

**MED SYSTEM INTEGRATED WITH TWIN-SCREW
COMPRESSOR**

BY

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MASTER OF SCIENCE

In

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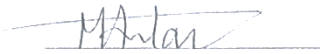
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Dedication

To my beloved family, your constant love, support, and encouragement have been the driving force behind my academic success. Your unwavering faith in me has inspired me to work harder and pursue my dreams relentlessly. I am forever grateful for your presence in my life and for the countless ways in which you have enriched my journey. Thank you for always being there for me, for celebrating my victories, and for standing by me through the challenges. I dedicate this achievement to you all.

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LIST OF ABBREVIATIONS

Abbreviation

AD	Adsorption Desalination
BF	Back Feed
CDI	Capacitive Deionization
CO ₂	Carbon Dioxide
COP	Coefficient Of Performance
Covid-19	Coronavirus Disease Of 2019
CPC	Combined Power Cycle
CR	Compression Ratio
DH	Gas Hydrates
DWC	Drop Wise Condensation
ECS	Evaporator-Condenser-Separated
ED	Electrodialysis
FD	Freeze Desalination
FF	Forward Feed
FO	Forward Osmosis
GOR	Gained Output Ratio
HDH	Humidification Dehumidification
IO	Ion Exchange
IRR	Internal Rate of Return
MB	Membrane Bioreactor
MD	Membrane Distillation

MED	Multi-Effect Distillation
MENA	Middle East-North Africa
MF	Microfiltration
MSF	Multi-Stage Flash
MVR	Mechanical Vapor Recompression
NF	Nanofiltration
NPV	Net Present Value
ORC	Organic Rankine Cycle
PCF	Parallel Cross Feed
PF	Parallel Feed
PR	Performance Ratio
PTC	Parabolic Trough Collectors
PTFE	Polytetrafluoroethylene
PV	Photovoltaic
RO	Reverse Osmosis
rpm	Revolution Per Minute
RR	Recovery Ratio
SC	Solar Chimney
SCOW	Simplified Cost of Water
SMER	Specific Moisture Extraction Rate
SPC	Specific Power Consumption
SS	Solar Still
TVC	Thermal Vapor Compression

TWP	Total Water Price
UAE	United Arab Emirates
UF	Ultrafiltration
VC	Vapor Compression
ZLD	Zero Liquid Discharge

Symbols

\$	US Dollars (\$)
$\dot{X}$	Exergy Rate (kW)
B	Brine
BPE	Boiling point elevation, (°C)
$\dot{C}_{\text{elect}}$	Unit Electricity Cost (\$·m ⁻³)
C _p	Specific Heat Capacity at Constant Pressure (kJ·kg ⁻¹ ·K ⁻¹)
CRF	Capital Recovery Factor
D	Distillate flow rate, (kg·s ⁻¹)
ex	Specific exergy (kJ·kg ⁻¹)
F	Feed flow rate, (kg·s ⁻¹)
h	enthalpy, (kJ/kg)
h _{fg}	Latent Heat of Vaporization (kJ·kg ⁻¹)
i	Interest Rate Per Annum
kJ	Kilo Joule
kPa	Kilo Pascal
LMTD	Log Mean Temperature Difference

m	Mass flow rate (kg.s^{-1})
m^3	Cubic Meter
MPa	Mega Pascal
N	Number of Effects
P	Pressure (kPa)
$\dot{Q}$	Heat Load (kW)
R	Feed To Distillate Ratio
s	Specific Entropy (kJ.K^{-1})
S	Brine concentration, (ppm)
SFF	Sinking Funding Factor
t	Plant Life Expectancy (year)
T	Temperature ($^{\circ}$)
W	Work (kW)
y	The portion of vapor produced from the brine through flashing
Z	Cost (\$)

Greek letters

Δ	Difference
η_c	Compressor Efficiency
η_s	Isentropic Efficiency

Subscripts

1,2, 3....	State Point
------------	-------------

cond	Condensate
cw	Cooling Water in the condenser
f	Feed
i	Inlet
n	Last Effect
o	Outlet
s	Steam
sw	Sea Water
v	Vapor
w	Water

ABSTRACT

Full Name : Osman Mohamed Osman Shamet
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This work presents a comprehensive review and comparison of the performance of multi-effect desalination systems (MED) operated by mechanical vapor compression, using different energy sources and compressor types. The literature shows that the unit cost varies between 0.842 and 10 \$/m³, while the specific power consumption ranges from 3.6 to 193 kWh/m³. The study suggests further research is needed in areas such as zero liquid discharge capabilities, wind energy operation, and heat exchanger component materials. Furthermore, the work proposes the use of a parallel cross feed multi-effect system with a twin-screw compressor and water injection to improve system performance. The system results in less specific power consumption (15% reduction in SPC at 70 °C steam temperature), greater exergy efficiency (16.3% higher on average), and lower freshwater production costs (\$3.14/m³ for twin-screw compressor configuration at 8 number of effects). Additionally, the work presents a model for a forward feed multi-effect system that utilizes a twin-screw compressor with water injection to enhance the isentropic efficiency of the system. The study compares the MED-MVC system with a normal compressor and a twin-screw compressor with water injection. Using the twin-screw compressor results in lower unit costs of freshwater production (\$4.23/m³ for the normal compressor configuration vs. \$3.14/m³ for the twin-screw compressor configuration at 8 number of effects) and higher exergy efficiency (16.3% higher on average). The study examines how operating conditions and external factors such as interest rates and electricity costs affect the final product cost.

ملخص الرسالة

الاسم الكامل: عثمان محمد عثمان شمت

عنوان الرسالة: نظام تكاملي لتحلية المياه بالتبخير المتعدد مع ضاغط برغي مزدوج

التخصص: الهندسة الميكانيكية

تاريخ الدرجة العلمية: نوفمبر 2023

يقدم هذا العمل مراجعة شاملة ومقارنة لأداء أنظمة التحلية متعددة التأثيرات (MED) التي تعمل بالضغط الميكانيكي للبخر، باستخدام مصادر طاقة وأنواع ضواغط مختلفة. تظهر المنشورات السابقة أن تكلفة المياه تتراوح بين 0.842 و10 دولارات / م³، بينما يتراوح استهلاك الطاقة النوعي من 3.6 إلى 193 كيلووات ساعة / م³. تشير الدراسة إلى الحاجة إلى مزيد من البحث في مجالات مثل قدرات تصريف السوائل الصفيرية وتشغيل طاقة الرياح ومواد مكونات المبادل الحراري. علاوة على ذلك، يقدم العمل استخدام نظام تغذية متعدد التأثيرات متقاطع مواز مع ضاغط مزدوج اللولب وحقن الماء لتحسين أداء النظام. ينتج عن النظام استهلاك أقل للطاقة النوعية (انخفاض بنسبة 15% في SPC عند درجة حرارة بخار 70 درجة مئوية)، وكفاءة إكسرجي أكبر (بمتوسط 16.3% أعلى)، وانخفاض تكاليف إنتاج المياه العذبة (3.14 دولار / م³ لضبط ضاغط مزدوج اللولب عند 8 عدد من التأثيرات). بالإضافة إلى ذلك، يقدم العمل نموذجاً لنظام تغذية أمامية متعدد التأثيرات يستخدم ضاغط مزدوج اللولب مع حقن الماء لتعزيز الكفاءة الأيزنتروبية للنظام. تقارن الدراسة نظام MED-MVC بضاغط عادي وضغط مزدوج اللولب مع حقن الماء. يؤدي استخدام ضاغط المسمار المزدوج إلى انخفاض تكاليف وحدة إنتاج المياه العذبة (4.23 دولار / م³ لتكوين الضواغط العادي مقابل 3.14 دولار / م³ لتكوين ضاغط المسمار المزدوج عند 8 عدد من التأثيرات) وكفاءة إكسرجية أعلى (بمتوسط 16.3% أعلى). تدرس الدراسة كيف تؤثر ظروف التشغيل والعوامل الخارجية مثل أسعار الفائدة وتكاليف الكهرباء على تكلفة المنتج النهائي.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The demand for residential, agricultural, and industrial water supplies is predicted to increase by more than 40% over the next 30 years, especially in emerging countries where water consumption is disproportionately high in contrast to population[1]. Since water supplies are quickly depleted in many places in the world, desalination of saltwater and brackish water concentrations is receiving increasing attention[2]. A potential solution to the rising global water deficiency is the use of seawater as a source of fresh water supply. Even though desalination technologies have unlimited access to seawater, their high energy requirements and high costs prevent their widespread use in many water-scarce communities[3].

The most common desalination technologies are phase change or thermal desalination ones, which include multi-stage flash (MSF), vapor compression (VC) and multi-effect distillation (MED). Technologies like Solar Still (SS), Solar Chimney (SC), and Humidification/Dehumidification (HDH) are popular in smaller scales[4]. There are also non-phase change technologies used for pretreatment or desalination such as Microfiltration (MF), Ultrafiltration (UF), Nanofiltration (NF), Membrane Bioreactor (MB), Electrodialysis (ED), and reverse osmosis (RO) [5]. Membrane Distillation (MD), on the other hand is thermally driven, but it has membranes through which vapor passes to condense in the permeate side.

