tag{3.12}$$

Now, based on all of the above-derived equations, performance ratio (PR) can be computed and this is simply the mass of distillate divided by the mass of heating steam required.

$$PR = \frac{D}{S} \tag{3.13}$$

The cooling water's flow rate can be expressed in the form of

$$sCw = \frac{\text{Cw}}{D} \tag{3.14}$$

The condenser and evaporator heat transfer areas can be given as

$$A_e = \frac{F.C_p.\left(T_b - T_f\right) + D.hfg}{U_e\,(T_s - T_b\,)} \tag{3.15}$$

$$A_c = \frac{Q_c}{U_c.LMTD} \tag{3.16}$$

Where LMTD is defined as

$$LMTD = \frac{(T_f - T_{cw})}{\ln\frac{(T_d - T_{cw})}{(T_d - T_f)}} \tag{3.17}$$

Finally, the specific heat transfer area can be given by

$$sA = \frac{A_e + A_c}{D} \tag{3.18}$$

3.2.3. SIMULATION OF A SINGLE EFFECT SYSTEM:

For the simulation of a single effect system [19], assume a system with the following characteristics:

Top Brine Temperature = T_b = 75°C

Temperature of Intake Sea Water = T_{cw} = 25°C

The temperature of the Feed Water = T_f = 70°C

Steam`s Temperature = T_s = 82°C

Incoming Feed water`s Salinity = X_f = 42,000 ppm

Rejected Brine's Salinity = X_b = 70,000 ppm

Inputting the data into the software and running simulation yields the following results:

Unit Settings: SI C kPa kJ mass deg

A_c = 65.31 [m^2]	A_e = 135.9 [m^2]	B = 1.5 [kg/s]	BPE = 0.9029 [C]
Cw = 9.794 [kg/s]	C_p = 4.2 [kJ/kg-C]	D = 1 [kg/s]	F = 2.5 [kg/s]
hfg = 2324 [kJ/kg]	hfg_s = 2304 [kJ/kg]	LMTD = 18.12 [C]	PR = 0.9711
Qc = 2324 [kJ/s]	Qe = 2372 [kJ/s]	S = 1.03 [kg/s]	sA = 201.2 [m^2-s/kg]
sCw = 9.794	T_b = 75 [C]	T_{cw} = 25 [C]	T_f = 70 [C]
T_s = 82 [C]	T_v = 74.1 [C]	U_c = 1.964 [kW/m^2-C]	U_e = 2.498 [kW/m^2-C]
X = 7	X_b = 70000 [ppm]	X_f = 42000 [ppm]	

3.2.4. GRAPHICAL ANALYSIS AND INTERPRETATION:

Changing the TBT and observing the change on other parameters revealed the following results:

Top Brine Temperature (TBT) vs. Performance Ratio (PR):

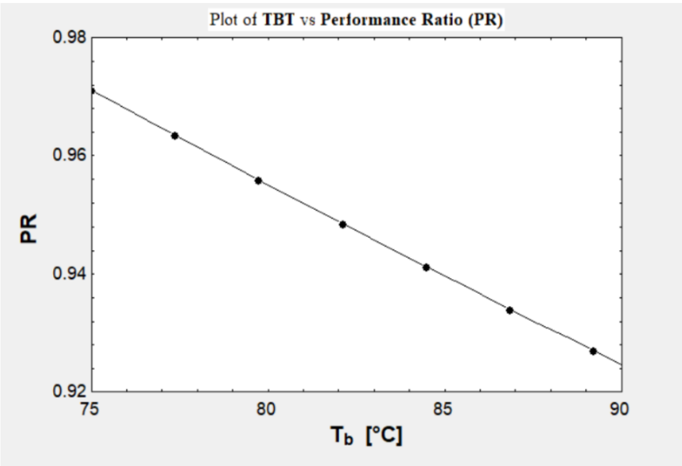


Figure 3.2 Graph between TBT vs. PR

As the top brine temperature rises, there comes a need to increase the steam's mass flow rate to achieve the heat transfer to the point where the salty water boils. Due to this rise in the steam's mass flow rate, the performance ratio drops which can also be observed graphically as shown in **Figure 3.2**

Top Brine Temperature (TBT) vs. Specific Area (sA):

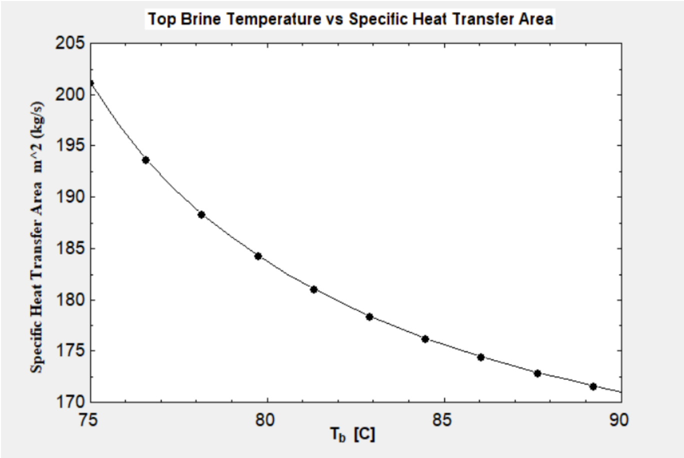


Figure 3.3 Graph between TBT vs. sA

As the TBT rises, the evaporator and condenser's specific area decreases; this consequence in a reduction in the specific area. This occurs because the heat transfer coefficient rises with rising temperature, therefore amplifying the heat transmission.

Top Brine Temperature (TBT) vs Cooling Water Rate (sCw):

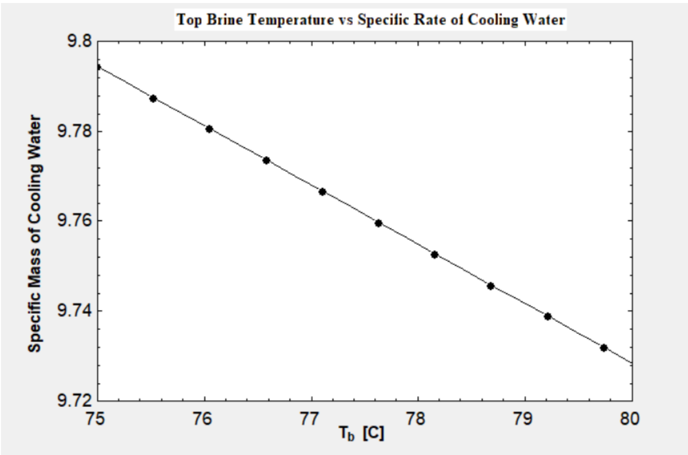


Figure 3.4 Graph between TBT vs. sCw

The rise in the TBT reduces the required area of heat transmission. Due to this reduction, the quantity of heat absorbed per unit feed (F) rises. This reduces the amount of heat that is extracted by the cooling seawater. Furthermore, at higher TBT, vapor temperature also increases, which lowers the heat of vaporization in the condenser, and hence condenser load decreases. Furthermore, lowering the temperature of the input seawater raises the thermal burden per unit mass of cooling seawater [19].

3.3. COMPARISON:

3.3.1. THERMAL VERSUS MEMBRANE TYPE:

The Thermal type desalination has the following benefits over the Membrane type:

- More purified or low TDS water is obtained through the thermal process.
- These types of desalination plants are capable of operating under extreme circumstances, such as high temperature, high impurity, high salinity etc.
- Thermally driven desalination systems have a greater unit capacity than membrane desalination systems.
- Thermal type processes may be coupled with power plants to produce cogeneration power desalting plants (CPDP).
- The feed water quality is not as important as it is in the RO system. As a result, the pretreatment and operation costs of these techniques are low.
- Membrane-type processes are more suitable for water having less TDS or low salinity seawater as compared to thermal type processes.

The Membrane type has the following benefits over the Thermal type desalination:

- Membrane desalination systems particularly reverse osmosis systems are the most efficient and widely used desalination systems in the world.
- Membrane type systems are more simple and easy to operate.
- This type of desalination system can be set up in areas where space is limited.
- This sort of technology is less prone to corrosion than thermal desalination.
- The reject brine from membrane-based procedures has a low temperature. As a result, the environmental effects are low.
- Membrane-based systems are highly reliable and need minimal maintenance.
- Technical development in reverse osmosis systems is more advanced as compared to other systems.
- Membrane-based processes are characterized by rapid startup and shutdown [26].

3.3.2. MED VERSUS MSF:

Each system has distinct advantages and disadvantages in comparison to the others. Following are the advantages of the MED system over the MSF system:

- The MED system is capable of being operated at low temperatures.
- In comparison to the MSF system, the MED system has lower capital and operational cost.
- The MED system is capable of operating with far less scaling than the MSF system [27]. As a result, low-quality materials can be used in construction.
- Compared to the MSF system, the Multi Effect Distillation system is more adaptable to cogeneration plants.
- The MED system consumes approximately half the amount of pumping power required by MSF systems. As a result, low-quality materials can be used in construction.
- The MED system is generally more efficient than the MSF system.
- When the Performance ratio of both systems has the same value, the number of effects in the MED system is less than half that of stages in the MSF plant [26].

Following are the advantages of the MSF system over the MED system:

- MSF systems are regarded as the most user-friendly system.
- In comparison to the MSF system, the Multi Effect Distillation plant is not completely developed.
- MSF systems are larger than MED systems in terms of size and capacity.
- In the first stage of the MSF system, the majority of non-condensing gases are vented to the atmosphere.
- For the time being, the MSF system is the most stable desalting system, with units working continuously for more than a year
- It is an established technique that reflects years of expertise in its design and material selection.

3.4. FUTURE OF DESALINATION:

The reverse osmosis (RO) and multistage flash (MSF) technologies are the major shareholders in the desalination market; however, multi-effect desalination (MED) has gained considerable interest in the past decades as it is energy efficient and has the ability to operate under harsh seawater conditions (high salinity) [28]–[30].

The multi-effect desalination (MED) consists of falling film heat exchangers (evaporators) connected in series and utilizes low-grade heat either from the bleed steam from power plant or from waste heat recovery or can be from the renewables [29], [31].

Extensive research has been carried out to improve the performance of MED plants in the past few years, which includes:

1. Integration of adsorption or absorption based compression system to reduce the overall energy consumption [32], [33].
2. Development and Integration of processes to increase the top brine temperature in order to provide room for more evaporators [31], [34].
3. Computational and numerical works to improve the film distribution and heat transfer around the tube [35]–[42].
4. Development of thermally enhanced polymer tubes to reduce the environmental impact and capital cost [43].
5. New evaporator design without the demister to reduce the thermal losses and temperature difference across the evaporators [44].

Chapter 4

EIGHT-EFFECT MED TVC SYSTEM

4.1. MULTI-EFFECT DISTILLATION (MED) SYSTEM:

The multi-effect distillation (MED) system encompasses multiple effects, also known as evaporators. In this type of system, the boiling of the water is not achieved in a single evaporator; instead, it is subsequently divided into multiple effects. The multi-effect system delivers a significant performance improvement, by minimizing the heat losses from the system and extracts back most of the energy supplied to the water. In comparison to a single effect system, where the fluid takes away the major chunk of energy, by extracting back the heat, multi-effect systems offer high energy efficacy. In industries, multi-effect systems are commonly used in combination with existing power plants, forming Cogeneration Power Desalting Plant (CPDP).

4.2. CHARACTERISTICS OF THE PROPOSED MODEL:

4.2.1. PARALLEL/CROSS FLOW FEED:

Amongst all the configurations of the multi-effect systems, the parallel feed is widely used because of its improved performance. This enhanced functioning arises from the absence of individual pumps for each effect. Moreover, most of the fluid flow in this arrangement is driven by gravity. In the parallel flow, there are two more available configurations in which the brine is either transported to the next effect where it flashes to contribute towards more distillate, or it is taken away directly from the effect to be disposed of properly. The former configuration yields more distillate which improves the performance of the system.

4.2.2. HYBRID SYSTEM:

The hybrid system employs the benefits of the two formerly tested configurations to strengthen the more robust model. Combining two or more desalting arrangements; to form the so-called hybrid system, can offer some merits over using separate desalting systems. This may lead towards diminishing the final cost of the distilled water and enhancing the performance of the existing cogeneration power-desalting plant.

4.2.3. THERMAL VAPOR COMPRESSION SYSTEM:

The TVC system compresses the generated distillate vapors through the ejector nozzle, thus lowering the system's cost and energy consumption. This practice is generally preferred over the Mechanical Vapor Compression (MVC), which consumes electrical power in running a compressor. The cost of running electric-powered equipment with a lubrication requirement for the moving part undermines the merits of this process. The TVC system has a relatively simpler design and process layout as it just utilizes a nozzle and motive steam to compress the vapors. In addition, the absence of any moving part makes the process reliable with little need for maintenance [19].

4.2.4. MED-TVC CONFIGURATION:

The coupling of the TVC unit with a multi-effect system amplifies the performance of the desalting system. This happens because of the lowering of the energy need by exploiting the vapors produced in the effect to be reused for boiling more feed. This process generally operates relatively quicker than the other types and is easy to maintain with proven and tested reliability. Additionally, the MED-TVC system's cost, installation, intake of seawater, and civil work are 35% less expensive than the Multi-Stage Flash system (MSF). Apart from that, the market share of the MED-TVC System is 5% which is five times more than that of MED-MVC [26].

4.2.5. LOCATION OF TVC UNIT:

The size of the ejector nozzle has a direct relation with the specific volume of the entrained vapors. As the process continues, the specific volume of the distillate vapor increases with the increasing number of effects. To keep the size of the ejector to a manageable scale, the most industrial-scale desalting units employ the TVC in the middle of the total effects. Additionally, at the beginning of the effects, the formation of vapor is relatively lower than those present at the end. There is a compromise to be made in between to either keep the specific volume lower or the quantity of vapor ample, as a general tradeoff TVC is placed in between the total effects.

Based on the above-stated reason it has been concluded that the MED-TVC Parallel Cross Flow System with TVC placed after the middle effect gives the optimal performance and efficiency.

4.3. OPERATIONAL DETAILS OF THE EIGHT-EFFECT MED-TVC SYSTEM:

The mixture of feed and cooling water is initially taken from the pretreatment plant to the condenser. This preheats the incoming feed from the temperature t_c to t_f by exchanging the heat from the distillate (vapors) of the last effect at T_v[8]. The cooling water is then taken away from the system. Eventually, the feed is sent to exchange the energy from the combined brine of all effects and distillate (liquid) from where its temperature rises from t_f to t_{ff}. The feed is then sent to the preheater 1-6 whereas, for 7th and 8th effect the feed enters at the same temperature t_{ff}. The preheaters further raise the temperature of the feed before it is being sprayed in the effects. The preheaters take the energy from the six distillate flashing boxes, which are present after the second and before the last effect. The flashing box is not required after the first effect as the distillate formed is consumed as heating fluid for the next step, and the remaining fraction is returned to the plant, and the last effect is maintained at the same temperature as the condenser. The distillate (vapor) formed in each effect (until the last effect) is transferred for providing the heat for boiling, and the distillate (liquid) is transferred to the distillate flashing boxes.

The feed sprayed in each effect (i) boils to form distillate vapor which is then sent to the tube side of the next effect (i+1), which then condenses in the tubes to boil the feed of (i+1) effect. The brine of effect (i) is also sent to the next effect (i+1) where it flashes and increases the yield. The distillate after being condensed is sent to the distillate flashing box, however, the uncondensed part of the distillate is sent to the next effect combined with the vapor produced as a result of boiling of feed and flashing of brine in that effect.

This procedure continues until the fourth effect, from where the distillate vapors produced are distributed into two streams. The x portion enters into the TVC unit, whereas, the (1-x) portion enters in the fifth effect. This x portion of the vapor is also called entrained vapor. The TVC takes up the motive steam from either co-generation or any other means. This motive steam creates a suction head by accelerating through the nozzle and converting the pressure energy into velocity energy. This creates a vacuum near the tip of the nozzle, which sucks the entrained vapor, and combined with the motive steam, this mixture enters into another nozzle which again converts this velocity energy into pressure energy. This compressed mixture is then sent to the first effect. The remaining (1-x) portion enters into the fifth effect, and the same cycle of boiling and flashing, similar to the 1-4 effect, repeats. However, the size of the 5-8 effect is smaller than the 1-4 because of the reduced flow entering in these effects. This lowers the manufacturing cost of the evaporators.

After the last effect, the distillate (vapor) enters into the condenser where it preheats the incoming feed. The brine being transported to every effect (except the first) is finally taken to the brine tank, which further preheats the feed. The distillate after being condensed in either tube of the evaporator, or preheater, and finally in the condenser, is accumulated in the distillate tank as shown in **Figure 4.1**

To make the water fit for drinking purposes, it is recommended to add lime and CO_2 after the process completes.

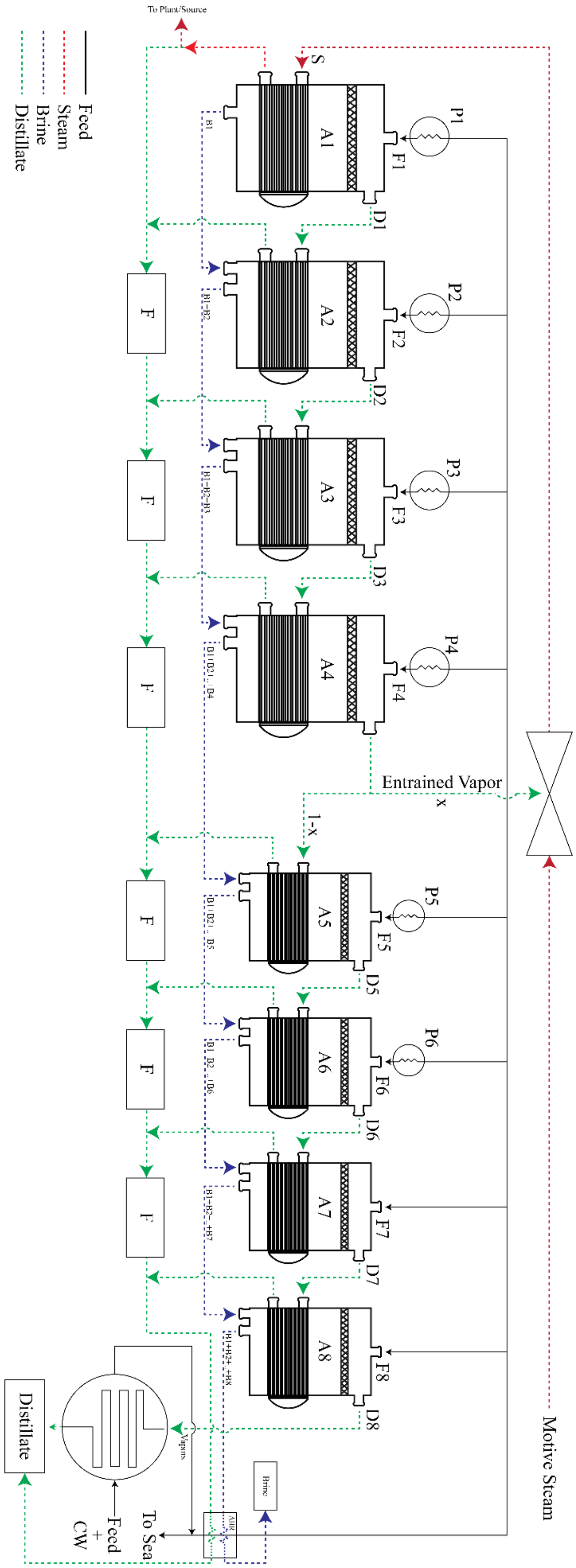


Figure 4.1 Schematic Diagram of Eight-Effect MED-TVC Unit

4.4. SIMULATION OF PROPOSED SYSTEMS:

The simulation of the MED-TVC systems is performed on the Engineering Equation Solver (EES) software. The software is generally preferred because of its efficiency in solving thermodynamic systems very effectively.

4.5. DETAILS OF EIGHT-EFFECT MED-TVC SYSTEM:

Following are the values of the characteristic parameters of the system which are taken from the industrial data specifically for domestic (Pakistani) conditions.

Number of Effects = n = 8

Distillate Production Rate = D = 316 kg/s

Top Brine Temperature = T_1 = 65°C

The temperature of the Feed Water = t_f = 35°C

Temperature of the Cooling water = t_c = 27°C

Incoming Feed water`s Salinity = X_f = 35 g/l

Rejected Brine`s Salinity = X_b = 60 g/l

Each Effect`s Overall heat transfer coefficient = U_e = 3.0 kW/m^2-C

Condenser`s Overall heat transfer coefficient = U_c = 2.4 kW/m^2-C

Temperature of last effect = T_n = 40°C

Motive Steam Pressure = P_m = 750 kPa

4.6. PROCESS MODELING:

Before proceeding with the process modeling, some assumptions should be made to ensure that the process is controllable and reasonably simple.

These are:

1. The resulting product water is devoid of salt and contaminants.
2. The pressure loss across the demister is negligible.
3. Feed water characteristics are temperature and salinity dependent.
4. For each model, the overall heat transfer coefficient is assumed to be constant.
5. The resistance between the condenser tubes is minimal.
6. The temperature of the steam is assumed to be 5 degrees higher than TBT.
7. The process is continuous and steady.

The global mass balance of the system is given by

$$F = D + B \tag{4.4}$$

The salt balance of the system can be expressed as

$$F.X_f = B.X_b \tag{4.2}$$

The temperature of each effect can be formulated as

$$\delta T = \frac{T[1] - T[n]}{n - 1} \tag{4.3}$$

$$T[i] = T[i - 1] - \delta T \tag{4.4}$$

Where, i indicates the effect`s number here; its value is taken from 2 to 7.

The boiling point elevation (BPE) of each effect can be calculated by the built-in function of EES, which is

$$BPE[i] = SW\_BPE(T[i], X_f) \tag{4.5}$$

Due to the presence of salt in the water, each effect's vapor temperature (T_v) is smaller than its temperature (T) by the factor BPE.

$$T_v[i] = T[i] - BPE[i] \tag{4.6}$$

To find the specific heat (C_p) of each effect at an average value, average salinity (X_{avg}) and the average temperature of each effect, (T_{avg}) should be known.

$$X_{avg} = \frac{X_f + X_b}{2} \tag{4.7}$$

$$T_{avg}[i] = \frac{T[i] + t_f}{2} \tag{4.8}$$

So, by the built-in function of EES

$$C_{avg}[i] = \frac{\mathrm{SW\_SpcHeat}(\mathrm{T_{avg}[i] + X_{avg}})}{1000} \tag{4.9}$$

For latent heat of each effect (hfg[i]) and latent heat of steam (hfg_s), the built-on function of EES is given by

$$\mathrm{hfg[i] = Enthalpy\_vaporization(Steam, T = T_v[i])} \tag{4.10}$$

$$\mathrm{hfg_s = Enthalpy\_vaporization(Steam, T = T_s)} \tag{4.11}$$

The feed distribution of each effect of the system can be formulated as

$$F = F_x * n * (1 - \frac{x}{2}) \tag{4.12}$$

For the first four effects

$$F[i] = F_x \tag{4.13}$$

For the last four effects

$$F[i] = (1 - x) * F_x \tag{4.14}$$

The latent heat of steam condensation is utilized to raise the temperature of the feed water from (T_f [1]) to the first effect's temperature (T[1]) and part of the feed water is evaporated and converted into distillate vapors (D_b[1]), so the energy balance of the first effect can be written as

$$S * hfg_s = F[1] * C_p[1] * \left(T[1] - T_f[1]\right) + D_b[1] * hfg[1] \tag{4.15}$$

Similarly, by utilizing the latent heat of vapors produced by boiling in the [i-1] effect to enhance the temperature from Tf[i] to T[i], and converting a portion of the feed water to vapors (Db[i]) via evaporation, so the energy balance of the remaining effects excluding the fifth effect is

$$D_b[i-1] * hfg[i-1] = F[i] * C_p[i] * \left(T[i] - T_f[i]\right) + D_b[i] * hfg[i] \tag{4.16}$$

The [1-x] portion of distillate vapors enters in the fifth effect, so the energy balance is,

$$(1 - x) * D_b[4] * hfg[4] = F[5] * C_p[5] * \left(T[5] - T_f[5]\right) + D_b[5] * hfg[5] \tag{4.17}$$

The sum of each effect's distillate in the distillate flashing box and sum of brine in each effect may be expressed as

$$D_{dd}[i] = sum(D[j], j = 1, i - 1) \tag{4.18}$$

$$B_f[i] = sum(B[j], j = 1, i - 1) \tag{4.19}$$

The flashing of distillate in each distillate flashing box can be represented as

$$D_d[i] = D_{dd}[i] * 4.2 * \frac{(T_v[i-1] - T_v[i])}{hfg[i]} \tag{4.20}$$

The flashing of brine in the first effect is zero

$$D_f[1] = 0 \tag{4.21}$$

The flashing of brine in each effect may be written as

$$D_f[i] = B_f[i] * C_p[i] * \frac{(T[i-1] - T[i])}{hfg[i]} \tag{4.22}$$

The flow rate of each effect's total distillate equals the sum of distillate produced by boiling and distillate generated by flashing of brine in each effect, so

$$D[i] = D_b[i] + D_f[i] \tag{4.23}$$

The sum of distillate in each effect is given by the built-in function of EES

$$D = sum(D[i], i = 1, n) \tag{4.24}$$

The amount of brine rejected from each effect may readily be determined by

$$B[i] = F[i] - D[i] \tag{4.25}$$

The salinity of brine rejected from each effect can be determined by

$$X_f * F[i] = X_b[i] * B[i] \tag{4.26}$$

The sum of brine and distillate of [n-1] effects can be expressed by the built-in function of EES,

$$B_{HR} = sum(B[j], j = 1, n - 1) \quad (4.27)$$

$$D_{HR} = sum(D[j], j = 1, n - 1) \quad (4.28)$$

After the condenser, the feed water again recovers heat from the combined brine of all effects and distillates (liquid), raising its temperature from t_f to t_{ff}.

$$F * 3.9 * \left(t_{ff} - t_f\right) = D_{HR} * 4.2 * \left(T_v[n-1] - t_f\right) + B_{HR} * 3.9 * (T[n-1] - t_f) \quad (4.29)$$

Subsequently, taking energy from the distillate flashing boxes, the pre-heaters further raise the feed water temperature from t_{ff} to $T_f[i]$ and it can be expressed as

$$D_d[n-i] * hfg[n-i] = F[i] * C_p[i] * (T_f[i] - t_{ff}) \quad (4.30)$$

Due to the absence of a preheater in the seventh and eighth effects, their feedwater temperature is identical to that of t_{ff}.

$$T_f[n-1] = t_{ff} \quad (4.31)$$

$$T_f[n] = t_{ff} \quad (4.32)$$

The entrained vapor pressure (Pr) and discharge pressure (Ps) may be computed using the EES's built-in function.

$$P_r = Pressure(Steam, T = T_v[4], x = 1) \quad (4.33)$$

$$P_s = Pressure(Steam, T = T_s, x = 1) \quad (4.34)$$

In the same manner, the motive steam temperature (T_m) can be computed as

$$T_m = T_{sat}(Steam, P = P_m) \tag{4.35}$$

Thus, for the entrainment ratio (Ra), which is defined as the amount of motive steam divided by the unit mass of entrained vapor, it is necessary to know the motive steam pressure correction factor (PCF) and the entrained vapor temperature correction factor (TCF).

$$PCF = 3 \times 10^{-7} * {P_m}^2 - 0.0009 * P_m + 1.6101 \tag{4.36}$$

$$TCF = 2 \times 10^{-8} * T_v[4]^2 - 0.0006 * T_v[4] + 1.0047 \tag{4.37}$$

$$Ra = 0.296 * \left(\frac{{P_s}^{1.19}}{{P_r}^{1.04}}\right) * \left(\frac{P_m}{P_r}\right)^{0.015} * \left(\frac{PCF}{TCF}\right) \tag{4.38}$$

The mass flow rates of the motive steam (S_m) and the entrained vapor (S_r) can be expressed in the following manner

$$S_m = \frac{S}{1 + \frac{1}{Ra}} \tag{4.39}$$

$$S_r = S - S_m \tag{4.40}$$

The portion of the distillate vapor (x) that enters the TVC can be determined by dividing the flow rate of entrained vapor (Sr) by the distillate generated in the fourth effect.

$$x = \frac{S_r}{D[4]} \tag{4.41}$$

Now for the compression ratio (CR) which can be interpreted as the pressure of entrained vapor (P_s) divided by the discharge pressure (P_r), can be expressed as

$$CR = \frac{P_s}{P_r} \tag{4.42}$$

The first effect's heat transfer surface area (A_e) is defined by

$$A_e[1] = \left(F[1] * C_p[1] * \left(T[1] - T_f[1]\right) + D_b[1] * hfg[1]\right) * \frac{(T_s - T_v[1])}{U_e} \tag{4.43}$$

For all other effects

$$A_e[i] = \left(F[i] * C_p[i] * \left(T[i] - T_f[i]\right) + D_b[i] * hfg[i]\right) * \frac{(T_v[i-1] - T_v[i])}{U_e} \tag{4.44}$$

The heat transfer area of the preheater (A_p) can be determined by

$$A_p[i] = F[i] * C_p[i] * \frac{\left(T_f[i] - t_{ff}\right) * \delta\mathrm{T}}{2.4} \tag{4.45}$$

In this case, 2.4 indicate the total heat transfer coefficient for the preheater.

The total area of all evaporators and preheaters can be written as

$$A_e = sum(A_e[i], i = 1, n) \tag{4.46}$$

$$A_p = \frac{sum(A_p[i], i = 1, n-2)}{0.8} \tag{4.47}$$

Here, 0.8 represents the effectiveness of preheater.

The condenser`s area (A_c) can be expressed as

$$A_c = \frac{F * 3.9 * \left(t_f - t_c\right) * 0.6}{lmtd * U_c} \tag{4.48}$$

Where 0.6 denotes the condenser effectiveness and the logarithmic mean temperature difference over the condenser, can be specified as

$$lmtd = \left(\frac{(t_f - t_{c)}) * (T_v[n] - t_f)}{(\ln(T_v[n] - t_c))}\right) \tag{4.49}$$

The combined brine distillate heat recovery area (A_{hr}) can be written as

$$A_{hr} = F * 3.9 * \frac{\left(t_{ff} - t_f\right) * 2}{0.6 * lmtd_{hr}} \tag{4.50}$$

Where the logarithmic mean temperature difference of A_{hr} can be expressed by

$$lmtd_{hr} = \left(T_v[n-1] - t_f - 2\right) + \frac{t_{ff} - t_f}{2} \tag{4.51}$$

The condenser`s energy balance equation can be specified by

$$(D[n]) * hfg[n] = (Cw * F) * C_p[n] * (t_f - t_c) \tag{4.52}$$

The flow rate of the cooling water (Cw) divided by the total distillate's flow rate (D) yields the flow rate of a specific mass of cooling water (sCW), which can be represented as

$$sCW = \frac{Cw}{D} \tag{4.53}$$

Now, for the performance ratio (PR), which can be defined as the total distillate's flow rate (D) divided by the motive steam's flow rate (S_m) and it can be expressed as

$$PR = \frac{D}{S_m} \tag{4.54}$$

The MED-TVC system`s gain ratio (GOR) can be written as follows

$$GOR = \frac{D * 2330 * hfg_s}{S_m} \tag{4.55}$$

The specific heat transfer area (sA) is the summation of all areas including the area of the evaporators (A_e), the area of preheaters (A_p), the area of the condenser (A_c), and the area of combined distillate brine heat recovery (A_{hr}) divided by the distillate mass flow rate and can be represented as

$$sA = \frac{A_e + A_p + A_c + A_{hr}}{D} \tag{4.56}$$

4.7. RESULTS:

Feeding the data in Engineering Equation Solver (EES) software, the following results can be obtained:

Unit Settings: SI C kPa kJ mass deg

A_c = 2055 [m2]	A_e = 65161 [m2]	A_{hr} = 1926 [m2]	A_p = 2268 [m2]	B = 442.4 [kg/s]	B_{HR} = 406.4 [kg/s]
CR = 2.087	Cw = 1251 [kg/s]	D = 316 [kg/s]	δ_T = 3.571 [C]	D_{HR} = 289.6 [kg/s]	F = 758.4 [kg/s·]
F_x = 127.2 [kg/s]	GOR = 9.503	hfg_s = 2333 [kJ/kg]	lmtd = 7.997 [C]	$lmtd_{hr}$ = 10.2	n = 8
PCF = 1.104	PR = 9.516	P_m = 750 [kPa]	P_r = 14.94 [kPa]	P_s = 31.18 [kPa]	Ra = 1.283
S = 59.1 [kg/s]	sA = 226 [m2-s/kg]	sCW = 3.959	S_m = 33.21 [kg/s]	S_r = 25.89 [kg/s]	TCF = 0.9724
t_c = 27 [C]	t_f = 35 [C]	t_{ff} = 42.97 [C]	T_m = 167.8 [C]	T_s = 70 [C]	U_c = 2.4 [kW/m2-C]
U_e = 3 [kW/m2-C]	x = 0.5095	X_{avg} = 47.5 [g/l]	X_b = 60 [g/l]	X_f = 35 [g/l]	

The individual effect data is found to be:

Sort	T_i [C]	BPE_i [C]	$T_{v,i}$ [C]	hfg_i [kJ/kg]	F_i [kg/s]	D_i [kg/s]	B_i [kg/s]	$C_{p,i}$ [kJ/kg-C]	$T_{avg,i}$ [C]
[1]	65	0.4142	64.59	2346	127.2	55.72	71.48	3.953	50
[2]	61.43	0.4043	61.02	2355	127.2	53.51	73.69	3.952	48.21
[3]	57.86	0.3944	57.46	2364	127.2	51.93	75.27	3.951	46.43
[4]	54.29	0.3846	53.9	2372	127.2	50.81	76.39	3.95	44.64
[5]	50.71	0.375	50.34	2381	62.4	25.84	36.56	3.95	42.86
[6]	47.14	0.3655	46.78	2390	62.4	25.88	36.52	3.949	41.07
[7]	43.57	0.3561	43.22	2398	62.4	25.94	36.46	3.948	39.29
[8]	40	0.3469	39.65	2407	62.4	26.36	36.03	3.947	37.5

Sort	$D_{b,i}$ [kg/s]	$D_{f,i}$ [kg/s]	$B_{f,i}$ [kg/s]	$T_{f,i}$ [C]	$D_{d,i}$ [kg/s]	$D_{dd,i}$ [kg/s]	$X_{b,i}$ [g/l]	$A_{e,i}$ [m2]	$A_{p,i}$ [m2]
[1]	55.72	0		50.82			62.28	8489	460.3
[2]	53.09	0.4284	71.48	50.05	0.3539	55.72	60.42	12237	415.1
[3]	51.07	0.8667	145.2	49.28	0.6913	109.2	59.15	11701	370
[4]	49.5	1.311	220.4	47.77	1.016	161.2	58.28	11297	281.3
[5]	24.08	1.758	296.8	49.6	1.332	212	59.74	5391	190.6
[6]	23.91	1.968	333.4	46.35	1.489	237.8	59.8	5365	97.24
[7]	23.76	2.175	369.9	42.97	1.645	263.7	59.9	5347	
[8]	23.98	2.38	406.4	42.97			60.61	5333	

Table 4.1 Individual effect data of 8 Effect MED-

4.8. GRAPHICAL ANALYSIS AND INTERPRETATION:

Top Brine Temperature (TBT) vs. Performance Ratio (PR):

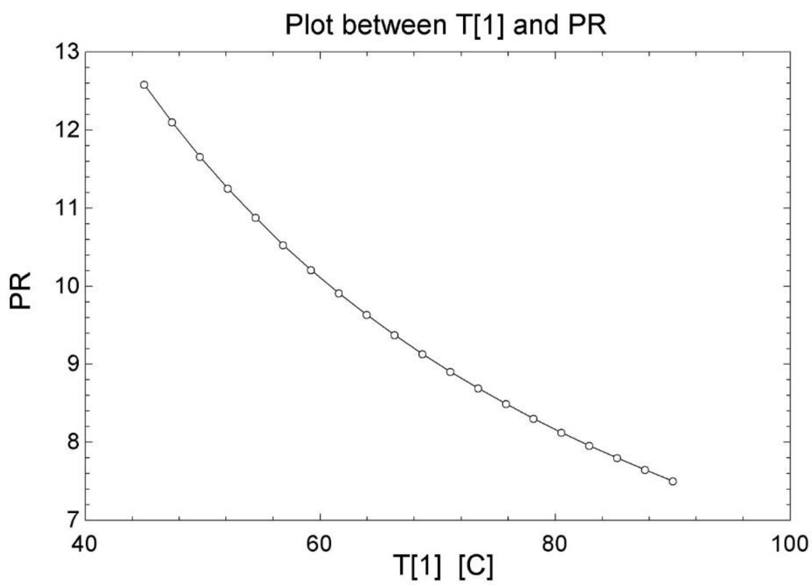


Figure 4.2 Graph between TBT vs. PR

As the brine boiling temperature of the first effect increases, the requirement for the motive steam also increases because the entrained vapors are kept at a constant temperature. Due to this, the motive steam`s mass flow rate increases to even out the effect of the increased temperature. Additionally, at a higher temperature the latent heat decreases which undermine the effective heat transfer. In addition, by the increase in the TBT of the system, the sensible heating of the feed also increases, which reduces the latent energy of the vapors formed. All of these factors combine to lower the performance ratio of the configuration as shown in **Figure 4.2**

Top Brine Temperature (TBT) vs. Specific Area (sA):

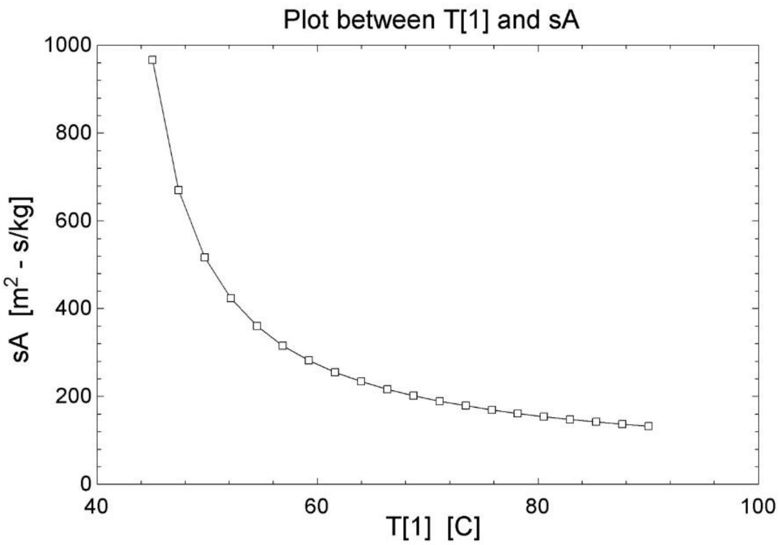
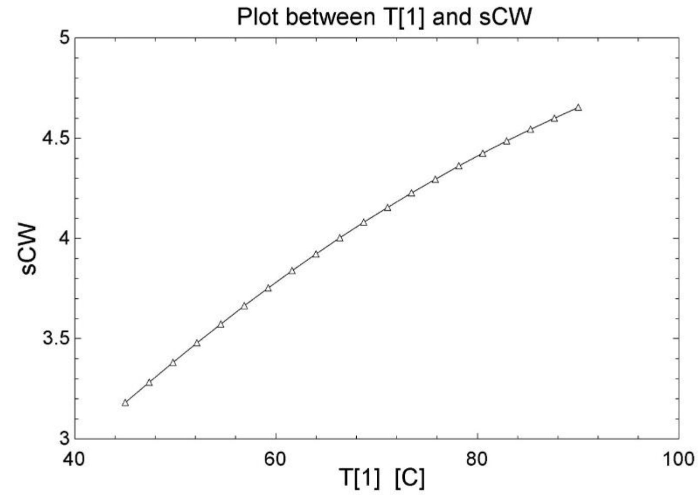


Figure 4.3 Graph between TBT vs. sA

At increasing temperatures, the heat transfer coefficient rises as thermal resistance decreases, enhancing the heat transfer in the evaporators and lowering the need for their big size. Due to this, the same heat transfer can be achieved in a smaller evaporator and condenser as shown in **Figure 4.3**

Top Brine Temperature (TBT) vs. Cooling Water Rate (sCw):



+

Figure 4.4 Graph between TBT vs. sCw

With the rise in TBT, the temperature of the distillate vapor also rises. Due to this increased temperature, the condenser cooling load increases. To meet the demand of the condenser cooling load, the amount of cooling water required to take the excess energy out of the system also increases. These all together pull the specific rate of cooling water above as shown in **Figure 4.4**

Brine Salinity (X_b) vs. Performance Ratio (PR):

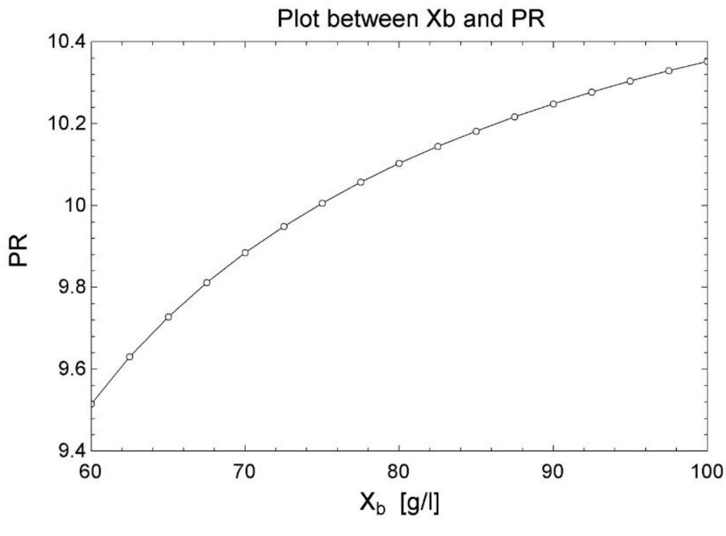


Figure 4.5 Graph between X_b vs. PR

As the salinity of the extracted brine increases, this indicates the good performance of the process in eliminating the dissolved salt from the water. As a result, more distillate is formed, or the requirement of steam drops. This intuitively increases the performance ratio of the system as shown in **Figure 4.5**

Brine Salinity (X_b) vs. Specific Area (sA):

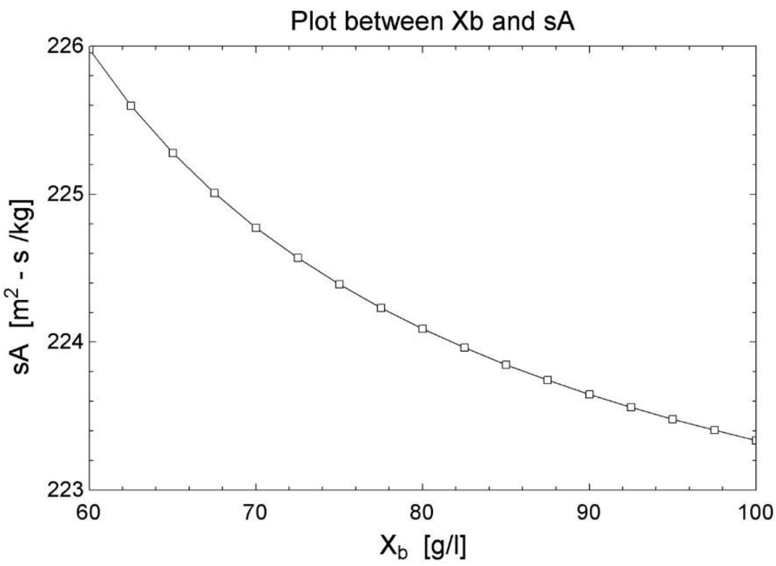


Figure 4.6 Graph between X_b vs. sA

The relationship of rejected brine salinity with the specific area is an inverse one. The increased salinity of the rejected brine lowers the need for the incoming feed in the evaporator. This lowers the requirement of the areas of evaporator and condenser, which results in a decrease in the specific heat transfer area as shown in **Figure 4.6**

Brine Salinity (X_b) vs. Cooling Water Rate (sCw):

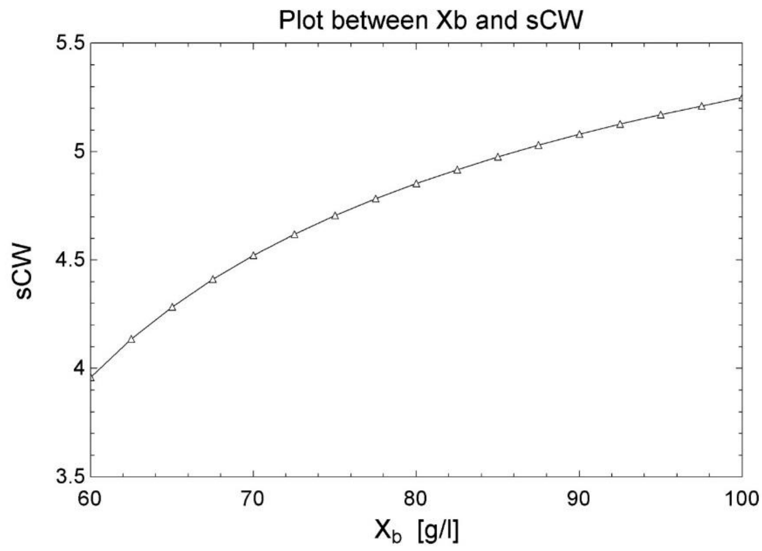


Figure 4.7 Graph between X_b vs. sCw

As the salinity of the rejected brine enhances, the need for feed water reduces because less feed generates the same distillate due to the high rejected salinity, and the demand for cooling water increases which eventually increases the specific cooling water flow rate as shown in **Figure 4.7**

Performance Ratio & Specific Area vs. Motive Steam Pressure:

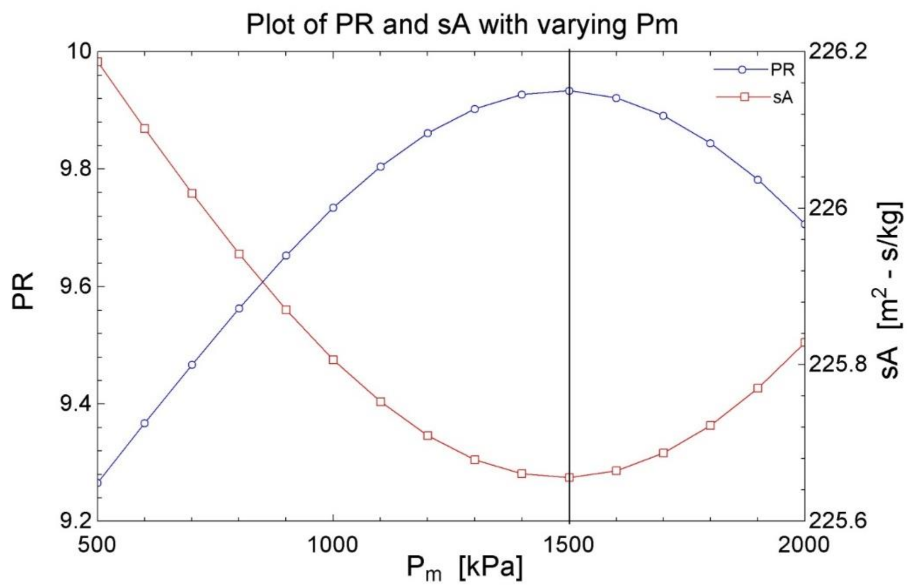


Figure 4.8 Graph between Pm vs. PR & sA

The performance ratio of the given configuration first surges with the rise in the pressure of the motive steam but further increases above 1500 kPa lessen the PR. This happens because after 1500 kPa the TVC unit does not create an effective vacuum at the tip of the nozzle which eventually draws less entrained vapor in the ejector. As the quantity of the entrained vapor decreases, there comes a need to increase the flow of motive steam to balance the lessening of the entrained vapor. This reduces the PR of the system.

Next, by increasing the PM the amount of entrained vapor being drawn in the ejector increases which lowers the quantity to be delivered in the effects after the TVC, due to this, their sizes minimize. However, this effect only holds till 1500 KPa and after that, the same phenomenon occurred which increases the sA. The optimal operating point can then be figured by the graph at a point where the distance between the two curves is maximum i.e. the PR is maximum and sA is minimum. This maximum distance occurs at P_m = 1500 KPa as shown in **Figure 4.8**

The reduction in the specific area enables the use of small size effects which require less material cost which pulls the CAPEX (Capital Cost) down.

The performance ratio is the metric to assess the performance of desalination systems. The increased performance ratio depicts the consumption of less motive steam which is a good sign as the saved steam will then be used to create any other value. This enables the production of distillate at a lower cost.

Chapter 5

TEN, TWELVE, FOURTEEN EFFECTS MED-TVC SYSTEMS

5.1 GENERAL OPERATION DETAILS:

The top brine temperature of any Multi-effect distillation configuration should not exceed above 65°C because high temperature causes scaling in the effects, affecting the system's performance ratio and additional parameters. However, there are some anti-scaling entities by which the top brine temperature can be raised to 80-85°C [31]. In this way, the system can provide more heat to the feed water, especially in the first effect, and there is no such amount of scaling produced.

The operational details of the ten-effect system, twelve-effect system, and fourteen-effect system coupled with TVC are approximately the same as the operational details of the eight-effect system coupled with TVC. However,

- In each system, there is an increase of 2 Effect.
- An increase in 5°C of Top Brine Temperature in each configuration.
- In each model, TVC placed after (n/2) effects means, in the middle position of n number of effects.

Similarly, the process modeling of the remaining configurations is nearly the same as the process modeling of the eight-effect system coupled with TVC; however, there are minor changes due to the increased number of effects and position of the Thermal Vapor Compression (TVC) system.