Figure 1 illustrates various desalination methods for brackish or seawater. Due to its high-water recovery rate, solute rejection, and lower energy consumption compared to competing desalination processes, RO is the most widely used water desalination technology, producing 65 percent of the fresh water in the world[6]. However, for treating

feeds with high temperatures and salinities, evaporation-based multi-effect desalination (MED) systems shown in Figure 2 (Parallel feed configuration) perform better than membrane-based systems[7]. Another disadvantage of the RO is that the fouling resistance is still a significant barrier to its treatment efficiency.

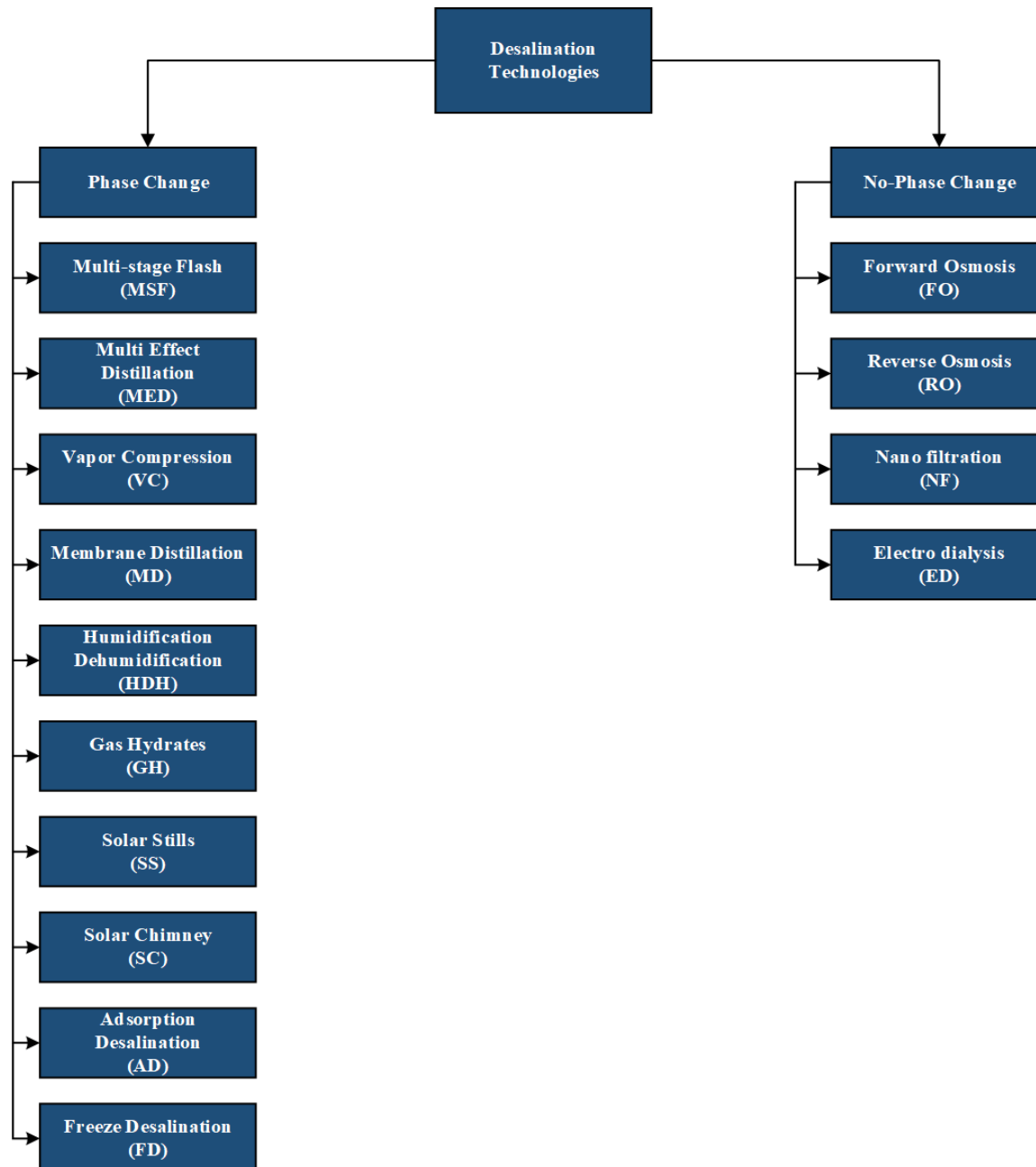


Figure 1: Available Water Desalination Technologies.

Pre-treatment of the water is another obstacle for RO systems; extensive pre-treatment procedures are needed for the supply [5][8] in addition RO is very sensitive to the quality of feed water. This makes thermal desalination technologies more reliable compared to the RO. The MED system is a very reliable technologies that comes in different configurations; namely, forward, backward, parallel (as shown in Figure 2) and parallel cross feed [9]. The system consists of evaporators also known as effects, condenser, and pumping system. In the parallel feed, Seawater is spread equally in the effects in the shell side while steam from external source passes through the tube side in the first evaporator. Steam latent heat is used to heat the feed to the effect temperature and part of it evaporates, the rest of the feed is rejected as form of brine and the evaporated part is used as the heat source in the next effect. the vapor generated in the last effect is condensed in the

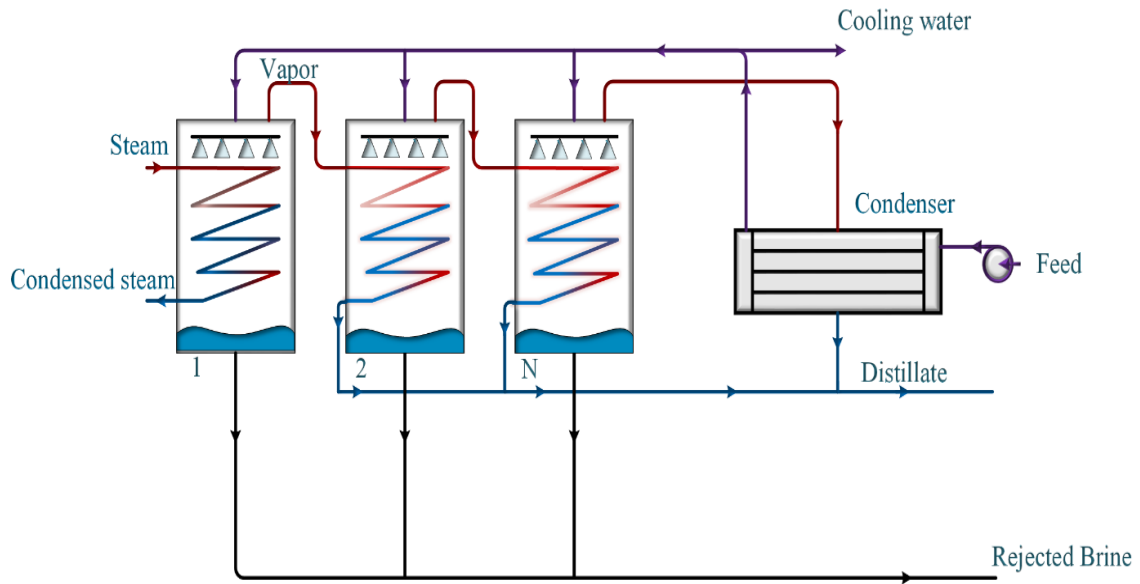


Figure 2: Multi Effect Desalination Unit.

condenser, where heat is recovered and used to pre-heat the feed. The condensed vapor from all the effects is then collected as distillate. Several system developments have been made to improve MED systems' performance. multi-effect desalination systems integrated with mechanical and thermal vapor compressors are always suggested as compelling alternatives to membrane-based desalination due to the reliability, salt-free output, and relatively low specific energy consumption, [7][10].

Al-Sahali and Ettouney [11] reported that for capacities smaller than 5000 m³/day, the MVC is cost-effective and appealing. They also supplied a simple model for single effect mechanical vapor compression system. The MED-MVC system is usually composed of falling film evaporators, mechanical compressor, pre -heaters to recover some energy from both the rejected brine and the fresh water to the incoming sea water, auxiliary boiler to generate steam for start-up, pumps, venting system, and other components for controlling the process[12]. The MED-MVC has also been found to show better performance compared to other desalination technologies. Chung et al. [13] compared the energy consumption between MED-MVC and MSF. Results showed 20% higher efficiency compared with the conventional MSF.

MED-MVC shown in Figure 3 is similar to the conventional MED system. However, the vapor in the last effect is compressed with the use of a mechanical compressor to the desired temperature and pressure and used as the source of heat in the first effect. this configuration does not require a condenser and the feed is pre-heated using the sensible heat in both the distillate and the rejected brine by the use of pre-heaters it also cuts the need for an external steam source which make the MED-MVC suitable for remote areas. Sea water is spread and heated on the outer surface of evaporator tubes by absorbing the latent heat of condensation of steam that flows inside of the tubes. in the first effect, sea water temperature is raised from what is known as the feed temperature to the saturation temperature of the effect known as the top brine temperature. Some of the feed water converts into vapor while the rest, known as brine, is either rejected or passed to the next effect depending on the system configuration. The evaporated part flows into the second effect which is at a lower pressure and temperature. Thus, similar to the conventional MED, vapor flowing from the first effect works as the heat source for the second effect. This process is repeated in the other effects. Vapor that is generated in the last effect is compressed to the desired conditions with mechanical vapor compressor and then directed to the first effect as heating steam to maintain the process.