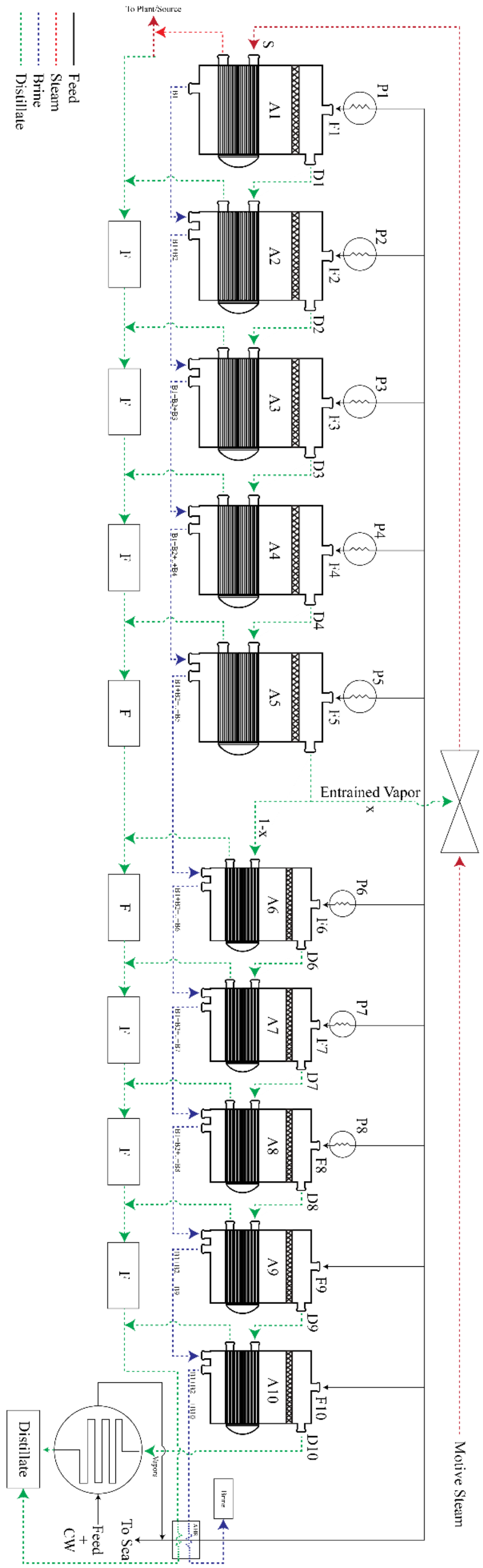


Figure 5.1 Schematic Diagram of Ten-Effect MED-TVC Unit

5.2 SIMULATION OF A TEN-EFFECT MED-TVC SYSTEM:

The two additional effects are added before and after the TVC unit of a size similar to their neighboring evaporators. Apart from that, the remaining characteristics of the system are similar to that of the previous system.

The data inputted to the proposed model is:

Number of effects = n = 10

Distillate Production Rate = D = 316 kg/s

Top Brine Temperature = T_1 = 70°C

Temperature of Incoming Feed = t_f = 35°C

Temperature of the Cooling water = tc = 27°C

Incoming Feed water`s Salinity = X_f = 35 g/l

Rejected Brine`s Salinity = X_b = 60 g/l

Each Effect`s Overall heat transfer coefficient = U_e = 3.0 kW/m^2-C

Condenser`s Overall heat transfer coefficient = U_c = 2.4 kW/m^2-C

Temperature of last effect = T_n = 40°C

Motive Steam Pressure = P_m = 750 kPa

The simulation yielded the following results:

Unit Settings: SI C kPa kJ mass deg

A_c = 2055 [m^2]	A_e = 69784 [m^2]	A_{hr} = 1959 [m^2]	A_p = 3101 [m^2]	B = 442.4 [kg/s]	B_{HR} = 413.3 [kg/s]	CR = 2.304
Cw = 826 [kg/s]	D = 316 [kg/s]	δ_T = 3.333 [C]	D_{HR} = 295.2 [kg/s]	F = 758.4 [kg/s]	F_x = 101.8 [kg/s]	GOR = 10.67
hfg_s = 2321 [kJ/kg]	lmtd = 7.997 [C]	$lmtd_{hr}$ = 9.921	n = 10	PCF = 1.104	PR = 10.63	P_m = 750 [kPa]
P_r = 16.74 [kPa]	P_s = 38.56 [kPa]	Ra = 1.468	S = 49.97 [kg/s]	sA = 243.4 [m^2-s/kg]	sCW = 2.614	S_m = 29.72 [kg/s]
S_r = 20.25 [kg/s]	TCF = 0.971	t_c = 27 [C]	t_f = 35 [C]	t_{ff} = 42.89 [C]	T_m = 167.8 [C]	T_s = 75 [C]
U_c = 2.4 [kW/m^2-C]	U_e = 3 [kW/m^2-C]	x = 0.5101	X_{avg} = 47.5 [g/l]	X_b = 60 [g/l]	X_f = 35 [g/l]	

The results of individual effects are as follow:

Sort	T_i [C]	BPE_i [C]	$T_{v,i}$ [C]	hfg_i [kJ/kg]	F_i [kg/s]	D_i [kg/s]	B_i [kg/s]	$C_{p,i}$ [kJ/kg-C]	$T_{avg,i}$ [C]
[1]	70	0.4284	69.57	2334	101.8	46.65	55.15	3.954	52.5
[2]	66.67	0.419	66.25	2342	101.8	44.23	57.57	3.953	50.83
[3]	63.33	0.4096	62.92	2350	101.8	42.29	59.51	3.953	49.17
[4]	60	0.4003	59.6	2359	101.8	40.82	60.98	3.952	47.5
[5]	56.67	0.3911	56.28	2367	101.8	39.71	62.1	3.951	45.83
[6]	53.33	0.3821	52.95	2375	49.88	20.31	29.57	3.95	44.17
[7]	50	0.3731	49.63	2383	49.88	20.35	29.53	3.949	42.5
[8]	46.67	0.3643	46.3	2391	49.88	20.4	29.48	3.949	40.83
[9]	43.33	0.3555	42.98	2399	49.88	20.46	29.42	3.948	39.17
[10]	40	0.3469	39.65	2407	49.88	20.79	29.09	3.947	37.5

Sort	$D_{b,i}$ [kg/s]	$D_{f,i}$ [kg/s]	$B_{f,i}$ [kg/s]	$T_{f,i}$ [C]	$D_{d,i}$ [kg/s]	$D_{dd,i}$ [kg/s]	$X_{b,i}$ [g/l]	$A_{e,i}$ [m2]	$A_{p,i}$ [m2]
[1]	46.65	0		52.42			64.61	7121	479.6
[2]	43.92	0.3103	55.15	51.71	0.278	46.65	61.89	10921	443.9
[3]	41.66	0.6318	112.7	51.01	0.5398	90.88	59.87	10317	408.4
[4]	39.86	0.9619	172.2	50.3	0.7883	133.2	58.43	9819	373
[5]	38.41	1.298	233.2	48.93	1.026	174	57.38	9427	303.7
[6]	18.67	1.637	295.3	52.32	1.256	213.7	59.04	4466	232.4
[7]	18.55	1.795	324.9	49.33	1.371	234	59.11	4446	158.6
[8]	18.45	1.951	354.4	46.19	1.486	254.4	59.23	4432	81.41
[9]	18.35	2.106	383.9	42.89	1.599	274.8	59.34	4423	
[10]	18.53	2.259	413.3	42.89			60.01	4414	

Table 5.1 Individual effect data of 10 Effect MED-TVC

5.2.1 RELATIONSHIP OF PERFORMANCE INDICATORS:

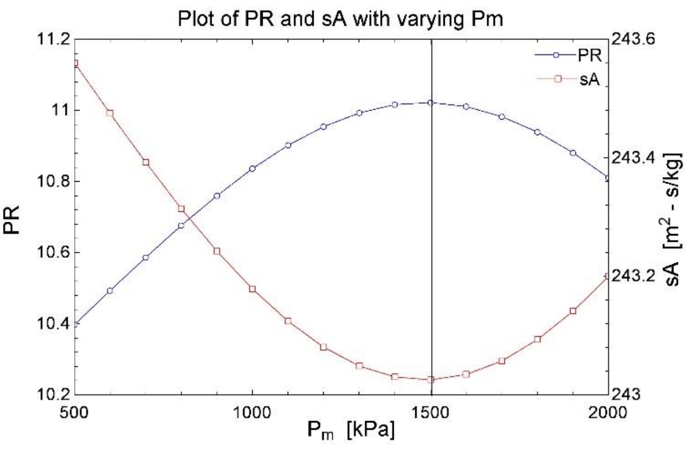


Figure 5.2 Graph between Pm vs. PR & sA

The following graph has been obtained as a product of plotting performance ratio and specific area against the motive steam pressure. The performance ratio primarily rises with the growth in pressure of the motive steam, but the further rise above 1500KPa lures the performance ratio down. This happens because of the lack of an adequate vacuum at the tip of the nozzle. This draws the less distillate vapor in the ejector, and additional steam is required to maintain the system's equilibrium. This degrades the performance ratio.

Similarly, the rise in motive steam pressure makes the drawing of the entrained vapor inside the nozzle efficient, which lowers the quantity to be delivered in the effects after the TVC. This reduces the overall size of the effects and consequently the specific area. However, this phenomenon holds only until the pressure of 1500KPa.

The graph obtained is of similar nature to that of an eight-effect system, where the point of feasibility can be obtained at the location where the distance between the two curves of performance ratio and the specific area is maximum. This trend is identical to the eight-effect system which substantiates the correctness of the simulation being carried out.

The following relationships of the top brine temperature with other key parameters, similar to the eight-effect system, have also been observed which gave a similar trend:

- As the boiling temperature hikes, the performance ratio falls.
- As the boiling temperature soars, the specific area declines exponentially
- The cooling water`s flow rate escalates with the rise in boiling temperature

The relationships of rejected brine salinity with other key parameters were as follow:

- The increased rejected brine salinity signifies the enhancement in the performance ratio, therefore, they follow direct relationship
- As the salinity of the rejected brine rises, the need for heat transfer region decreases.
- The pace at which cooling water-specific rate changes with rejected brine salinity is linked directly.

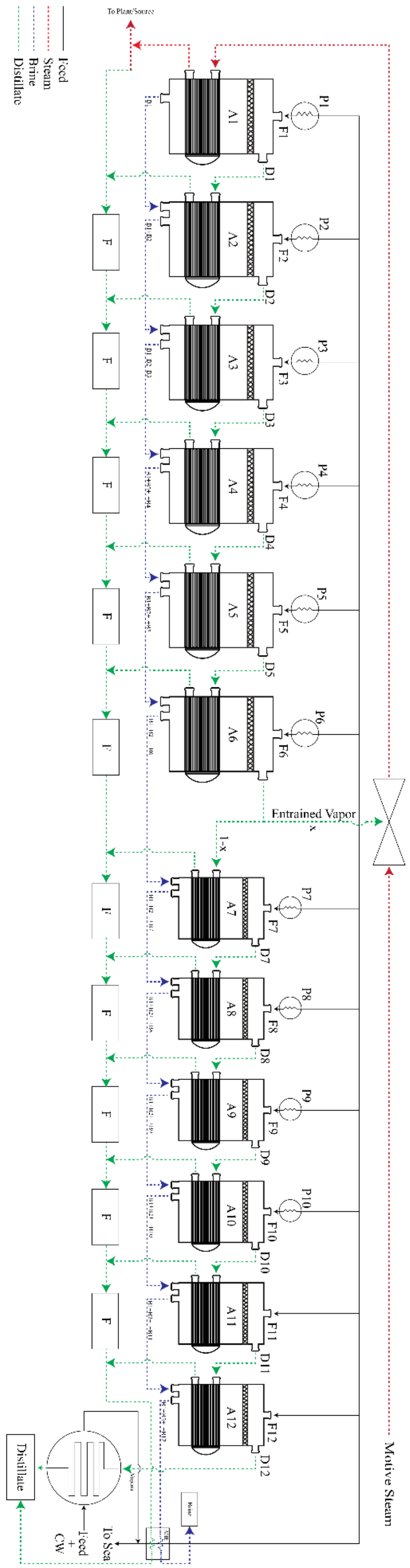


Figure 5.3 Schematic Diagram of Twelve-Effect MED-TVC Unit

5.3 SIMULATION OF A TWELVE-EFFECT MED-TVC SYSTEM:

For a twelve-effect system, two additional effects are again added before and after the TVC unit of a size similar to their neighboring evaporators. Apart from that, the remaining characteristics of the system are similar to that of the previous system.

The data inputted to the proposed model is:

Number of effects = n = 12
Distillate Production Rate = D = 316 kg/s
Top Brine Temperature = T_1 = 75°C
Temperature of Incoming Feed = t_f = 35°C
Temperature of the Cooling water = tc = 27°C
Incoming Feed water`s Salinity = X_f = 35 g/l
Rejected Brine`s Salinity = X_b = 60 g/l
Each Effect`s Overall heat transfer coefficient = U_e = 3.0 kW/m^2-C
Condenser`s Overall heat transfer coefficient = U_c = 2.4 kW/m^2-C
Temperature of last effect = T_n = 40°C
Motive Steam Pressure = P_m = 750 kPa

Inputting the data into the model and running the simulation yields:

Unit Settings: SI C kPa kJ mass deg

A_c = 2055 [m^2]	A_e = 73035 [m^2]	A_{hr} = 1982 [m^2]	A_p = 3974 [m^2]	B = 442.4 [kg/s]	B_{HR} = 418.2 [kg/s]	CR = 2.526
Cw = 526 [kg/s]	D = 316 [kg/s]	δ_T = 3.182 [C]	D_{HR} = 299.1 [kg/s]	F = 758.4 [kg/s·]	F_x = 85.37 [kg/s]	GOR = 11.45
hfg_s = 2308 [kJ/kg]	lmtd = 7.997 [C]	$lmtd_{hr}$ = 9.745	n = 12	PCF = 1.104	PR = 11.34	P_m = 750 [kPa]
P_r = 18.76 [kPa]	P_s = 47.37 [kPa]	Ra = 1.665	S = 44.61 [kg/s]	sA = 256.5 [m^2-s/kg]	sCW = 1.664	S_m = 27.87 [kg/s]
S_r = 16.74 [kg/s]	TCF = 0.9696	t_c = 27 [C]	t_f = 35 [C]	t_{ff} = 42.84 [C]	T_m = 167.8 [C]	T_s = 80 [C]
U_c = 2.4 [kW/m^2-C]	U_e = 3 [kW/m^2-C]	x = 0.5194	X_{avg} = 47.5 [g/l]	X_b = 60 [g/l]	X_f = 35 [g/l]	

The other properties observed on each effect are:

Sort	T_i [C]	BPE_i [C]	$T_{v,i}$ [C]	hfg_i [kJ/kg]	F_i [kg/s]	D_i [kg/s]	B_i [kg/s]	$C_{p,i}$ [kJ/kg-C]	$T_{avg,i}$ [C]
[1]	75	0.4429	74.56	2322	85.37	41.29	44.08	3.955	55
[2]	71.82	0.4337	71.38	2330	85.37	38.71	46.66	3.955	53.41
[3]	68.64	0.4245	68.21	2338	85.37	36.53	48.84	3.954	51.82
[4]	65.45	0.4155	65.04	2345	85.37	34.74	50.63	3.953	50.23
[5]	62.27	0.4066	61.87	2353	85.37	33.34	52.03	3.952	48.64
[6]	59.09	0.3978	58.69	2361	85.37	32.22	53.15	3.952	47.05
[7]	55.91	0.389	55.52	2369	41.02	16.34	24.68	3.951	45.45
[8]	52.73	0.3804	52.35	2376	41.02	16.4	24.62	3.95	43.86
[9]	49.55	0.3719	49.17	2384	41.02	16.47	24.55	3.949	42.27
[10]	46.36	0.3635	46	2391	41.02	16.53	24.49	3.948	40.68
[11]	43.18	0.3551	42.83	2399	41.02	16.59	24.43	3.948	39.09
[12]	40	0.3469	39.65	2407	41.02	16.85	24.17	3.947	37.5

Sort	$D_{b,i}$ [kg/s]	$D_{f,i}$ [kg/s]	$B_{f,i}$ [kg/s]	$T_{f,i}$ [C]	$D_{d,i}$ [kg/s]	$D_{dd,i}$ [kg/s]	$X_{b,i}$ [g/l]	$A_{e,i}$ [m2]	$A_{p,i}$ [m2]
[1]	41.29	0		53.99			67.78	6306	493.2
[2]	38.47	0.2381	44.08	53.34	0.2362	41.29	64.04	10072	464.3
[3]	36.04	0.4884	90.74	52.69	0.4561	80	61.18	9416	435.6
[4]	33.99	0.7486	139.6	52.04	0.6621	116.5	59.01	8851	406.9
[5]	32.32	1.017	190.2	51.4	0.8567	151.3	57.42	8375	378.4
[6]	30.93	1.29	242.2	50.13	1.042	184.6	56.22	7989	322.2
[7]	14.77	1.568	295.4	55.27	1.22	216.8	58.18	3687	264
[8]	14.7	1.693	320.1	52.42	1.308	233.2	58.31	3676	203.3
[9]	14.65	1.817	344.7	49.42	1.395	249.6	58.47	3670	139.6
[10]	14.59	1.94	369.2	46.23	1.483	266	58.63	3668	72.05
[11]	14.52	2.061	393.7	42.84	1.57	282.6	58.76	3666	
[12]	14.67	2.182	418.2	42.84			59.4	3660	

Table 5.2 Individual effect data of 12 Effect MED-TVC

5.3.1 RELATIONSHIP OF PERFORMANCE INDICATORS:

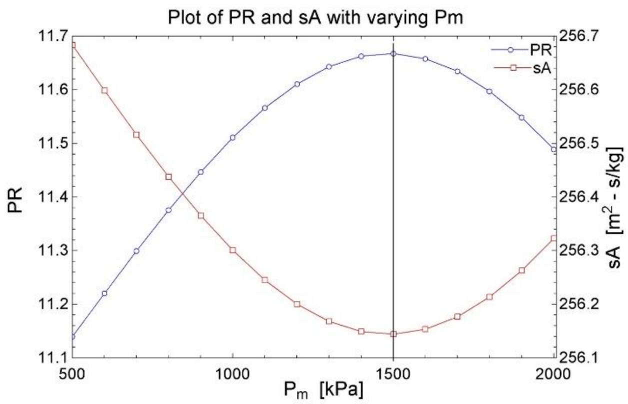


Figure 5.4 Graph between Pm vs. PR & sA

A similar relationship, as witnessed during the simulation of the previous configurations, has been observed again. The performance ratio first rises but again falls after 1500KPa. Attributed to the same phenomenon there is a decline in the specific area first. However, it rises after the limit of 1500KPa.

The resulting graph is of a similar type to that of the eight and ten effect systems, where the region or point of feasibility maybe derived in the same manner as to where the gap between the two curves of performance ratio and the specific area is greatest.

This pattern is comparable to that of eight and ten effect systems, which demonstrates the simulation's accuracy. Additionally, the same pattern has been found in the relation between boiling temperature and salinity of rejected brine with other important parameters, comparable to the previous systems.

5.4 SIMULATION OF A FOURTEEN-EFFECT MED-TVC SYSTEM:

The Fourteen-effect system is again kept identical to its competitors. There is again an accumulation of two effects before and after the TVC unit of a size similar to their neighboring evaporators. Apart from that, the remaining characteristics of the system are similar to that of the previous system. The data inputted to the proposed model is:

Number of effects = n = 14
Distillate Production Rate = D = 316 kg/s
Top Brine Temperature = T_1 = 80°C
Temperature of Incoming Feed = t_f = 35°C
Temperature of the Cooling water = tc = 27°C
Incoming Feed water`s Salinity = X_f = 35 g/l
Rejected Brine`s Salinity = X_b = 60 g/l
Each Effect`s Overall heat transfer coefficient = U_e = 3.0 kW/m^2-C
Condenser`s Overall heat transfer coefficient = U_c = 2.4 kW/m^2-C
Temperature of last effect = T_n = 40°C
Motive Steam Pressure = P_m = 750 kPa

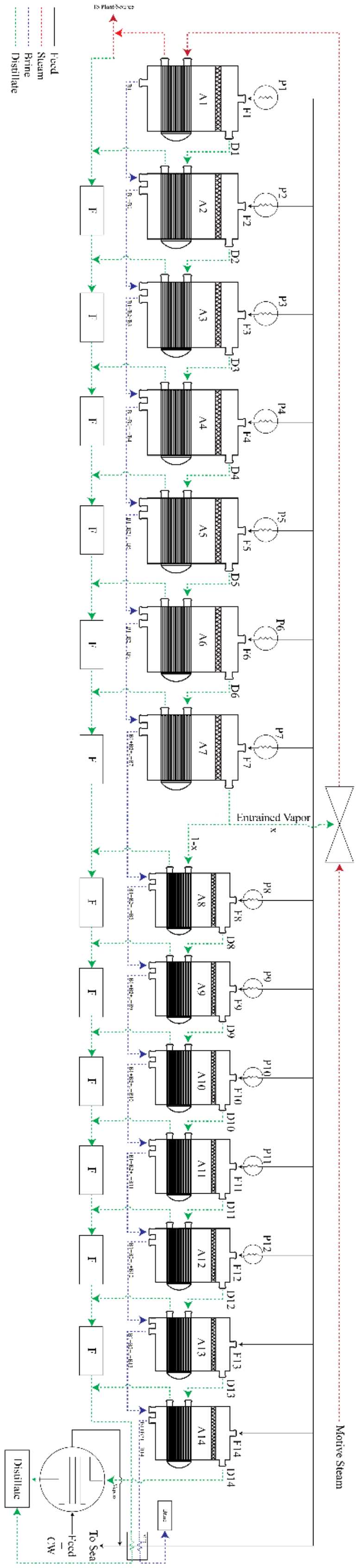


Figure 5.5 Schematic Diagram of Fourteen-Effect MED-TVC Unit

The simulation of this system once provided the above-mentioned data yields:

Unit Settings: SI C kPa kJ mass deg

A_c = 2055 [m2]	A_e = 75350 [m2]	A_{hr} = 1999 [m2]	A_p = 4896 [m2]	B = 442.4 [kg/s]	B_{HR} = 422.1 [kg/s]	CR = 2.753
Cw = 300.4 [kg/s]	D = 316 [kg/s]	δ_T = 3.077 [C]	D_{HR} = 302.1 [kg/s]	F = 758.4 [kg/s]	F_x = 74.14 [kg/s]	GOR = 11.86
hfg_s = 2295 [kJ/kg]	lmtd = 7.997 [C]	$lmtd_{hr}$ = 9.626	n = 14	PCF = 1.104	PR = 11.69	P_m = 750 [kPa]
P_r = 21 [kPa]	P_s = 57.81 [kPa]	Ra = 1.876	S = 41.45 [kg/s]	sA = 266.8 [m2-s/kg]	sCW = 0.9507	S_m = 27.04 [kg/s]
S_r = 14.41 [kg/s]	TCF = 0.9681	t_c = 27 [C]	t_f = 35 [C]	t_{ff} = 42.81 [C]	T_m = 167.8 [C]	T_s = 85 [C]
U_c = 2.4 [kW/m2-C]	U_e = 3 [kW/m2-C]	x = 0.5387	X_{avg} = 47.5 [g/l]	X_b = 60 [g/l]	X_f = 35 [g/l]	

The properties of individual effects can be given as:

Sort	1 T_i [C]	2 BPE_i [C]	3 $T_{v,i}$ [C]	4 hfg_i [kJ/kg]	5 F_i [kg/s]	6 D_i [kg/s]	7 B_i [kg/s]	8 $C_{p,i}$ [kJ/kg-C]	9 $T_{avg,i}$ [C]
[1]	80	0.4576	79.54	2309	74.14	38.08	36.06	3.957	57.5
[2]	76.92	0.4485	76.47	2317	74.14	35.36	38.78	3.956	55.96
[3]	73.85	0.4395	73.41	2325	74.14	32.98	41.16	3.955	54.42
[4]	70.77	0.4306	70.34	2332	74.14	30.94	43.2	3.954	52.88
[5]	67.69	0.4219	67.27	2340	74.14	29.24	44.9	3.954	51.35
[6]	64.62	0.4132	64.2	2347	74.14	27.87	46.27	3.953	49.81
[7]	61.54	0.4046	61.13	2355	74.14	26.75	47.39	3.952	48.27
[8]	58.46	0.396	58.07	2362	34.2	13.25	20.95	3.951	46.73
[9]	55.38	0.3876	55	2370	34.2	13.35	20.85	3.951	45.19
[10]	52.31	0.3793	51.93	2377	34.2	13.45	20.75	3.95	43.65
[11]	49.23	0.371	48.86	2385	34.2	13.55	20.65	3.949	42.12
[12]	46.15	0.3629	45.79	2392	34.2	13.63	20.57	3.948	40.58
[13]	43.08	0.3548	42.72	2399	34.2	13.67	20.53	3.948	39.04
[14]	40	0.3469	39.65	2407	34.2	13.89	20.31	3.947	37.5

Sort	10 $D_{b,i}$ [kg/s]	11 $D_{f,i}$ [kg/s]	12 $B_{f,i}$ [kg/s]	13 $T_{f,i}$ [C]	14 $D_{d,i}$ [kg/s]	15 $D_{dd,i}$ [kg/s]	16 $X_{b,i}$ [g/l]	17 $A_{e,i}$ [m2]	18 $A_{p,i}$ [m2]
[1]	38.08	0		55.48			71.97	5811	503.4
[2]	35.17	0.1894	36.06	54.88	0.2118	38.08	66.91	9556	479.6
[3]	32.59	0.3918	74.84	54.29	0.4071	73.44	63.04	8853	456
[4]	30.33	0.6052	116	53.7	0.588	106.4	60.07	8230	432.5
[5]	28.41	0.8277	159.2	53.12	0.7565	137.4	57.79	7686	409.2
[6]	26.81	1.058	204.1	52.54	0.9146	166.6	56.08	7222	386.1
[7]	25.46	1.293	250.4	51.36	1.064	194.5	54.76	6837	339.4
[8]	11.72	1.533	297.8	58.69	1.207	221.2	57.14	3004	290.7
[9]	11.71	1.635	318.7	55.91	1.275	234.5	57.41	3008	239.7
[10]	11.71	1.736	339.6	52.96	1.344	247.8	57.69	3015	185.7
[11]	11.71	1.836	360.3	49.81	1.412	261.3	57.96	3025	128.1
[12]	11.69	1.935	381	46.44	1.481	274.8	58.18	3033	66.45
[13]	11.64	2.033	401.5	42.81	1.549	288.4	58.31	3037	
[14]	11.76	2.13	422.1	42.81			58.94	3033	

Table 5.3 Individual effect data of 14-Effect MED-TVC

5.4.1 RELATIONSHIP OF PERFORMANCE INDICATORS:

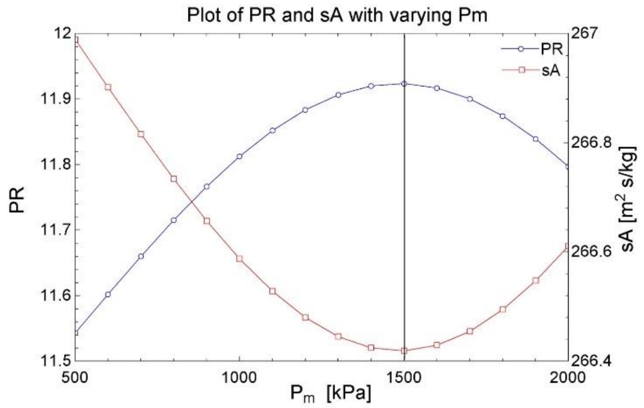


Figure 5.6 Graph between Pm vs. PR & sA

Again, a similar relationship has been observed as perceived during the simulation of other configurations. The performance ratio first escalates but again falls after 1500KPa. Similarly, there is a decline in the specific area first. However, it rises after the limit of 1500KPa.

The operating point can be measured by computing the distance between the two curves and the pressure which gives the maximum distance between performance ratio and heat transfer specific area is the optimum pressure.

This pattern is similar to the preceding configurations, demonstrating the simulation's accuracy. Similar to the prior systems, the same pattern has been discovered in the relationship between boiling temperature and salinity of rejected brine with other key parameters.

Chapter 6
VALIDATION AND RESULTS

6.1 VALIDATION OF SIMULATION:

To substantiate the proposed model of a multi-effect evaporation system coupled with TVC, as introduced in a former section, validation is being carried out. Validation is the process of assessing how accurate a simulation model and its accompanying data are in representing the real world from the perspective of the model's intended usage. If the simulation of the validation data gives the same result as observed in the field, or the real world, this corroborates the correctness of the process modeling. The validation data evincing the right choice of equations does not only verify the authenticity of the methodology, instead, it provides the way forward to install any desalination system according to the demand by using the proposed set of equations. This essentially means that, if the outputs of the simulation, been given the input of the validation data, comes out adjacent to that been observed in the already known plant, this automatically renders the previously done simulation of the eight/ten/twelve/fourteen effect system simulation to be appropriate and technically sound. The validation will be done with and without the TVC to study the entire solution space.

6.1.1. VALIDATION OF A SEVEN-EFFECT MED-TVC UNIT:

To test the claims of the proposed model, the industrial data similar to that of an already installed plant known as Ras Laffan, Qatar, would be cross-checked by measuring the nearness of the output values with already known performance indicators of this plant. The configuration and the location of the TVC will also be kept intact to obtain outputs as close as possible. If the outputs come near to the real output as measured on the field, this will substantiate the authenticity of the proposed model of the multi-effect boiling system.

The location of the TVC is kept after the fourth effect. The size of the first four effects is similar to each other while, the size of the three evaporators after the TVC unit has been reduced to accommodate the decrease in the quantity of the vapor, as discussed in the previous section.

The actual result from Ras Laffan, Qatar plant (seven-effect MED system with a TVC) [43] are as follows:

Number of effects = n = 7
Production, MIGD = 6
Tube Surface Area (m^2) = 223443
Specific Surface Area m^2/(t/h) = 195

The complete data of the developed model (seven-effect MED system with a TVC) is as follows:

Number of effects = n = 7
Distillate Production Rate = D = 316 kg/s
Top Brine Temperature = T[1] = 65°C
Temperature of Incoming Feed = t_f = 35°C
Temperature of the Cooling water = t_c = 27°C
Incoming Feed water`s Salinity = X_f = 35 g/l
Rejected Brine`s Salinity = X_b = 60 g/l
Each Effect`s Overall heat transfer coefficient = U_e = 3.0 kW/m^2-C
Condenser`s Overall heat transfer coefficient = U_c = 2.4 kW/m^2-C
Temperature of last effect = T[n] = 40°C
Motive Steam Pressure = Pm = 1250 kPa

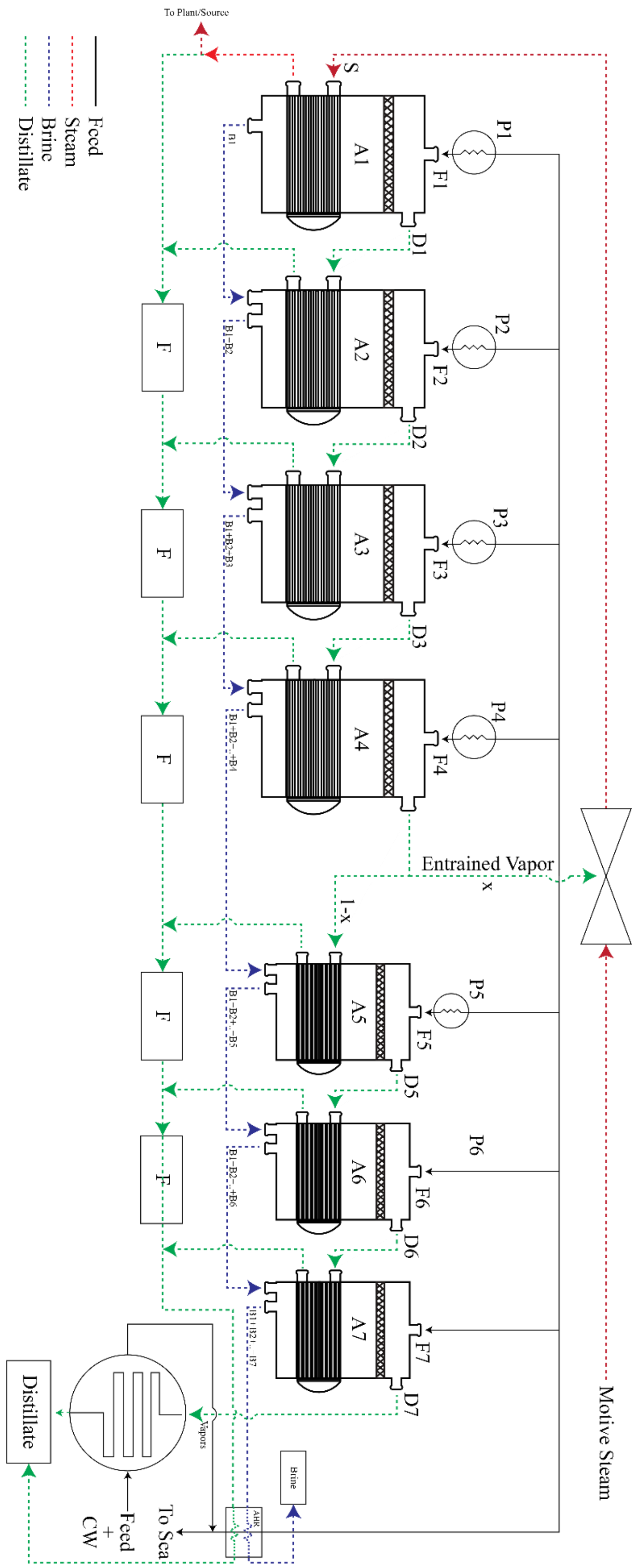


Figure 6.1 Schematic Diagram of Proposed Seven-Effect MED-TVC Unit

By inputting this data into the proposed model inside EES, the following results have been obtained:

Unit Settings: SI C kPa kJ mass deg

A_c = 2055 [m2]	A_e = 56791 [m2]	A_{hr} = 1898 [m2]	A_p = 1838 [m2]	B = 442.4 [kg/s]	B_{HR} = 408.3 [kg/s]	CR = 2.275
Cw = 1440 [kg/s]	D = 316 [kg/s]	δ_T = 4.167 [C]	D_{HR} = 287.2 [kg/s]	F = 758.4 [kg/s·]	F_x = 146 [kg/s]	GOR = 8.997
hfg_s = 2333 [kJ/kg]	lmtd = 7.997 [C]	$lmtd_{hr}$ = 11.07	n = 7	PCF = 0.9539	PR = 9.009	P_m = 1250 [kPa]
P_r = 13.7 [kPa]	P_s = 31.18 [kPa]	Ra = 1.222	S = 63.77 [kg/s]	sA = 198 [m2-s/kg]	sCW = 4.556	S_m = 35.08 [kg/s]
S_r = 28.7 [kg/s]	TCF = 0.9735	t_c = 27 [C]	t_f = 35 [C]	t_{ff} = 43.53 [C]	T_m = 189.8 [C]	T_s = 70 [C]
U_c = 2.4 [kW/m2-C]	U_e = 3 [kW/m2-C]	x = 0.5154	X_{avg} = 47.5 [g/l]	X_b = 60 [g/l]	X_f = 35 [g/l]	

The results over each effect are as follow:

Sort	T_i [C]	BPE_i [C]	$T_{v,i}$ [C]	hfg_i [kJ/kg]	F_i [kg/s]	D_i [kg/s]	B_i [kg/s]	$C_{p,i}$ [kJ/kg-C]	$T_{avg,i}$ [C]
[1]	65	0.4142	64.59	2346	142.4	60.18	82.22	3.953	50
[2]	60.83	0.4026	60.43	2357	142.4	58.07	84.33	3.952	47.92
[3]	56.67	0.3911	56.28	2367	142.4	56.58	85.82	3.951	45.83
[4]	52.5	0.3798	52.12	2377	142.4	55.68	86.72	3.95	43.75
[5]	48.33	0.3687	47.96	2387	62.93	28.3	34.63	3.949	41.67
[6]	44.17	0.3577	43.81	2397	62.93	28.35	34.58	3.948	39.58
[7]	40	0.3469	39.65	2407	62.93	28.84	34.1	3.947	37.5

Sort	$D_{b,i}$ [kg/s]	$D_{f,i}$ [kg/s]	$B_{f,i}$ [kg/s]	$T_{f,i}$ [C]	$D_{d,i}$ [kg/s]	$D_{dd,i}$ [kg/s]	$X_{b,i}$ [g/l]	$A_{e,i}$ [m2]	$A_{p,i}$ [m2]
[1]	60.18	0		51.55			60.62	9160	451.7
[2]	57.5	0.5745	82.22	50.68	0.4457	60.18	59.1	11329	402.3
[3]	55.42	1.158	166.5	48.95	0.872	118.3	58.07	10870	305.1
[4]	53.93	1.748	252.4	47.2	1.284	174.8	57.47	10521	206.4
[5]	25.96	2.338	339.1	47.75	1.686	230.5	63.6	4982	105
[6]	25.79	2.565	373.7	43.53	1.885	258.8	63.7	4971	
[7]	26.05	2.79	408.3	43.53			64.6	4958	

Table 6.1 Individual effect data of 7-Effect MED-TVC

Comparing the parameters obtained as a result of running the simulation with the one been observed on the plant:

COMPARISON OF ACTUAL AND DEVELOPED DATA	
ACTUAL DATA (RAS LAFFAN)	DEVELOPED DATA
GAIN RATIO (GOR)	
9	8.997
SPECIFIC SURFACE AREA (sA) - m^2.s/kg	
195	198
DISTILLATE PRODUCTION RATE (D) – MIGD	
6	6

Table 6.2 Comparison of Actual and Developed Data

It can be clearly examined that the two data are almost analogous. The slight difference in the results is because of the difference in input parameters and the updated seawater properties such as feed, salinity, etc. If there was access to the complete plant data, the difference would be subtler. However, the current difference is still well under the control limit and may be credited to the ignored thermodynamic losses and seasonal temperature variations. This comparison demonstrates that the generated model's operational details and process modeling are true and reliable.

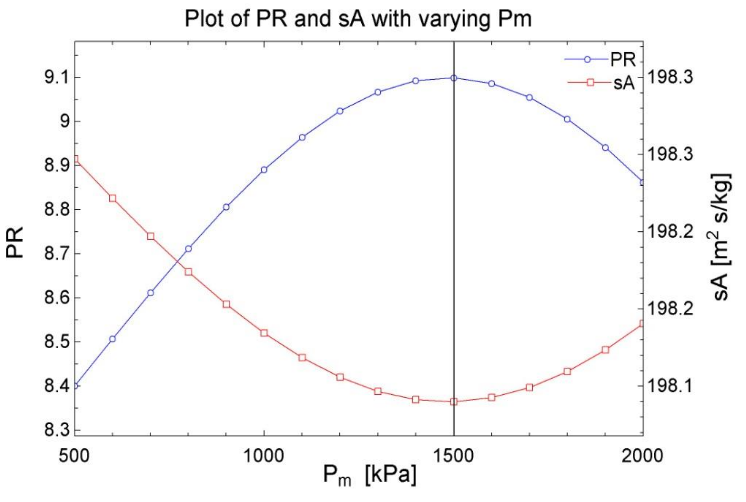


Figure 6.2 Graph between Pm vs. PR & sA

Additionally, the graphical relationship of performance ratio (PR) and specific surface area (sA) with motive steam pressure (Pm) of seven-effect MED system coupled with TVC is following a similar trend as for each eight/ten/twelve/fourteen effect configuration. This also holds for the validation data, which manifest that the results obtained from the eight/ten/twelve/fourteen effect systems coupled with TVC are also accurate and technically sound.

6.1.2. VALIDATION OF A SEVEN-EFFECT MED UNIT:

Now, the analysis is being conducted by removing the TVC, while keeping all the parameters constant. Here, the size of all the evaporators will be equal to each other.

This analysis is being conducted using the following data:

Number of effects = n = 7

Distillate Production Rate = D = 316 kg/s

Top Brine Temperature = T[1] = 65°C

Temperature of Incoming Feed = t_f = 35°C

Temperature of the Cooling water = t_c = 27°C

Incoming Feed water`s Salinity = X_f = 35 g/l

Rejected Brine`s Salinity = X_b = 60 g/l

Each Effect`s Overall heat transfer coefficient = U_e = 3.0 kW/m^2-C

Condenser`s Overall heat transfer coefficient = U_c = 2.4 kW/m^2-C

Temperature of last effect = T[n] = 40°C

Motive Steam Pressure = Pm = 1250 kPa

This data yielded the following outcomes:

Unit Settings: SI C kPa kJ mass deg

A_c = 2055 [m^2]	A_e = 57624 [m^2]	A_{hr} = 1820 [m^2]	A_p = 1510 [m^2]	B = 442.4 [kg/s]	B_{HR} = 378.8 [kg/s]	Cw = 2651 [kg/s]
D = 316 [kg/s]	δ_T = 4.167 [C]	D_{HR} = 271.3 [kg/s]	F = 758.4 [kg/s]	GOR = 6.245	hfg_s = 2333 [kJ/kg]	lmtd = 7.997 [C]
$lmtd_{hr}$ = 10.79	n = 7	PR = 6.254	S = 50.53 [kg/s]	sA = 199.4 [m^2-s/kg]	sCW = 8.389	t_c = 27 [C]
t_f = 35 [C]	t_{ff} = 42.97 [C]	T_s = 70 [C]	U_c = 2.4 [kW/m^2-C]	U_e = 3 [kW/m^2-C]	X_{avg} = 47.5 [g/l]	X_b = 60 [g/l]
X_f = 35 [g/l]						

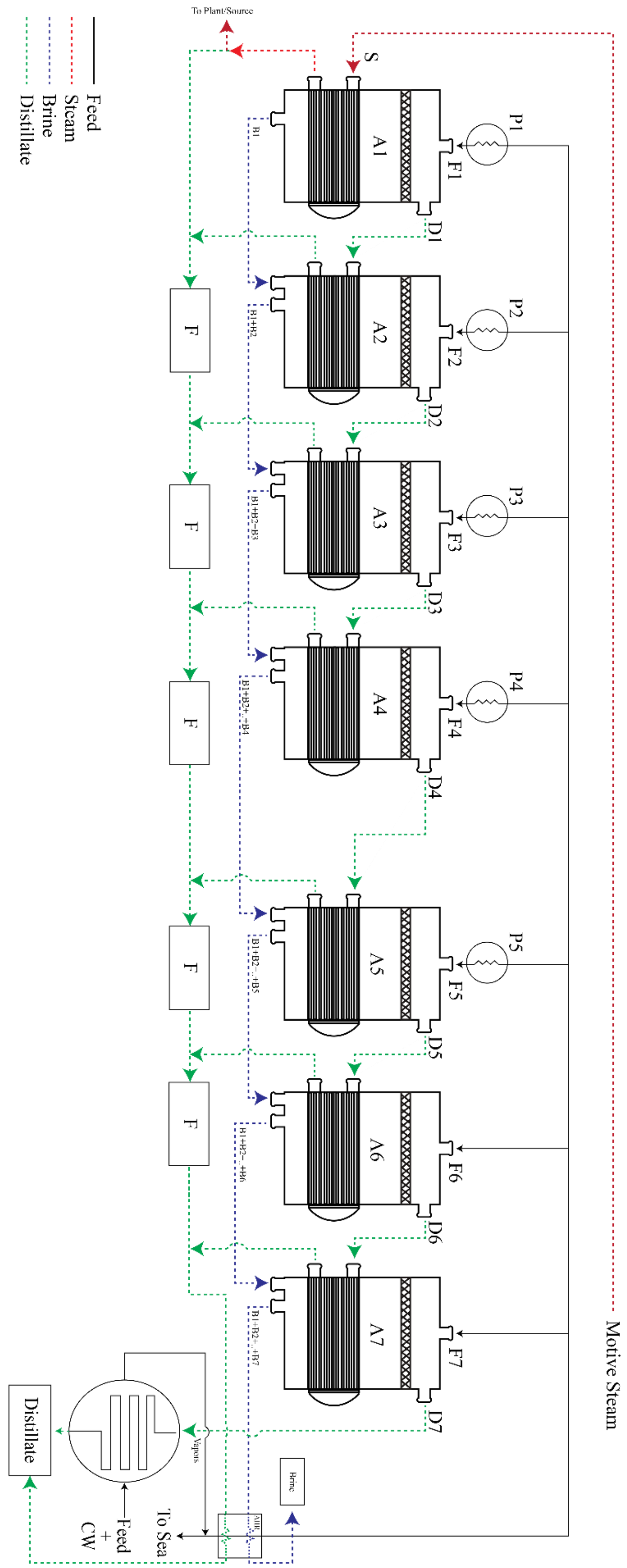


Figure 6.3 Schematic Diagram of Proposed Seven-Effect MED Unit

The individual effect properties are:

Sort	T_i [C]	BPE_i [C]	$T_{v,i}$ [C]	hfg_i [kJ/kg]	F_i [kg/s]	D_i [kg/s]	B_i [kg/s]	$C_{p,i}$ [kJ/kg-C]	$T_{avg,i}$ [C]
[1]	65	0.4142	64.59	2346	108.3	47.91	60.43	3.953	50
[2]	60.83	0.4026	60.43	2357	108.3	46.24	62.1	3.952	47.92
[3]	56.67	0.3911	56.28	2367	108.3	45.03	63.32	3.951	45.83
[4]	52.5	0.3798	52.12	2377	108.3	44.25	64.09	3.95	43.75
[5]	48.33	0.3687	47.96	2387	108.3	43.9	64.45	3.949	41.67
[6]	44.17	0.3577	43.81	2397	108.3	43.94	64.4	3.948	39.58
[7]	40	0.3469	39.65	2407	108.3	44.73	63.62	3.947	37.5

Sort	$D_{b,i}$ [kg/s]	$D_{f,i}$ [kg/s]	$B_{f,i}$ [kg/s]	$T_{f,i}$ [C]	$D_{d,i}$ [kg/s]	$D_{dd,i}$ [kg/s]	$X_{b,i}$ [g/l]	$A_{e,i}$ [m2]	$A_{p,i}$ [m2]
[1]	60.18	0		51.55			60.62	9160	451.7
[2]	57.5	0.5745	82.22	50.68	0.4457	60.18	59.1	11329	402.3
[3]	55.42	1.158	166.5	48.95	0.872	118.3	58.07	10870	305.1
[4]	53.93	1.748	252.4	47.2	1.284	174.8	57.47	10521	206.4
[5]	25.96	2.338	339.1	47.75	1.686	230.5	63.6	4982	105
[6]	25.79	2.565	373.7	43.53	1.885	258.8	63.7	4971	
[7]	26.05	2.79	408.3	43.53			64.6	4958	

Table 6.3 Individual effect data of 7-Effect MED

According to the model of Darwish and Alsairafi [28], [45], for seven number of effects, the performance ratio of the MED configuration is approximately 6.25 and the proposed model`s performance ratio is 6.254. The comparison demonstrates that the performance ratio of the developed model and Darwish and Alsairafi model, the results are almost identical, e.g.

PR of the developed model = 6.254

PR of Darwish and Alsairafi = 6.25

The minor discrepancy in the results is because of the difference in input parameters. This comparison indicates that operational details and process modeling of the developed model are correct, which manifests that the working of all developed models are also correct and technically sound as all models are based on the same working procedure.

6.2 RESULTS AND INTERPRETATION:

The following results and relationships have been observed by adjusting the number of effects along with the boiling temperature. For evaluation purposes, the temperature of the seven and eight effect system has been kept constant at 65°C, nevertheless, for the system with the number of effects more than eight, the boiling temperature is enlarged by a factor of five in response to an increase of two effects in a desalination system. This further increase in the temperature has been aided by the help of the latest antiscalant has been extensively researched [31].

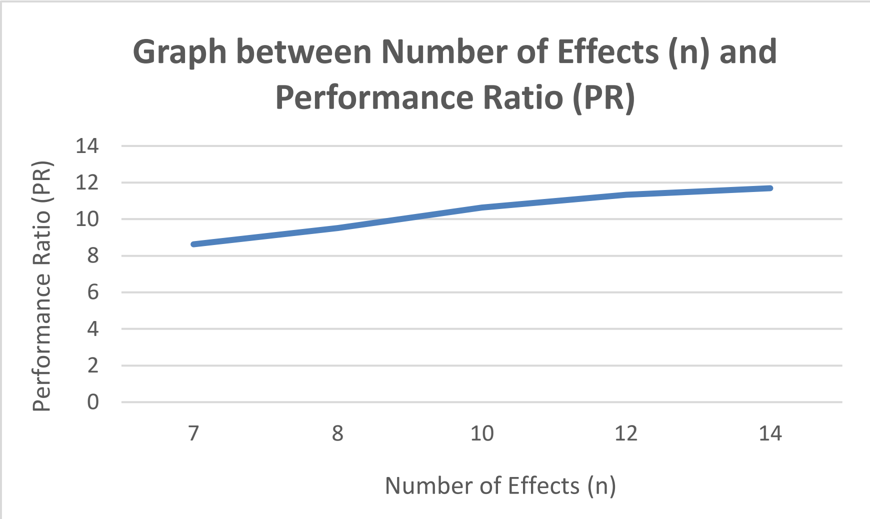


Figure 6.4 Graph between n and PR

The enhancement in the performance ratio by the escalation in the number of effects has been realized. As the number of effects upsurges, the system becomes more efficient in reprocessing the vapors it produces. This process is further enhanced by the increased flashing of brine in each effect. Additionally, the distillate flashing will also rise. This will result in the enhancement of the number of distillate flashing boxes and preheaters used to facilitate the process. This will increase the temperature of the feed been admitted to each effect, which will improve the performance ratio. Since the performance ratio is the defining metric of the desalination system, it is desired to keep it as high as possible.