Both produced water and brine leaving the last effect pass through pre-heaters to recover some of the heat to the inlet sea water. The feed seawater is divided into two streams, one passes through the brine pre-heater while the other stream passes through the product pre-

heater. The compressor is the main component of the system, it is also the largest energy consumer in the system. Energy requirements of the compressor depend on the compression ratio and the compressor efficiency. Besides treating sea water, MVC is also used in treating water that is a by-product of the oil industry.

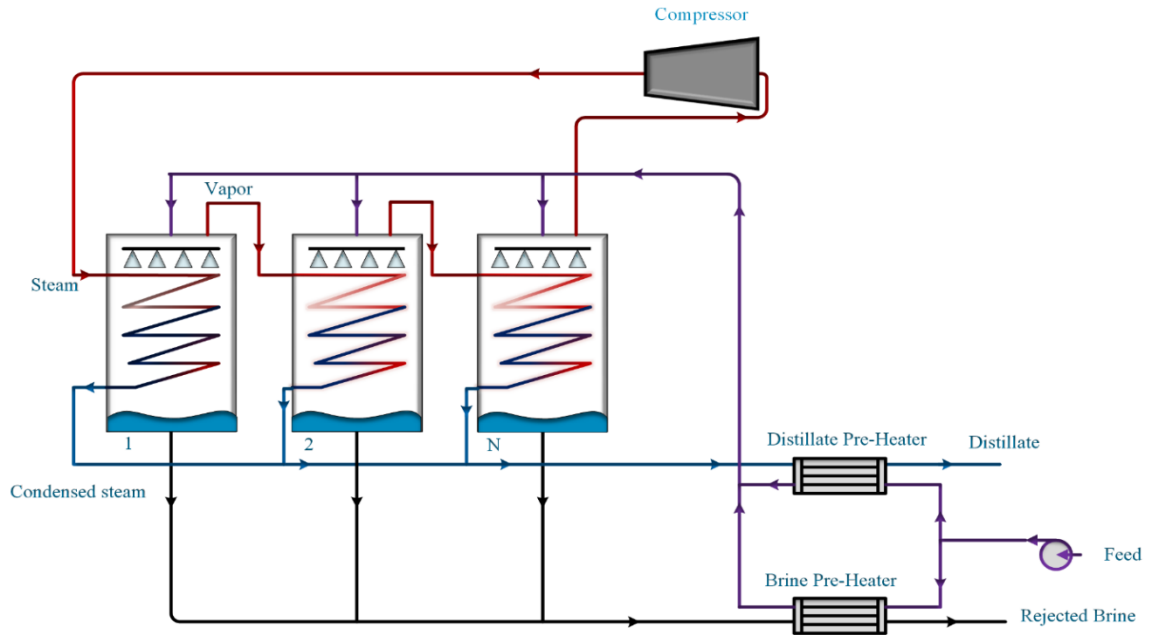


Figure 3: MED-MVC.

Osipi et al. [14] performed a comparative study to assess different electrical driven desalination systems used to treat onshore water as a by-product of oil and gas exploration. The systems include microfiltration and mechanical vapor compression system (MF-MVC). The system is reported to have water production at a cost of 4.02 \$/m³. Also, Zhang et al. [15] investigated experimentally the performance of Mechanical Vapor Compression system used to treat wastewater in oil exploration. Experimental data was used as benchmark for comparison against data extracted from a model where a slight deviation was shown. The results showed that as the discharge pressure increases the compressor work increases as well.

Ibrahimi et al. [16] presented conceptual design for a single-effect mechanical vapor compression (MVC) system. Zimmerman [17] investigated the development of high-capacity, high-efficiency Mechanical Vapor Compression desalination systems based on

low-temperature distillation technology that uses a multi-effect, horizontal tube, falling film structure.

This work presents and discusses experimental and theoretical work of MVC technology. It introduces the process of how the system works followed by mentioning works including some models that are available in the literature to design and evaluate the system. Findings from experimental works have also been presented. The cost of freshwater produced from MVC system has also been provided. Additionally, different energy sources to power the MED-MVC system as well as integrating the system with thermal cycle such as organic Rankine Cycle (ORC), combined cycle (CC), CO₂ super critical are reported in this work. Furthermore, this work contains studies on the effect of some of the system components such as the evaporator and the compressor as well as the effect of operation parameters on the system performance.

The specific power consumption that has been reported in the literature for this technology are summarized in tabular form. Lastly a summary of all the important findings in most of the papers mentioned is provided.

CHAPTER 2

LITERATURE REVIEW

Different parameters have been used in the literature to evaluate the performance of the MVC system such as Specific power Consumption (SPC) which is defined as the power needed to generate a unit flowrate of freshwater. Another parameter that is used in the literature is the Coefficient of performance (COP) which is defined as the ratio of the heat absorbed by the feed stream to the power consumed by the system. Performance Ratio (PR) has also been used to evaluate MVC systems which is defined as the ratio of the evaporative ratio to the primary energy input. Another parameter used when the system is integrated with thermal cycles is the Gained Output Ratio (GOR) which is defined as the ratio of the latent heat of evaporation of the generated vapor to the total heat input of the cycle. This chapter provides a comprehensive review on the MVC technology. A summary for the reported SPC and the major findings in the literature are provided at the end of this chapter in a tabular form.

2.2 Approach for Analysis:

MVC, like other thermodynamic systems, can be analyzed theoretically by using mass and energy balance equations. This approach is implemented by many researchers, [18] , [12], [14], [16], [19] [20], [21], [22], [23]. It can also be investigated experimentally using existing or prototype plants to assess the performance and the effect of the operating conditions on water production [15], [24],[25],[26],[27],[28],[29]. In some studies researchers have provided both experimental data and mathematical models [30] ,[31], [32], [33], [34], [35].

2.3 Mathematical models

MED-MVC has been modeled by many researchers using mass and energy balance equations. Some models are simple and require a small number of inputs to evaluate the system. For example, Ibrahim et al. [16] presented a simple design model of single effect mechanical vapor compression system. The model evaluates the system power consumption and the system architecture based on simple input design variables namely freshwater flowrate, seawater temperature, salinity of both feed sea water and rejected brine, heat transfer coefficient of the evaporator and the efficiency of the compressor. On the other hand, Ettouney [36] introduced a comprehensive model for the single effect mechanical vapor compression process that considers more detailed specifications such as evaporator dimensions, demister dimension, dimension of the non-condensable gases space, etc. His model has been validated against available data sets from the field and it showed good agreement.

Another comprehensive model was developed by Marcovecchio et al. [37] for designing mechanical vapor compression desalination process. The system contains real-physical constraints for the evaporation process. It includes nonlinear equations for chemical-physical properties and design equations, efficiencies, Non-Allowance Equilibrium, Boiling Point Elevation, and heat transfer coefficients. Furthermore, some of the models developed considered the entropy generated in the system components like, Mistry et al. [38] who presented a comprehensive model to calculate entropy generation in various desalination systems including mechanical vapor compression desalination system. They have taken into consideration the entropy generated by components and individual processes. Similarly, Warsinger et al. [39] presented a mathematical model to evaluate the second law efficiency of several desalination systems including mechanical vapor compression system, that are powered by waste heat energy at different temperatures.

In addition, in order to make designing and evaluating of MED-MVC more convenient, Ettouney and El-Dessouky [40] Developed a software package that designs, rates, and examines the performance of different thermal desalination systems including single and multi-effect mechanical vapor compression units. The package also includes

both parallel and forward feed layouts in multi-effect systems. Similarly, Abdel-Jabbar et al. [41] developed a web-based package for single and multi-effect mechanical vapor compression systems. The package designs and evaluates the system performance. Results of the model used in the package were validated against real data and showed good agreement. The user can use the package to calculate heat transfer area, power consumption and the cost related to the system.

2.4 Experimental analysis

The experimental analyses developed for mechanical vapor compression system include the work done by Li et al. [24] who carried out an experimental analysis to evaluate the effect of the raw solution concentration and the distillation pressure on the performance of a single effect mechanical vapor compression system used for wastewater concentration. The authors reported that increasing the concentration of the raw solution results in higher concentration for both dilute and concentrated solutions. They also mentioned that the system's COP and water production rate when operated under atmospheric pressure were 20.17 and 70.80 kg/h, respectively however, when the system operated under vacuum, the COP and distilled water production rate were 5.44 and 18.2 kg/h, respectively which indicate that the system performs well under atmospheric pressure compared to working under vacuum.

Another experimental work was performed by Junling Yang et al. [25]. They experimentally examined the performance of a mechanical vapor compression system with water injection. Water injection is used to cool the superheated vapor generated in the compressor. Cooling the vapor results in less work needed and hence lower the specific power consumption. The authors compared the performance of the system with and without the use of water injection. Water injection is found to increase the compression ratio, evaporation rate and reduce the temperature difference in the system which results in better performance. The system evaporation rate with water injection reached more than 300 kg/h compared to 275 kg/h when no water was spread in the compressor, which indicates that water injection results in production of more freshwater with the same power consumption.