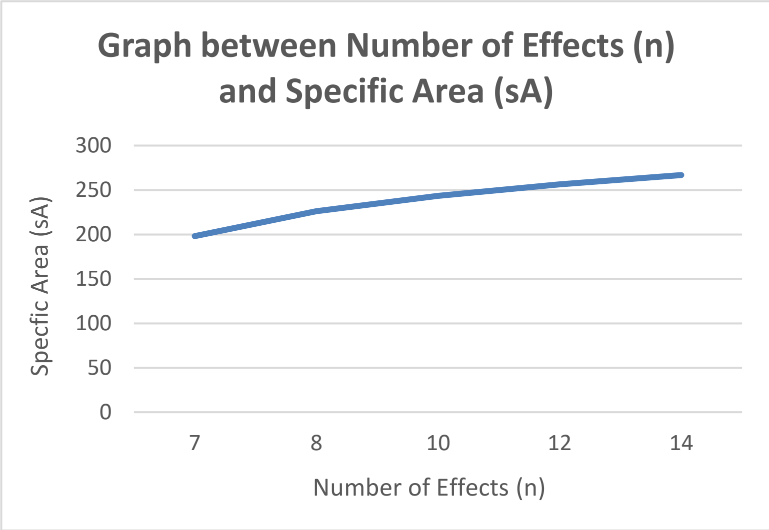


Figure 6.5 Graph between n and sA

It can be observed that the specific heat transfer area enlarges as additional degrees of effects are utilized. Since the total heat transfer coefficient and the temperature of the final effect are kept constant, this will subordinate the force to drive heat transfer, such as heat transfer coefficient as well as temperature drop per effect. This reduction will lead to the need for more area to achieve the transfer of heat between the two streams. The specific heat transfer area is an important metric to define the one-time construction cost (CAPEX), the increase in the need for the evaporator and preheaters will wrench the cost of the plant to be significantly astronomical.

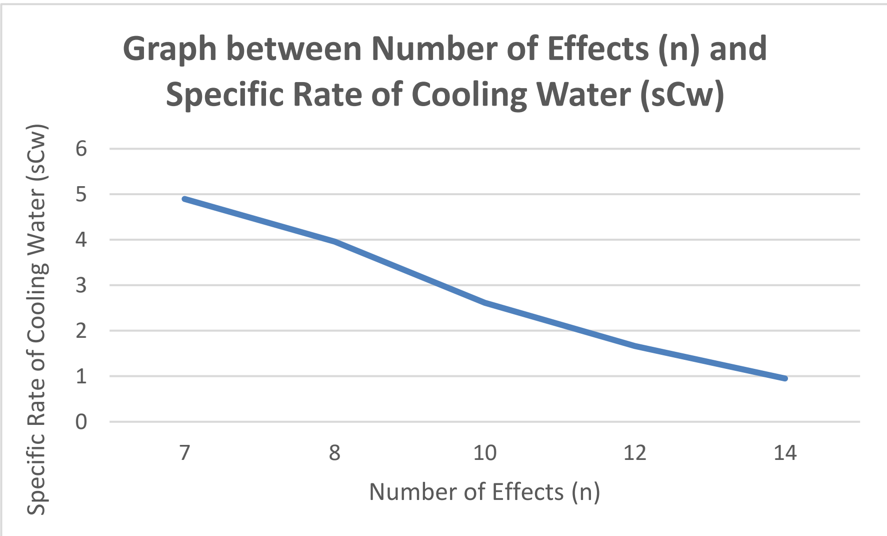


Figure 6.6 Graph between n and sCw

Since the amount of distillate is kept constant for each configuration, the surge in the n number of effects reduces the volume of vapor generated in each effect. This reduction lowers the need for cooling water, as most of the energy from the system is already consumed to heat the feed equal to the saturation temperature. The specific rate of cooling water defines the operational and handling cost (OPEX) of the plant. The lower operational cost is preferred to make the desalination process attractive to fill the demand.

In summary the performance indicators of seven, eight, ten, twelve and fourteen effects MED-TVC configurations are as follows:

NO. OF EFFECTS	Performance Ratio (PR)	Specific Area (sA) $m^2.s/kg$	Cooling Water`s Rate (sCw)
7	8.625	198.1	4.897
8	9.516	226	3.959
10	10.63	243.4	2.614
12	11.34	256.5	1.664
14	11.69	266.8	0.9507

Table 6.4 Performance Indicators of Developed Models

In general, the installation cost (CAPEX) of the plant is roughly estimated to be three times that of the heat transmission surface zone. Similarly, the operating cost (OPEX) of the plant is estimated to be around 1.25 times of consumption of steam. The growth in the number of effects also escalates the number of preheaters, flashing box and the connections of the system. Owing to this, the system becomes costly and difficult to handle [26].

Indeed, the rise in the n number of effects upsurges the performance ratio; however, the percentage increase declines between systems to systems. Similarly, the increase in the percentage of specific heat transfer areas decreases with the growth in the number of effects; however, these small percentage increases accumulate to give a major rise in CAPEX at a large number of effects. This relationship can be examined from the **Table 6.5**

Main Parameters	8 to 10 Effects	10 to 12 Effects	12 to 14 Effects
Percentage Increase			
Performance Ratio (PR)	11.7%	6.68%	3.08%
Percentage Increase			
Specific HT Area (sA)	7.7%	5.38%	4.01%
Percentage Decrease			
Rate of Cooling water (sCW)	33.97%	36.34%	42.86%

Table 6.5 Percentage Increase in Performance Indicators

Above the temperature of 65°C, the problem of scaling arises in the evaporators. This happens because of the deposition of the brine, which causes fouling on the evaporator tube. This reduces the overall heat transfer coefficient and makes the process inefficient. The problem of elimination of scaling is still under research and not available commercially. Some antiscalants can increase the TBT as high as 85°C without fouling; however, most of the MED plants operate around 65°C [31]. Additionally, there is a requirement of high-temperature steam at higher TBT's which increases the cost of the steam required for desalination.

Analyzing the above-mentioned facts, it can be stated that for a given system, the choice of eight effects is economically attractive and efficient. Nevertheless, to fill the massive demand, it is recommended to install a greater number of eight-effect systems, instead of installing a fourteen effect or sixteen effect systems.

However, it is recommended to simulate techno-economic modeling of the multi-effect system to get a better understanding of the finances. The techno-economic analysis involves various factors in a calculation like the price of steel, tubes, and other equipment. Similarly, the cost of steam is also incorporated in the analysis. Also, the modeling is inflation-adjusted to give the real-world projection of CAPEX and OPEX.

The techno-economic analysis gives the direction for the analysis of the plant to gauge the optimum number of effects for the optimum economics. After the optimum point, the techno-economic becomes negative and the system does not remain financially viable.

Chapter 7
CONCLUSIONS

7.1 SUMMARY:

The design, modeling, calculations, and optimization carried out in the former sections revealed some deeper insights over the approach to establish a desalination system. Firstly, it became very clear after the simulation of a single effect system that it does not hold any technical or economic merit to be installed in any industry. Since most of the energy is filched out by the distillate, the system has a performance ratio less than unity. For a multi-effect system, the simulation for seven, eight, ten, twelve, and fourteen effect system is carried out, and the key parameters in each case have been compared with each other. For several parameters such as top brine temperature, specific heat transfer area, the salinity of rejected brine, and specific rate of cooling water, the performance of the plant, and design concerns have been examined.

Further analysis of the number of effects on the key performance indicators has been conducted. The number of effects directly varies the performance ratio, and specific heat transfer area, and inversely varies the specific rate of cooling water. The motive steam pressure also influences performance ratio and heat transfer specific area. The finest operating point is obtained at a location where the distance between the two curves is maximum, which is close to 1500 kPa. These relationships were important to evaluate the performance of each configuration. The validation study has also been carried out to ensure the authenticity of the modeling equations. The Ras Laffan Plant, Qatar has been cross-validated with a seven-effect MEE-TVC system. Since the results of validation were close to the real-world data, it can be safely assumed that the choice of the equation is technically correct.

This competitive study paraded the eight-effect system to be economically and technically viable for the demand of 6MIGD. However, this conclusion is based on the pure engineering analysis without weighing the techno-economic factors. A detailed study is required to make the ultimate judgment before physically installing the plant.

7.2 <u>OUTCOMES OF PROJECT:</u>

Complete Engineering Analysis of MED Systems:

A multi-layered analysis is conducted before installing any desalination plant. This typically has two stages, first is the engineering feasibility and choice of parameters that give the maximum performance. This performance is measured by a performance ratio of the plant, and finding the correct performance ratio is the first step. The future phase is a techno-economic analysis which generally handles the economic analysis of installing the plant and concludes, based on an economic perspective, whether the investment in the current configuration is optimum. This project has successfully dealt with the first stage and paved the way for future researchers to conduct the techno-economic analysis of the presented configuration.

Simulation of a Parallel/Cross Flow Eight-Effect MEE-TVC System:

The main finding of the project entails the merit of using the parallel/crossflow eight-effect MEE-TVC system to satisfy the demand of 6MIGD of freshwater. The current analysis concluded the engineering feasibility and effectiveness of using the current configuration, which has given a significant improvement in the performance, as compared to its competitors. This process tends to effectively cover the need for the desired distillate production by reusing most of its energy.

Relationships of Different Parameters with Each Other:

The outcomes of various key parameters on the performance of the system have been observed, which set the stage for anyone who wants to establish a desalination plant. The important relationships between the top brine temperature with the performance ratio, heat transfer specific area, and specific cooling water rate can pave a guiding path to pick and choose the right TBT for anyone as per requirement. Additionally, the relationship between the brine salinity with some of these parameters can also aid to gauge the required salinity extracted from the water to keep the supply to the process at an optimum level. The motive steam pressure also affects the performance ratio and the heat transfer area which was found to be 1500 kPa. At this point, the maximum performance ratio at the expense of minimum heat transfer area was achieved. The right trade-off between these parameters can assist in picking the right set of parameters that gives the maximum output.

Relationship Between the Number of Effects and Performance Indicators:

The study presented in the project has also examined the outcomes of changing the number of effects and gave an important conclusion regarding the choice of the number of effects. In general, the percentage increase in the performance ratio drops by increasing the number of effects. This essentially means that medium-sized plants, in terms of the number of effects, tend to give healthier performance than the plant with a large number of effects. Therefore, it is generally recommended to use two or more medium-size plants to gratify the demand instead of installing a single plant with too many effects.

Research Conducted on the Effects of the Modern Antiscalant Before They Are Commercialized:

Generally, it has been unearthed that the top brine temperature is a characteristic parameter that single-handedly defines the performance of any MED system. It has been observed that the higher TBT tends to give a better improvement in the performance of the MED system. With the advent of breakthrough research in antiscalants, the TBT would go as high as 82-85°C. This will significantly enhance the performance of MED systems. Sooner when these antiscalants would be available commercially, the present research conducted under this project would be of utmost importance. The performance indicator calculated now would then be of critical importance, as they are already being analyzed through this project.

7.3 LIMITATIONS:

Ignored Thermodynamic and Pressure Losses in Heat Exchangers and Connections:

The simulation of the proposed configurations of the MEE-TVC system is carried out by ignoring the thermodynamic losses. In the real world, thermodynamic losses are an important factor and play a critical role in design considerations. The allowances and the special considerations are given to the design aspects by making the necessary alterations in the system or using more efficient materials for heat exchangers tubes and chemicals. The pressure losses through the demister and the connections between the joints tend to decrease the performance too; however, these changes are small and can be safely ignored in an initial simplified analysis. The effect of resistance induced by foiling over the tubes of evaporators are also been ignored.

Approximate Modeling of the Steam Jet (TVC Unit):

The modeling of the ejector has also been performed using the correlations which may deviate from the actual industrial ejector modeling. Also, the overall heat transfer coefficient has been approximated from the evaporators of the same size. The analysis is done by assuming the process to be steady-state. No special care has been given to the startup of the process or the varying load conditions. The distillate has also been assumed to be free of any salt. In a real case, the distillate has some salinity around 20-25 ppm. The effectiveness of the condenser, and evaporator, are taken to be 0.8 and 0.9 subsequently. This, however, may degrade over time.

Static Modeling of the Process with Data Specific to Domestic Conditions of Pakistan:

The analysis had been conducted using static data of the domestic conditions. However, the conditions keep changing throughout the year, and the results of KPI's may come discrete at different times. The salinity of rejected brine and condenser temperature is also being taken relative to the domestic condition of Pakistan, however, for plants to be installed in a different part of the world, the collection of domestic data is recommended.

7.4 RECOMMENDATIONS FOR FUTURE WORK:

Techno-Economic Analysis and Comparison of the Presented Configurations:

In upcoming years, the simulation and modeling can be further improved by incorporating the techno-economic analysis of the eight, ten, twelve, and fourteen effect MEE-TVC system. The techno-economic analysis will give detailed insights into the choice of the optimum configuration for the 6 MIGD plant. Currently, it will be naïve to make the final judgment before considering the cost considerations; however, based on the current analysis, the choice of eight effects is perfect for the given demand.

Impact of the Position of TVC Unit on Performance Indicators:

Furthermore, the placement of the TVC unit may also be tried and tested on different locations, and based on that, the analysis can be made. This will help identify the correct location of the TVC, which will help in increasing the yield or decreasing the need for motive steam in the ejector. Additionally, the performance with and without the TVC can also be analyzed and compared.

Comparison of MVC with TVC and its Effects:

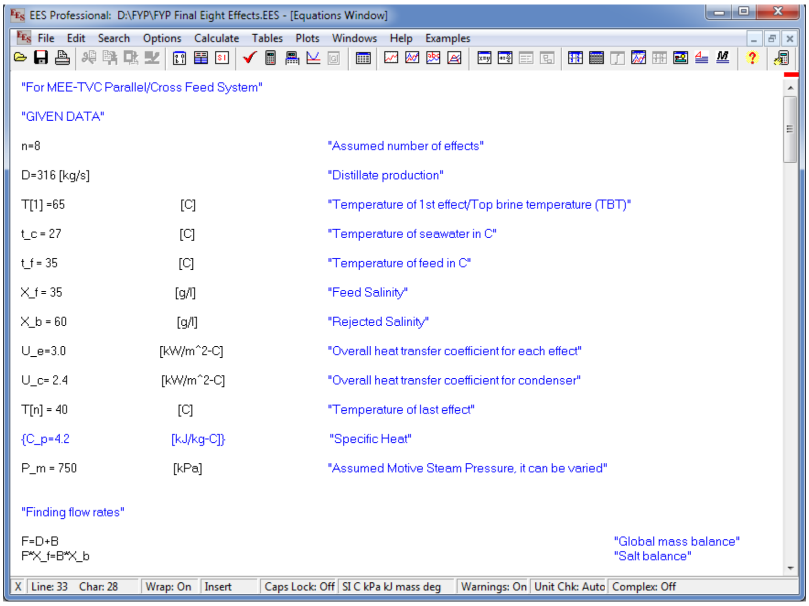
In the same vein, the TVC can be replaced by MVC, and the performance ratio of the two configurations can be compared. The TVC is usually preferred over MVC, however, it is recommended to challenge the findings and juxtapose the reduction or increase in performance indicators. Similarly, the different processes of admission of feed in the forward and backward effect can be tested, and the reduction or improvement in the performance of the system can be judged correctly.

Study of Safe Brine Disposal and Operational Code of Conduct:

As a step further, it is been suggested to carry out the study regarding the disposal and safer practices to dispose of the rejected brine properly so that it could not harm the aquatic life in the sea. Safety analysis can also be conducted to get a wholesome understanding and analysis of the MEE-TVC parallel/crossflow types of system.