Wu et al. [26] , also conducted an experiment on a single effect mechanical vapor compressor that employs a rotating disk evaporator similar to the one shown in Figure 4 to separate the evaporator from the condenser to enhance heat transfer. The system produces 1.5 m³/day of freshwater. They evaluated the system performance under different compressor frequencies and evaporating temperature. Results revealed that increasing the compressor frequency causes a linear drop in the pressure. In addition, according to results, the system's COP increases as the evaporating temperature increases with a maximum value of 20.89.

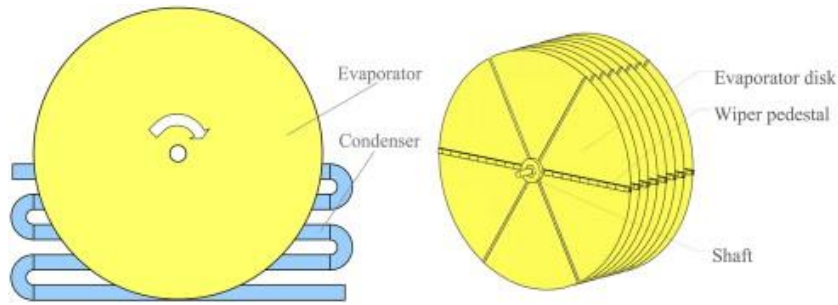


Figure 4 : Schematic diagram for the evaporator and condenser[26].

2.5 Exergo/Thermo-Economic Analysis

Economic analysis is important to evaluate the unit price of freshwater. The unit cost of freshwater determines whether a certain technology is economically feasible or not. Some of the major findings in the literature regarding the cost of MED-MVC systems are that the evaporator is found to represent the largest capital cost contributor in the MED-MVC system [19],[20],[21],[42],[43]. Therefore, efforts to reduce the cost of the evaporator and improve its efficiency would result in less water production cost. Also, increasing the number of effects is found to reduce water production cost [20],[44],[45]. Increasing the number of effects results in a better system performance and reduces the power consumption to produce clean water since it lowers the cost associated with power consumption and hence lower unit prices. Since the compressor is a main component in the system, the efficiency of the compressor affects the system performance significantly [20],[21]. Efforts to improve the compressor efficiency result in significant water cost reduction. Additionally, increasing the plant capacity is reported to reduce the water production cost [43] [46].

Thermo-economic or exergo-economic method is used to find the price of a product based on its thermodynamic or exergy analysis. In order to calculate freshwater price, the capital cost of components and the cost of each stream must be calculated. Jamil et al. [47] presented a broad framework for analyzing commercial-scale desalination systems including single and multi-effect mechanical vapor compression system. The model provides detailed economic calculation for systems components using the Exergo-economic approach. Examples of the reported work in the literature include the work done by Jamil and Zubair [19] where the authors carried out an Exergo-economic analysis on a single effect mechanical vapor compression desalination unit operating with and without brine recirculation. The specific power consumption, second law efficiency and the water cost for the MVC were found to be between 10 – 13 kWh/m³, 8 - 9 % and 1.7 - 2.3 \$/m³, respectively. The evaporator was found to have the highest exergy destruction among the system's other components contributing to 86% of the total exergy destruction in the system. Furthermore, the exergy efficiency was found to increase with the feed salinity. Then, the same authors in [20] carried out an Exergo-economic analysis of a forward-feed multi-effect mechanical vapor compression where they assessed the effect of important system parameters such as the number of effects and the compressor efficiency on the second efficiency and water cost. Increasing both the number of effects and/or the compressor efficiency result in higher exergy efficiency and lower both the SEC and water cost. The specific energy consumption, second law efficiency and product costs are observed to be ranging from 7.67 - 11.36 kWh/m³, 7 - 11%, and 0.86 - 1.19 \$/m³, respectively.

Similarly, Nafey et al. [48] presented a thermo-economic design for a multi-effect mechanical vapor compression system based on design data for a MED–MVC (1500 m³/day) that already exists. They examined the effect of using external steam to initiate the process. They found that the system with external steam is 8% less from a thermal performance point of view when compared to the system without external steam. Moreover, the system with external steam resulted in 29% higher cost. They also reported that the capital cost of VC is lower by 16 % in the system without external steam. It is also mentioned that by lowering the pressure ratio of the vapor compressor from 1.35 to 1.15

the power consumption is lowered by 50% as well as reducing the water cost by 27%. Fellah [49] performed thermo-economic analysis for single effect-mechanical vapor compression desalination unit. The effect of the compressor efficiency on the specific power consumption was also investigated. The system has a unit price of 2.59 $\$/\text{m}^3$. Almoghrabi and Fellah [21] performed a thermo-economic analysis for multi- effect mechanical vapor compression desalination unit. They reported that the least cost of water production is reported for a system with three stages with a 1.005 $\$/\text{m}^3$ compared to 2.46 $\$/\text{m}^3$ for a single stage. Results also showed that there is an optimum value for the compressor efficiency to produce freshwater at the lowest cost. This value is 91% for a single effect and 82% for multi-effect systems. Elsayed et al. [12] presented a mathematical model to evaluate the performance of multi-effect mechanical vapor compression system that produces 1500 m^3/day . The authors performed an exergo-economic analysis on parallel cross feed system and reported that with 10 effects, the exergy efficiency is 2.8% and the evaporator is the predominate contributor to exergy destruction with 52% of the total exergy destruction in the system. The evaporator was found to be the most expensive component with a cost of 10.13 $\$/\text{h}$ while the pump had the lowest cost of 0.3 $\$/\text{h}$. the freshwater price cost is reported to be 1.63 $\$/\text{m}^3$ when using the specific exergy model compared to 1.7 $\$/\text{m}^3$ when using the conventional economic model. Other works on the economics of the MED-MVC system can be found in [22] [50].

2.6 Energy source:

In 2021, the world's energy-related carbon dioxide emissions increased by 6% to reach 36.3 billion tonnes, the highest amount ever, as the global economy recovered quickly from the Covid-19 crisis and was largely dependent on coal to fuel that rise[51]. The world is now focusing on implementing renewable technologies in all applications to reduce carbon emissions and avert global warming threat.

Water desalination is an energy demanding application. Therefore, efforts to reduce the dependence on fossil fuel to power water desalination plants are needed. Most of the plants are powered by conventional fuel but, research shows that there is a trend toward renewables. If the cost of environmental and health impacts is included, renewable energy

will be less expensive when compared to fossil fuel energy. Several researchers have studied the performance using renewable energy as the main source of energy or integrated with conventional energy sources to power desalination plants including MED-MVC system.

2.6.1 Solar Energy

Solar energy is an abundant and free energy source that produces zero carbon emission. The steam needed in the first effect can be produced directly by using solar energy as the heat source in a conventional multi-effect desalination system or indirectly through generating electric power from the sun to run the compressor in mechanical vapor compression unit.

Farahat et al. [52] evaluated energy and exergy performance of a solar driven mechanical vapor compression desalination system with a nanofiltration pre-treatment unit that produces 500 m³/day. The electrical and thermal requirements of the system are provided through photovoltaic and parabolic trough collectors, respectively. They found that the system's exergy efficiency ranges from 14.59 to 20%. Photovoltaic modules and the parabolic trough (used during the startup) account for 85.79% and 69.53% exergy destruction, respectively. Freshwater unit price is reported to be 1.54 \$/m³. Likewise, Eisavi et al. [42] presented a model of an integration of concentrated photovoltaic panels with organic Rankine cycle to produce electricity for consumers and the excessive electricity is used to drive a mechanical vapor compression unit. The panels produce electricity while the collected heat is used to power the ORC. The panels and the ORC produced 43.43 kW and 33.24 kW, respectively. The MVC system is reported to produce 141 m³/day of pure water at a cost of 1.02 \$/m³. The authors also reported that the evaporator/condenser unit and the compressor accounted for the highest capital cost with 24.1% and 22% of the total cost, respectively.

Another study was performed by Morales-Ruiz et al. [53] who developed a mathematical model of a mechanical vapor compression system driven by solar energy that is used to power the mechanical vapor compressor through photovoltaic panels. The model predicts energy consumption as well as the effect of the operation conditions on the system performance. The model was validated using experimental data where the validation

showed good agreement. The system that was reported to have a power consumption ranging between 2000 W and 4000 can generate vapor at rate between 700 to 800 m³/h.

Ibrahimi et al. [54] carried out a theoretical analysis of a single-effect mechanical vapor compression driven by a grid-connected PV. Increasing the area of the PV module was found to result in a higher freshwater production rate. The study indicated that the system could reduce the electricity needs by 61%. Another finding is that higher temperature difference resulted in smaller heat transfer area however, it results in higher power consumption. Another study analyzed the use of PV was done by Gao et al. [43] who proposed a design of a mechanical vapor compression model driven by PV to produce 10,000 m³/day in San Francisco, California. The system was analyzed thermodynamically, and the effect of different parameters such as the compressor pressure ratio, compressor efficiency and evaporator temperature on the system performance was studied. The system was found to have 14.4 kWh/m³ with 70°C evaporation temperature. In addition, an economic analysis found that there is an optimum pressure ratio between 1.3 and 1.4 that results in the lowest levelized cost of electricity. Similarly, there is an optimum value for the compressor efficiency between 70 % to 80%. The study showed that the system's lowest levelized cost was \$0.76/m³.

Helal et al. [55] presented a comparative assessment between grid-connected PV mechanical vapor compression and PV reverse osmosis with 100 m³/day capacity each, the systems are designed to produce water for a remote location in UAE. The authors presented a mathematical model to analyze and design both systems. The study also presented an economic evaluation and presented the findings that the MED system has a power requirement of 15.7 kWh/m³ and the freshwater unit price of 7.29 \$/m³. While for the PV-RO systems these numbers are 6.45 kWh/m³ and 3.7 7.29 \$/m³, respectively.

2.6.2 Wind Energy

Wind energy is another abundant source that is considered to be a green energy source. Although wind energy is not popular as solar, especially in the MENA Region, some researchers considered the use of wind as a source to power MVC desalination plants. For example, Karameldin and Mekhemar [56] theoretically investigated the performance of a wind-driven mechanical vapor compression desalination system that is designed to

operate in three areas in Egypt. The results obtained showed that water production for the separate locations was 203 ,398 and 938 m³/day. The effect of different operating parameters on the system performance was also studied such as temperature difference and the average wind speed. The study showed that increasing the temperature difference results in higher specific power consumption. On the other hand, water productivity of the system was found to increase linearly with the increase in the average wind speed.

likewise, Forstmeier et al. [57] investigated the feasibility of using wind energy to power MVC desalination systems. The authors reported that the MVC technology is very suitable for stand-alone application due to the operation's variability related to this technology. The analysis showed that the system can produce up to 1350 m³/day at a cost ranging between 1.10 and 1.50 \$/m³.

Plantikow [27] presented operational results of demonstrational MVC desalination plant in the island of Rtlgen in the Baltic Sea powered by wind energy, the plant produces 15m³/h at a wind energy input of 300 kW. Chermiti et al. [58] carried out a study to evaluate the feasibility of single effect mechanical vapor compression powered by wind in Gabes. The study examined the effect of the operation temperature on the compressor specific power consumption.

2.6.3 Hybrid Energy Systems

Hybrid systems of renewables-renewables or renewables-fossil are also considered to power MVC desalination plants. Using hybrid energy sources to power MED systems is a reliable solution for supplying the needed demand for freshwater where studies showed that it can satisfy the required needs of water. Zejli et al. [46] presented an optimization model of mechanical vapor desalination unit with a capacity higher than 120 m³/day powered by renewable energy (wind and PV). The system was proposed to work in three distinct locations in Morocco. The demands were always fulfilled and made available to consumers in the three different cases. Likewise, Castro et al. [59] performed a techno-economic study to compare between different desalination systems powered by solar photovoltaic-lithium ion-diesel hybrid system. The authors reported that the RO had the lowest energy consumption and water production rate. On the other hand, MED and MSF

were found easier and more convenient to implement with such a configuration owing to the system's resilience.

Additionally, the use of hybrid systems can reduce the cost of producing fresh water depending on the chosen location. Considering the cost associated with carbon dioxide emission makes it more attractive to use hybrid systems to power MVC units to generate water. For example, Ismail et al. [60] Presented a mathematical model to analyze MED-MVC system powered by renewable energy (solar and wind energy) in different locations in Egypt. Results showed that the cost of fresh water when utilizing renewable energy is 2.71, 1.7 and 0.73 \$/m³ for three different locations compared to 1.79, 2.02 and 1.86 \$/m³ for the same locations when using fossil fuels however if the cost of the CO₂ credit is considered the cost of fresh water would be 2.66 ,1.65 and 0.732 \$/m³.

Similarly, Koroneos et al. [61] proposed mathematical equations to model both renewable energy sources (solar and wind) and several desalination technologies including MED-MVC system. The model can be used to calculate energy needed, the size of the renewable energy source and water production cost. Among the proposed configurations, the MVC-PV was found to be the most expensive choice while the MVC-wind option is considered to be a feasible solution. Henderson et al. [62] presented a feasibility study for hybrid wind/diesel system that produces electricity in summer and is used to utilize excessive electricity during winter months to produce pure water from variable-power mechanical vapor compression in New Hampshire. The authors reported that using MVC powered by excessive wind to produce freshwater instead of using RO powered only by generated electricity can save up to 7000 \$/year in electricity.

hybrid systems cut back the emissions of CO₂ because they reduce the reliance on fossil fuels. Some works examined the effect of using hybrid systems on reducing CO₂ emissions. For example, Ghazi et al. [63] studied theoretically the performance of a mechanical vapor compression system that is designed to produce 17 m³/h. the system is driven by hybrid wind-photovoltaic system for two different sites in Morocco. They proposed different configurations and shares of the hybrid PV-Wind hybrid system to power the MVC unit, the system is predicted to reduce the CO₂ emissions by up to 3,469 Tons/year. Increasing the PV contribution fraction is found to reduce CO₂ emissions and the freshwater capital

cost. However, the dependence on PV solely reduces the total productivity through the day since the PV generates electricity only through daylight. Likewise, Helal and Al-Malek [64] proposed an optimized design for desalination system with mechanical vapor compression powered by hybrid system of diesel and solar energy to produce a 120 m³/day in a remote area in UAE. The system is reported to reduce CO₂ emissions by 179 ton/year.

Using hybrid systems with mechanical vapor compression units can guarantee a continuous freshwater supply, especially in remote areas with an attractive price. It also reduces the amount of carbon dioxide emissions because it reduces the consumption of fossil fuels.

2.7 Integration with Thermodynamic cycles:

Integrating MVC systems with thermodynamic power cycles is widely used where the cycle can be used to power the compressor. Organic Rankine cycle which is less complex than steam Rankine cycle and can operate with low grade energy to power the mechanical compressor has been analyzed in the literature and it showed satisfactory performance. The cycle can be powered by solar energy or any other source of low-grade energy to heat the working fluid. Steam generated in the cycle can be either used to generate electricity to power the mechanical vapor compressor or used to drive the compressor directly by coupling it with a turbine similar to the configuration shown in Figure 5. For example, He et al. [65] carried out a theoretical study on a mechanical vapor compression system powered by an organic Rankine cycle powered by a boiler that utilizes heat found in solar, geothermal or any other source of low-grade energy. The boiler is used to heat seawater which is then used to evaporate the organic fluid. The power generated by the cycle's turbine is used to drive the compressor. Their analysis was extended to include entropy generation rate to assess the feasibility of the suggested desalination system. A GOR of 3.15 and water production of 1.09 kg/s were achieved in this study.

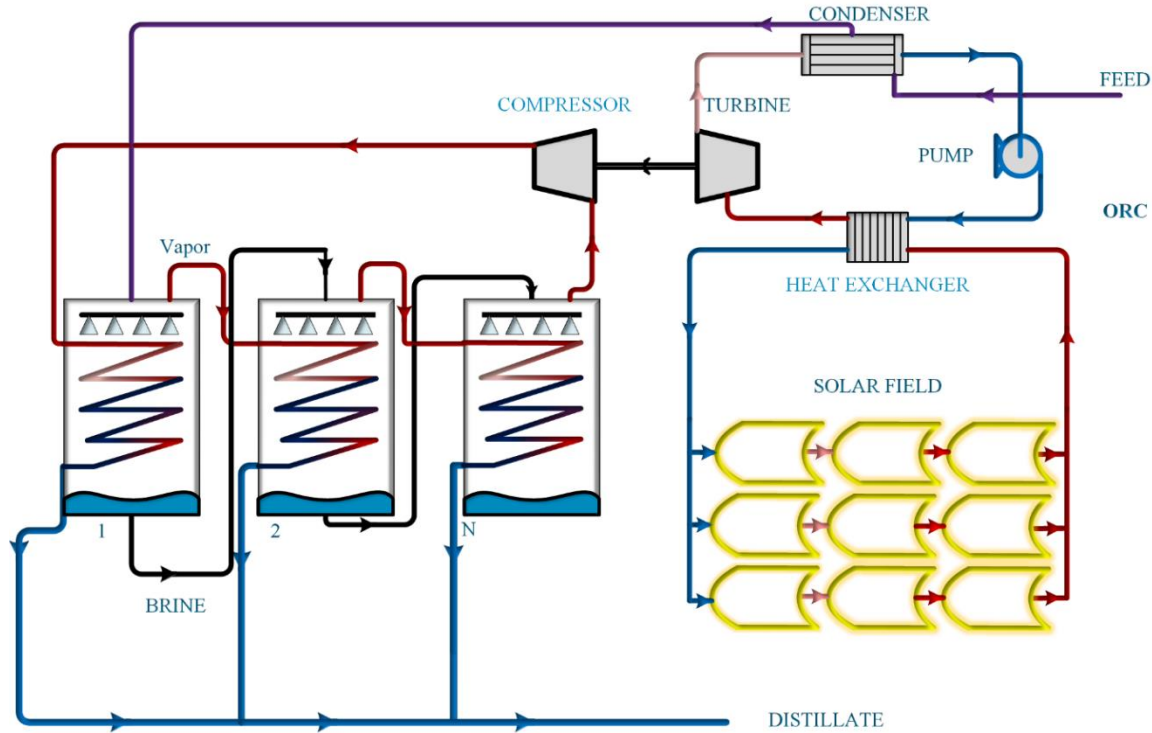


Figure 5 : Solar Organic Rankine Cycle.