APPENDIX

<u>EES PROGRAMMING OF THE EIGHT-EFFECT MED-TVC SYSTEM:</u>



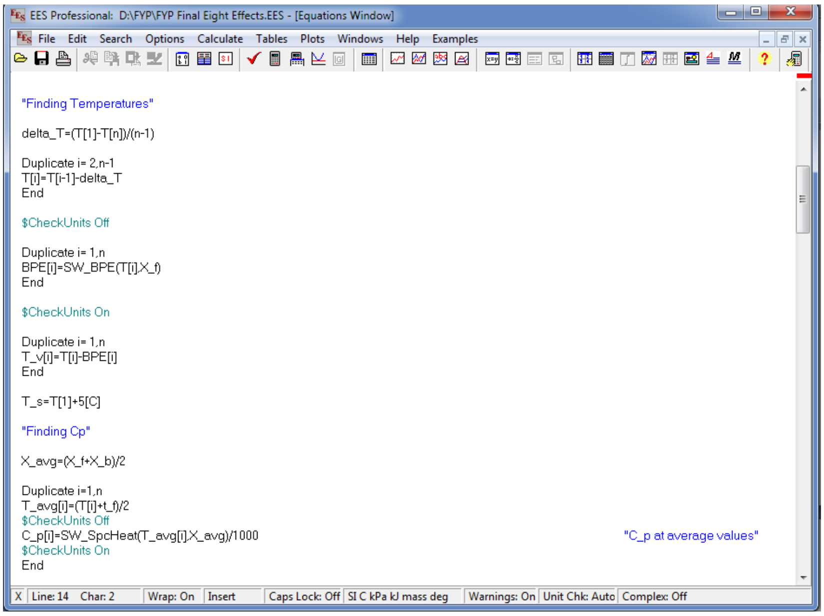

```
"For MEE-TVC Parallel/Cross Feed System"

"GIVEN DATA"

n=8                                   "Assumed number of effects"
D=316 [kg/s]                          "Distillate production"
T[1] =65            [C]               "Temperature of 1st effect/Top brine temperature (TBT)"
t_c = 27            [C]               "Temperature of seawater in C"
t_f = 35            [C]               "Temperature of feed in C"
X_f = 35            [g/l]             "Feed Salinity"
X_b = 60            [g/l]             "Rejected Salinity"
U_e=3.0             [kW/m^2-C]        "Overall heat transfer coefficient for each effect"
U_c= 2.4            [kW/m^2-C]        "Overall heat transfer coefficient for condenser"
T[n] = 40           [C]               "Temperature of last effect"
{C_p=4.2            [kJ/kg-C]}        "Specific Heat"
P_m = 750           [kPa]             "Assumed Motive Steam Pressure, it can be varied"

"Finding flow rates"

F=D+B                                 "Global mass balance"
F*X_f=B*X_b                           "Salt balance"
```




```
"Finding Temperatures"

delta_T=(T[1]-T[n])/(n-1)

Duplicate i= 2,n-1
T[i]=T[i-1]-delta_T
End

$CheckUnits Off

Duplicate i= 1,n
BPE[i]=SW_BPE(T[i],X_f)
End

$CheckUnits On

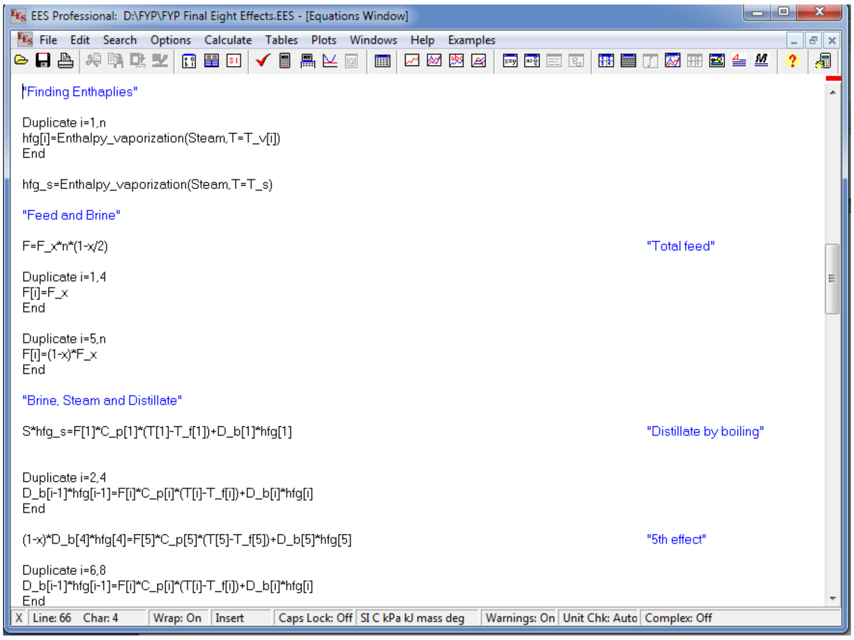
Duplicate i= 1,n
T_v[i]=T[i]-BPE[i]
End

T_s=T[1]+5[C]

"Finding Cp"

X_avg=(X_f+X_b)/2

Duplicate i=1,n
T_avg[i]=(T[i]+t_f)/2
$CheckUnits Off
C_p[i]=SW_SpcHeat(T_avg[i],X_avg)/1000          "C_p at average values"
$CheckUnits On
End
```



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"Finding Enthaplies"

Duplicate i=1,n
hfg[i]=Enthalpy_vaporization(Steam,T=T_v[i])
End

hfg_s=Enthalpy_vaporization(Steam,T=T_s)

"Feed and Brine"

F=F_x*n*(1-x/2)                                        "Total feed"

Duplicate i=1,4
F[i]=F_x
End

Duplicate i=5,n
F[i]=(1-x)*F_x
End

"Brine, Steam and Distillate"

S*hfg_s=F[1]*C_p[1]*(T[1]-T_f[1])+D_b[1]*hfg[1]        "Distillate by boiling"


Duplicate i=2,4
D_b[i-1]*hfg[i-1]=F[i]*C_p[i]*(T[i]-T_f[i])+D_b[i]*hfg[i]
End

(1-x)*D_b[4]*hfg[4]=F[5]*C_p[5]*(T[5]-T_f[5])+D_b[5]*hfg[5]    "5th effect"

Duplicate i=6,8
D_b[i-1]*hfg[i-1]=F[i]*C_p[i]*(T[i]-T_f[i])+D_b[i]*hfg[i]
End

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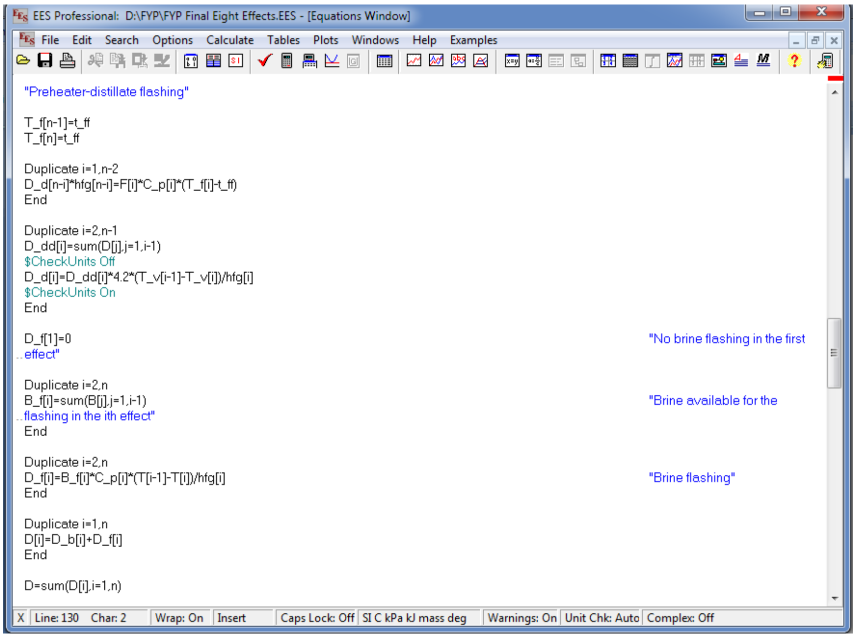

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"Preheater-distillate flashing"

T_f[n-1]=t_ff
T_f[n]=t_ff

Duplicate i=1,n-2
D_d[n-i]*hfg[n-i]=F[i]*C_p[i]*(T_f[i]-t_ff)
End

Duplicate i=2,n-1
D_dd[i]=sum(D[j],j=1,i-1)
$CheckUnits Off
D_d[i]=D_dd[i]*4.2*(T_v[i-1]-T_v[i])/hfg[i]
$CheckUnits On
End

D_f[1]=0                                               "No brine flashing in the first
..effect"

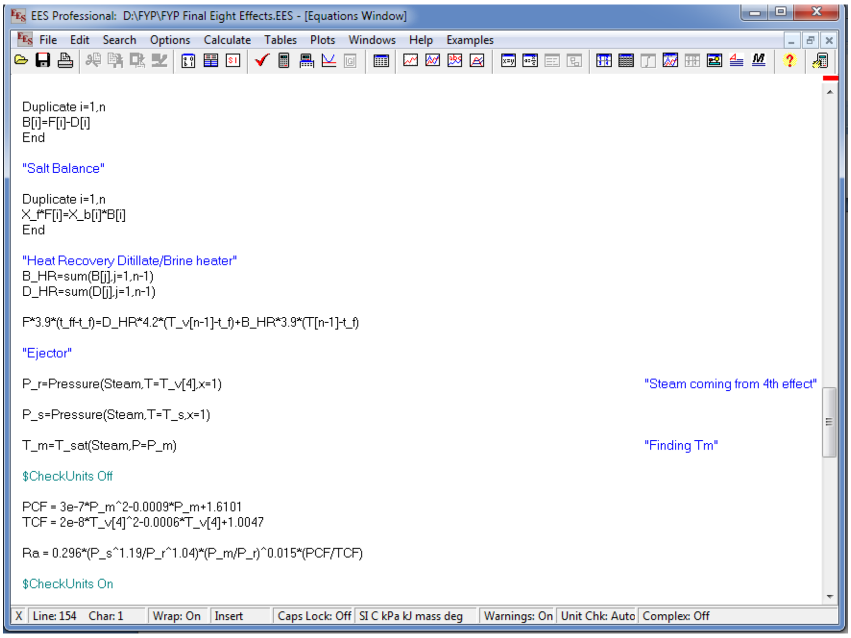
Duplicate i=2,n
B_f[i]=sum(B[j],j=1,i-1)                               "Brine available for the
..flashing in the ith effect"
End

Duplicate i=2,n
D_f[i]=B_f[i]*C_p[i]*(T[i-1]-T[i])/hfg[i]              "Brine flashing"
End

Duplicate i=1,n
D[i]=D_b[i]+D_f[i]
End

D=sum(D[i],i=1,n)

X | Line: 130  Char: 2 | Wrap: On | Insert | Caps Lock: Off | SI C kPa kJ mass deg | Warnings: On | Unit Chk: Auto | Complex: Off
```



```
Duplicate i=1,n
B[i]=F[i]-D[i]
End

"Salt Balance"

Duplicate i=1,n
X_f*F[i]=X_b[i]*B[i]
End

"Heat Recovery Ditillate/Brine heater"
B_HR=sum(B[j],j=1,n-1)
D_HR=sum(D[j],j=1,n-1)

F*3.9*(t_ff-t_f)=D_HR*4.2*(T_v[n-1]-t_f)+B_HR*3.9*(T[n-1]-t_f)

"Ejector"

P_r=Pressure(Steam,T=T_v[4],x=1)                    "Steam coming from 4th effect"

P_s=Pressure(Steam,T=T_s,x=1)

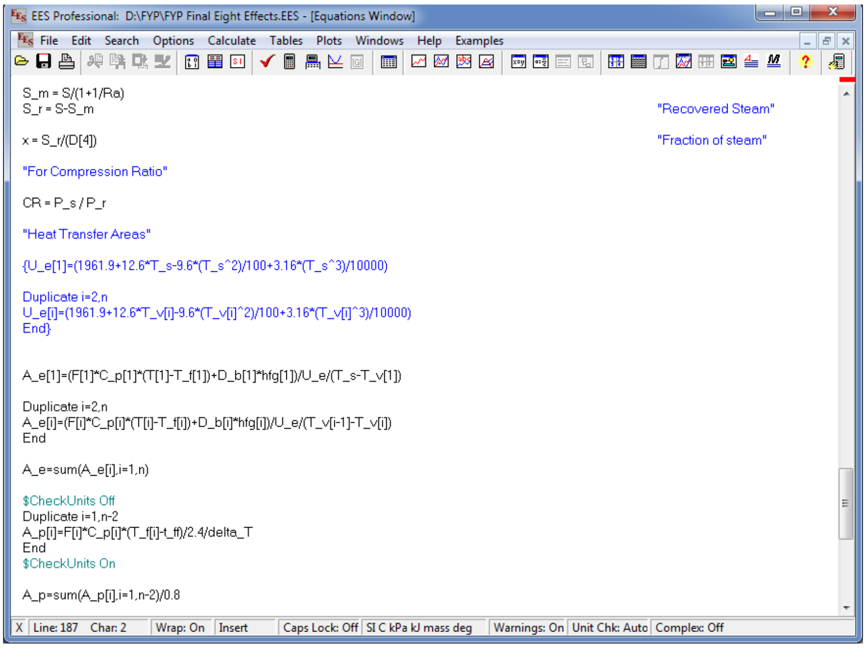
T_m=T_sat(Steam,P=P_m)                              "Finding Tm"

$CheckUnits Off

PCF = 3e-7*P_m^2-0.0009*P_m+1.6101
TCF = 2e-8*T_v[4]^2-0.0006*T_v[4]+1.0047

Ra = 0.296*(P_s^1.19/P_r^1.04)*(P_m/P_r)^0.015*(PCF/TCF)

$CheckUnits On
```

```
S_m = S/(1+1/Ra)
S_r = S-S_m                                         "Recovered Steam"

x = S_r/(D[4])                                      "Fraction of steam"

"For Compression Ratio"

CR = P_s / P_r

"Heat Transfer Areas"

{U_e[1]=(1961.9+12.6*T_s-9.6*(T_s^2)/100+3.16*(T_s^3)/10000)

Duplicate i=2,n
U_e[i]=(1961.9+12.6*T_v[i]-9.6*(T_v[i]^2)/100+3.16*(T_v[i]^3)/10000)
End}

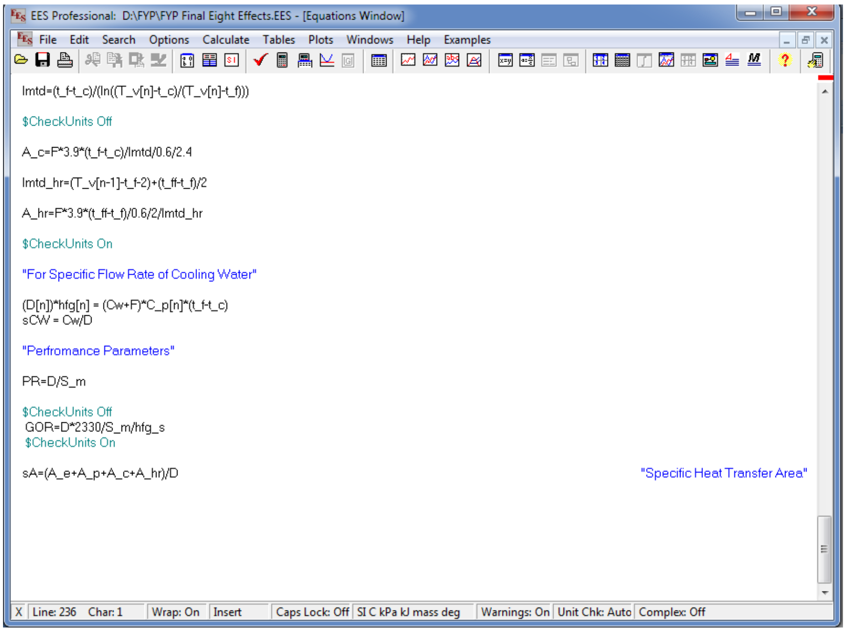

A_e[1]=(F[1]*C_p[1]*(T[1]-T_f[1])+D_b[1]*hfg[1])/U_e/(T_s-T_v[1])

Duplicate i=2,n
A_e[i]=(F[i]*C_p[i]*(T[i]-T_f[i])+D_b[i]*hfg[i])/U_e/(T_v[i-1]-T_v[i])
End

A_e=sum(A_e[i],i=1,n)

$CheckUnits Off
Duplicate i=1,n-2
A_p[i]=F[i]*C_p[i]*(T_f[i]-t_ff)/2.4/delta_T
End
$CheckUnits On

A_p=sum(A_p[i],i=1,n-2)/0.8
```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lmtd=(t_f-t_c)/(ln((T_v[n]-t_c)/(T_v[n]-t_f)))
$CheckUnits Off
A_c=F*3.9*(t_f-t_c)/lmtd/0.6/2.4
lmtd_hr=(T_v[n-1]-t_f-2)+(t_ff-t_f)/2
A_hr=F*3.9*(t_ff-t_f)/0.6/2/lmtd_hr
$CheckUnits On
"For Specific Flow Rate of Cooling Water"
(D[n])*hfg[n] = (Cw+F)*C_p[n]*(t_f-t_c)
sCW = Cw/D
"Perfromance Parameters"
PR=D/S_m
$CheckUnits Off
GOR=D*2330/S_m/hfg_s
$CheckUnits On
sA=(A_e+A_p+A_c+A_hr)/D
"Specific Heat Transfer Area"
X Line: 236 Char: 1 Wrap: On Insert Caps Lock: Off SI C kPa kJ mass deg Warnings: On Unit Chk: Auto Complex: Off

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