Similarly, Sharaf et al. [44] analyzed theoretically a multi effect distillation-vapor compression driven by Solar Organic Rankine Cycle from a thermo-economic point of view. The study indicates that the system produces 4545 m³/day of distillate product with 0.94 \$/m³ freshwater cost and 4.18 kWh/m³ specific power consumption. Likewise, Almatrafi and Moloney [66] presented a novel design of multi-effect mechanical vapor compression powered by organic Rankine cycle using low grade solar energy through the use of evacuated tube collectors. The compressor is powered by the electricity generated from the organic Rankine cycle. The study evaluated the effect of the number of effects on several parameters including the SPC. The authors reported that the specific power consumption can reach less than 1 kWh/m³ for feed water salinity of 42,000 ppm with 14 forward feed effect and RR of 50%. Then Almatrafi et al.[67] [68] also presented a novel design similar to their design in [66]. However, in this analysis the compressor is powered by a turbine that utilizes the steam generated in the organic cycle. The heat rejected in the condenser is used to heat the feed stream before flowing into feed heaters. The study demonstrated the effect the number of effects and the feed salinity on the system

parameters. For example, Increasing the number of effects from 4 to 16 lowered the specific power consumption from 13 kWh/m³ to almost 3.4 kWh/m³. The optimum performance is found with 14 effects and the system is reported to have 3.6 kWh/m³ specific power consumption and 14% overall system efficiency at this number of effects.

Others cycle have also been reported in the literature, Lara et al. [69] presented a detailed analysis of mechanical vapor compression desalination system integrated with a combined-power cycle (CPC) that produces 37,854 m³/d and operates under a high temperature of 172°C. Water price is mentioned to be 0.49 and 0.38 \$/m³ in the US and the Middle East, respectively (the US energy cost is \$5.00/GJ energy and \$0.5 /GJ energy in the middle east). Also, He et al. [70] proposed a study of mechanical desalination system powered by trans-critical CO₂ cycle with a net power of 64.96 kW and 5.84 thermal efficiency. The analysis was made on different operating conditions, they also calculated heat transfer area and added a financial study. The system achieved a GOR of 2.42 and the total cost of the destination system was found to be 212,040.86¥. Another observation in their study is that water production increases with the increase in top temperature.

Integrating MED-MVC system with other thermal cycles is found to reduce the power consumption of the system as well as increasing the overall efficiency. It also produces water at a competitive price.

2.8 System Compressor:

Since the compressor is a major component in the MVC system, researchers studied the key parameters related to the compressor to improve the performance of the MVC system. Steam can be compressed using either dry compression (employing centrifugal compressor) or wet compression. Usually, dry compression results in highly superheated steam, which results in high consumed power. On the other hand, using a wet compression improves the isentropic efficiency compared to dry steam and hence leads to less power consumption. However, wet compression requires a special compressor to avoid damaging the compressor due to the presence of the liquid phase. The water injected twin screw compressor is a great option for achieving wet compression. A small amount of water is injected in the compressor in an intermediate pressure to reach an approximated isentropic

compression process as illustrated in Figure 6. Researchers studied the feasibility of using twin screw compressors in MVC systems to reduce the specific power consumption.

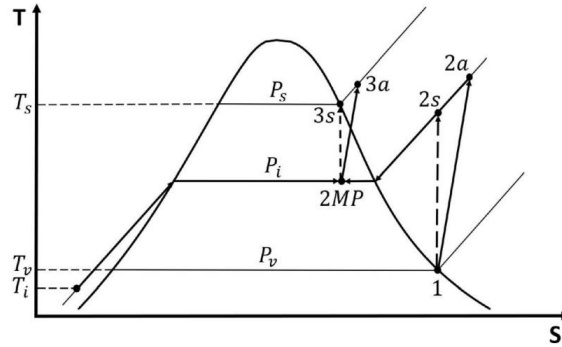


Figure 6: The T-s diagram for two stage compression process using twin-screw compressor[71].

Shen et al. [72] investigated theoretically the operational condition of a twin-screw compressor in a single effect mechanical vapor compression system. They reported that the fraction of water injected in the twin-screw compressor is less than 5%. A specific power consumption of 9 kWh/m³ is reported in the study at a brine temperature that ranges between 75 and 100 °C and 4 °C temperature difference. Then, Shen et al. [28] presented an experimental study of a double effect mechanical vapor compression desalination unit with water-injected twin-screw compressor in a MVC system that produces 50 m³/day. They investigated the effect of different parameters such as compressor speed, water injection flow rate and compressor inlet temperature on the compressor performance. They reported that the compressor work increases linearly with the increase in the rotation speed. Another important finding is the effect of increasing the water injection flow rate that improves the twin-screw compressor's isentropic efficiency, which reduces the power consumption. Increasing the water injection flowrate from 1 L/min to 3 L/min increases the isentropic efficiency from 57 to 72%.

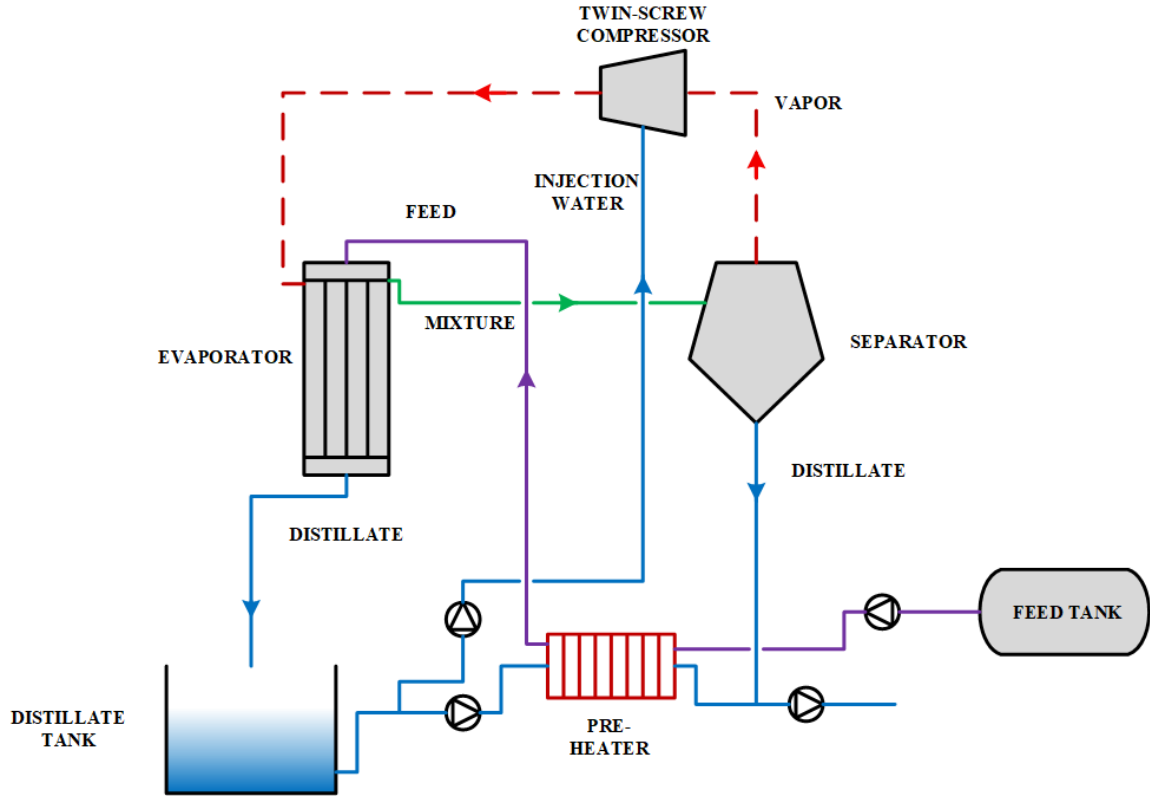


Figure 7 : Single effect evaporation powered by Twin-Screw Compressor.

In a similar study, Alkhulaifi et al. [71] presented a theoretical analysis on single effect mechanical vapor compression desalination system that uses a twin-screw water-injected compressor to produce 400 m³/day. They analyzed the effect of operating conditions on the system performance as well as the effect of water injection on the compressor work. The power reduction when using water injection was found to be around 7.3 percent at a high compression ratio.

He et al.[73] presented a mathematical model for a double effect mechanical vapor compression system that uses twin-screw compressor with water injection to improve the performance of the system. The authors studied the effect of water quantity on the produced steam rate and the influence of water injection on the compressor work was examined. The study concluded that increasing the water injection rate results in a higher inlet volume flow rate to the compressor. Additionally, the compressor was influenced heavily by the temperature difference in the system. Increasing the temperature difference results in more compressor work. Likewise, Guangbin et al. [74] developed a mathematical model to

analyze a MVC system using screw compressor with water injection. Results showed that the isentropic efficiency is not affected by water flow rate if exceeded 35 L/h which at this point is 95.5%. They also reported that the mass of pure water increases from 0.38t/h to 2.56 as the rotating speed is increased from 1000 rpm to 6000 rpm.

Root compressors similar to the one shown in Figure 8 have also been investigated when used to compress the vapor in mechanical vapor compression systems. Hong et al. [32] investigated the thermal performance of mechanical vapor compression unit that works with a root compressor that produces 100 kg/h both theoretically and experimentally. The influence of feed temperature, evaporation pressure, compressor speed, and vapor pressure affect evaporation rate. Specific Moisture Extraction Rate (SMER), and power consumption was investigated to assess the performance of the MVC system. Increasing the compressor speed from 900 to 1200 rpm results in increasing the power consumption from 3.75 to 6.25 kW while the evaporation rate also increased from 55 to 85 kg/h. The study also indicates that increasing pressure resulted in increasing the power consumed by the compressor.

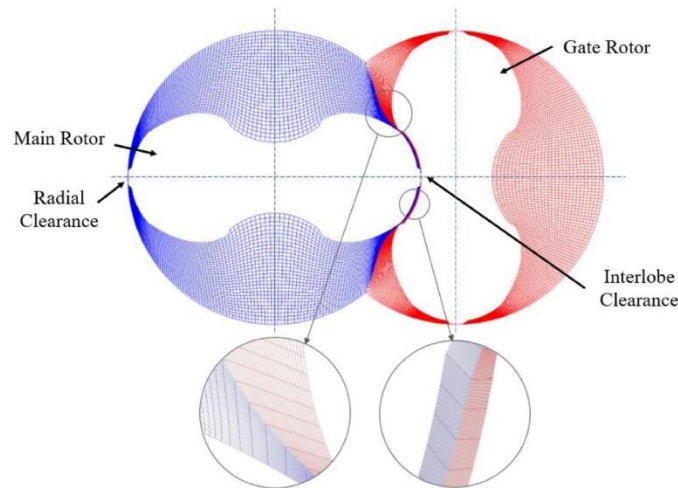


Figure 8 : Root compressor schematic[75].

On the other hand, Shen et al. [76] developed a mathematical model for two compression methods cascaded centrifugal compressor and a combined centrifugal and twin-screw compressor. They studied the effect of thermal parameters such as volume flow rate and saturation temperature rise for the two proposed systems. The analysis concluded that using combined compressors showed superior performance compared to using

cascaded compression. The authors found that the increase in the pressure ratio of the first-stage centrifugal compressor and the total saturation temperature increase resulted in an increase in the total compression efficiency.

Labib et al. [77] studied the effect of inlet skew angle of the mechanical vapor compressor mathematically for four different angles. The authors found that higher skew angle resulted in higher compression ratio and hence, better pure water production.

The compressor has a significant effect on the MED-MVC systems. Improving and utilizing better compression technologies reduces the specific power consumption and results in cheaper freshwater.

2.9 MED System Configurations:

MVC is usually found in two configurations: parallel/parallel cross or forward feed configuration. Some studies focus on the effect of the configuration on the system overall performance like Jamil and Zubair [78] who studied the effect of different flow configurations on the performance of a multi-effect mechanical vapor compression desalination unit. They studied the effect on power consumption, exergy destruction, heat transfer area and the water produced cost. they concluded that the parallel cross feed resulted in the least power consumption while forward feed resulted in the highest energy consumption followed by parallel feed with 6.76, 8.6 and 7.35 kWh/m³ respectively with a freshwater production cost of 0.867 for FF ,0.865 for PCF and 0.842 \$/m³ for PF MVC systems with four stages. They observed that as the number of effects increases the specific energy consumption decreases for all the configurations. Another finding is that the evaporator resulted in the highest exergy destruction among the other components with 96%, 91% and 93% for FF, PF, and PCF, respectively.

El-Dessouky et al. [79] developed a model to analyze multi-effect mechanical desalination system with parallel feed and parallel cross configurations. Results from the model were validated against actual data and showed good agreement. Specific power consumption was found to decrease at lower temperature difference opposed to the heat

transfer area which increase with the reducing the temperature difference. In addition, the parallel cross configuration has lower power consumption compared to the parallel feed.

Elsayed [45] carried out an Exergo-economic study of four MED-MVC configurations, namely forward feed (FF), back feed (BF), parallel feed (PF) and parallel cross feed (PCF). The PCF and FF showed lower work requirement compared to PF and BF with 13.9, 13.7, 23 and 30 kWh/m³ respectively. Regarding the second law analysis, the PCF has the best efficiency, while the backward feed (BF) configuration showed the lowest efficiency of 2.9 and 2.4 % respectively. In the economic evaluation, three models were used, and the results showed that the PCF has the lowest water production cost while, the BF has the highest production cost of 1.7 and 3.0 \$/m³, respectively while the FF and PF had a unit price cost of 1.7 and 2.7 \$/m³ respectively. They also mentioned that the SPC is reduced by 39% when the number of effects for PCF is increased from 1 to 6, whereas the effectiveness of the second law was increased by 70%.

Looking at investigations discussed in this section, it can be concluded that parallel cross feed configuration integrated with mechanical vapor compressor results in the lowest specific power consumption compared to other configurations available.

2.10 Integration with other Desalination systems:

MED-MVC can be integrated with other thermal desalination technologies to improve the overall performance of the system.

Yinan et al. [33] presented a desalination system that consists of a membrane distillation system integrated with a mechanical vapor compression. Theoretical and experimental results showed that at 1000 kg/h feed flow rate with 1% salt content, the system produced 875 kg/h at a PTFE membrane area of 75.24 m² with 3.31 kW power consumption. Swaminathan et al. [80] proposed a novel design of mechanical vapor compression system where the preheater of the system is replaced with a membrane distillation system. The system is reported to reduce the cost of water by about 6%. Furthermore, the conductive gap configuration of the MD system is found to lead to the highest saving followed by air gap and permeating gap systems.

Alasfour and Abdulrahim [81] developed a model for a hybrid system that consists of MVC and MSF. They studied the influence of temperature difference of MVC thermal performance. Results showed that the increase in temperature difference resulted in increasing the specific power consumption and exergy destruction. However, specific heat transfer area and water production decrease.

2.11 ZLD:

The brine rejected from desalination technology is usually thrown back to sea without any added treatment. This may have a harmful impact on the environment. Zero liquid discharge technologies are used to minimize the amount of brine rejected. Some research studies on the performance of the MVC system consider zero liquid discharge.

A single effect mechanical vapor compression unit for zero-liquid discharge application was proposed by Randoon et al. [82]. The model goal is to reach a near zero liquid discharge. The feed of the system is concentrated brine, vapor is extracted from the feed in the evaporator which concentrates the feed further. The rejected brine is in near saturation conditions. Feed is being supplied at a salinity of 68.513 g/kg and the brine is rejected at 73.33% concentration. The system produces 7.441 kg/s of freshwater at a price of 0.038 US\$/gallon and has a specific power consumption of 37.722 kWh/kg.

Dahmardeh et al. [83] theoretically compared the configurations of single/multi-effect evaporation interconnected with single/multi-stage mechanical vapor compressors for high salinity water treatment of 70 g/kg with the aim to reach near zero liquid discharge. The multi-effect single vapor recompression system showed the best performance among the other configurations. The system specific power consumption is reported to be in the range of 64 to 193 kWh/m³.

Han et al. [84] developed a model of mechanical vapor compression desalination system designed for zero discharge. The system is analyzed from an energy and exergy perspective. The system was found to reach a zero discharge when the brine concentration exceeding 25% of the feed, the power consumption in a single stage is found to increase with the increase of brine salinity. Another observation is that the multi-stage design

reduces power consumption. A 15.07 % reduction in power is achieved when the number of stages increases from 1 to 2.

MVC has been analyzed theoretically for zero or near zero liquid discharge applications. Studies done on this technology indicate that this process is highly power consuming and lucrative, work needs to be done to reduce the power consumption associated with zero liquid discharge.

2.12 Heat exchanger:

The evaporator is an important part in evaporation desalination systems. The most popular type of evaporator used in designing the system is the falling film evaporator. Very Few researchers studied the effect of the evaporator type on the total performance of MVC systems. For example, El-Dessouky and Ettouney [85] studied the effect of using plastic based material in the heat exchanger in a single effect mechanical vapor compression. The analysis focused on the effect of tube material on the specific power and the heat area. The specific power consumption was found to be independent of the construction material and depends solely on the compression ratio.

Jiang et al. [86] developed a mathematical model for a double effect parallel connected mechanical vapor compression system that utilizes both falling film evaporator and forced circulation evaporator for treating wastewater with high salinity. The system performance was analyzed and the effect of different parameters on the system was examined in the study. The results showed that based on a trade-off between power consumption and heat transfer area, the optimum values of evaporation temperature and saturation temperature difference could be calculated. The proposed system was compared against a conventional multi-effect evaporation crystallization system with the same capacity and showed better performance. The specific energy consumption is found to be 130.3 and 739.2 kJ/kg while the exergy efficiency is 49.1% and 32.4 % for the MVR system and the conventional system, respectively.

2.13 Effect of Operating Parameters:

Many researchers studied the effect of different parameters on the MVC performance. Some of the findings that have been identified from the literature are, increasing the temperature difference is found to reduce the specific heat transfer area however, it increases the power consumption [16], [34], [36], [54], [60], [72], [82], [83], [85], [87], [88]. Also, another finding is that, increasing the evaporating temperature results in more production [26], [30], [34]. Increasing the number of effects is also found to enhance the system performance and results in less specific power consumption [12], [20], [44],[45], [60], [66]. Another parameter that affects the system performance is the feed temperature and flow rate. Researchers reported that increasing the feed temperature and/or flow rate results in better performance since this reduces the energy requirements[31] [89]. Feed salinity, brine boiling temperature have also been examined Increasing the feed salinity is found to reduce the recovery ratio although it results in a lower specific power consumption[19]. Higher boiling temperature reduces the power consumption [36], [71].

Some of the work done to evaluate the effect of the different operating condition is done experimentally by Bahar et al. [29] they studied different operating conditions on a mechanical vapor compression pilot unit with two vertical evaporators with brine recirculation producing 1 m³/day of freshwater. The effect of the brine concentration on the performance was investigated within the range of 20,000 to 33,000 ppm, also the effect of the compressor speed on the system performance was studied. They found that the unit has a better performance on lower brine concentration (increasing the brine concentration reduces the water production). Additionally, increasing the compressor speed was found to enhance the system performance. A maximum PR of 2.52 was reached in their analysis.

Nevertheless, Aybar [90] modelled a desalination system with mechanical vapor compressor and studied the effect of evaporation side pressure, condenser side pressure, the water inlet temperature on the compressor work and the mass flow rate. The study concluded that increasing the pressure does not have a significant effect on the compressor work. However, water production increases substantially. Another finding is that when the inlet temperature is higher than the evaporator side temperature the system has better performance compared to the opposed situation. Increasing the water inlet temperature

results in less work. For example, increasing the inlet temperature from 75 to 85 °C reduces the work from almost 115 to almost 85 kW. The specific power consumption is reported to be 11.47 kWh/m³ at 50 kPa evaporation side pressure and 62.5 kPa condensation side pressure with 85 °C water inlet temperature.

Likewise, IBRAHIMI et al. [87] presented theoretical economic and thermal analysis of a single-effect mechanical vapor compression unit. The study demonstrates the effect of unit capacity and temperature difference on the water production cost. They concluded that the increase in the pure water flow rate increases the power consumption and the total area of heat transfer linearly. The analysis also revealed that elevated temperature difference was found to decrease the heat transfer area but increases the power consumed. Increasing the temperature difference from 1 to 10 °C increases the specific power consumption from almost 5 to 32.5 kWh/m³. However, it reduces the required specific area from 7.5 to 0.75 m². The cost of 1.5 €/m³ freshwater unit cost was achieved in the study.

It can be observed from looking at the literature several values for the specific power consumption for the MED-MVC. Table 1 summarizes the values that have been reported in this work.

Table 1 : Summary of some of the reported SPC for the MVC system.

Number of stages	Power source	SPC kWh	Unit Cost \$/m³	Comments	Ref
single	-	10-13	1.7-2.3	The values are for a system with and without brine recirculation.	[19]
Multiple	-	7.67-11.36	0.86-1.19	The number of effects changes from 2 to 6.	[20]

-	-	8.35	-	The system employs evaporator-condenser-separated unit	[23]
single	-	55.6	-	The system is used to treat wastewater at evaporating temperature of 80.1 °C	[34]
single	PV	14.4	-	The evaporation temperature is at 70 °C.	[43]
Multiple	SORC	4.18	0.94	The system has 16 effects and produced 52.6 kg/s at 60 °C steam temperature.	[44]
Multiple	-	13.9	1.7	PCF	[45]
		13.7	1.7	FF	
		23	2.7	PF	
		30	3.0	BF	
Single	PV	15.7	7.29	The temperature difference is 3.5 °C.	[55]
Multiple	SORC	< 1	-	-	[67]
Multiple	SORC	3.6	-	-	[68]
Single	-	9	-	The compressor used is a twin-screw compressor	[72]
Multiple	-	6.76	0.865	PCF	[78]
		7.35	0.842	PF	

		8.6	0.867	FF	
single	-	37.722	10.04	The system is used for ZLD	[82]
Single/multiple	-	64-193	-	The system is used to treating water with high salinity.	[83]
single	-	5-32.5	1.55	Changing the temperature difference from 1 to 10 °C	[87]
				The cost has been evaluated at 3 °C temperature difference	
single	-	10.5	3.81		[88]
single	-	11.47	-	Water inlet temperature is set at 85 °C.	[90]

Table 2 provides a summary of all the cited papers in Chapter one and Chapter two concerning the MVC technology.

Table 2 : Summary of MVC papers.

Ref no.	Economic	Analysis approach	Summary
[12]	√	Theoretical	• The evaporator unit resulted in the most exergy destruction. • The water cost is found to be less when calculated by exergy-based model compared to the simple model. • Increasing the number of effects resulted in less power consumption, higher exergy efficiency. • Increasing the number of effects from 1 to 2 results in a significant TWP reduction. Further increase in the effect results in higher TWP. • Compressor work has a higher impact of the system transient behavior compared to sea water temperature. • Reducing the inlet seawater temperature results in less freshwater production and pr and increases the SPC.
[13]	X	Theoretical	• MED-MVC has 20% higher efficiency compared to MSF technology.
[14]	√	Theoretical	• The system was found to consume more energy when compared to membrane distillation for onshore applications
[15]	X	Experimental	• The power consumption was found to increase with increasing the discharge pressure when treating oil byproduct water.
[16]	X	Theoretical	• Smaller temperature difference results in lower power consumption but higher heat exchange area. • Increasing the brine boiling temperature increases the compressed vapor temperature and reduces both the compression ratio and SPC.
[19]	√	Theoretical	• The power consumption without brine recirculation is lower. • Salinity variation has a smaller effect on power consumption.

			• The evaporator is the largest exergy destructor. • The evaporator cost is the largest compared to other components
[20]	√	Theoretical	• Increasing the number of effects results in less power consumption. • The evaporator is the largest exergy destructor. • The evaporator contributes to the highest capital cost. • There is an Optimum number of effects that results in the lowest water cost. • Higher compressor efficiency results in less water cost, less sec and higher exergy efficiency.
[21]	√	Theoretical	• Three evaporators provide the lowest cost per unit of the product. • The evaporator is the largest exergy destructor. • The evaporator contributes to the highest capital cost. • There is an optimum point for compressor efficiency at which the product unit cost is the lowest.
[22]	√	Theoretical	• The feed pre-heaters have the lowest exergy efficiency and the highest relative cost difference.
[23]	X	Theoretical	• Evaporator-condenser-separated MVC system used in sewage treatment found to have SPC of 8.35 kWh/m³. • ECS-MVC unit has the largest exergy destruction among other components (56.8%).
[24]	√	Experimental	• The system performed better in atmospheric pressure compared to vacuum.
[25]	X	Experimental	• Water injection increases compression ratio, evaporation rate and reduces temperature difference.
[26]	X	Experimental	• Using rotating disk evaporator, the highest COP recorded was 20.98. • The COP rises as the evaporating temperature rises.

			• The evaporator and condenser pressures drop with the increase in the compressor frequency.
[27]	√	Experimental	• Powering MVC with wind is found to be attractive and 15 m³/h water production is achieved with wind energy input of 300kW.
[28]	X	Experimental	• Increasing the rotation speed of the twin screw compressor increases power consumption, volumetric flow rate and volumetric efficiency. • Water injection increases the isentropic efficiency.
[29]	X	Experimental	• Increasing the brine concentration results in less distillate flow rate while increasing the recirculation rate results in more distillate flow rate. • Increasing the compressor speed results in more distillate flow rate and PR.
[30]	X	Theoretical Experimental	• The water production increases as the evaporator temperature increases it also improves the heat coefficient.
[31]	X	Theoretical Experimental	• Power consumption is reduced for higher feed temperature. • Higher feed temperature results in better production. • Increasing the feed concentration reduces the freshwater production however it increases the power consumption.
[32]	X	Theoretical Experimental	• Increasing the speed of a root compressor that powers an MVC unit is found to increase the evaporation rate and the power consumption of the compressor. • Increasing the compressor pressure results in more power consumption in the compressor and less power consumption in the auxiliary heat, it also increases the evaporation rate and the SMER. • Increasing the feed temperature results in less power consumption and more evaporation rate.

[33]	X	Theoretical Experimental	• A hybrid desalination system (MD+MVR) that combines mechanical vapor compression and membrane distillation resulted in of 3.31 kW power consumption to produce 875 kg/h fresh water from 1000 kg/h saline water with 1% salinity.
[34]	X	Theoretical Experimental	• The specific power consumption is 55.6 kWh/m³ for a single effect MVR system that treats wastewater. • Increasing the evaporating temperature increases the evaporation rate. • Increasing the temperature difference is found to increase both the evaporation rate and the power consumption while it reduces the specific heat transfer area.
[35]	√	Theoretical Experimental	• Increasing the evaporator temperature increases the water production. • The production rate rises by 72% when the salinity drops from 40% to 20%.
[36]	X	Theoretical	• Power consumption is reduced by increasing the boiling temperature. • The heat transfer area is reduced for higher temperature differences; however higher temperature difference increases the power consumption.
[38]	X		• The MVC has the second highest second law efficiency compared to other desalination technologies examined.
[42]	√		• The evaporator and the condenser account for the largest capital cost. • The evaporator is the largest entropy producer in the desalination unit and the second in the entire system following the photovoltaic thermal panels.
[43]	√	Theoretical	• Although improving economic performance, a higher evaporation temperature decreases energy efficiency. • There is an optimum value for both the compression ratio and the compressor efficiency. • Increasing the system capacity reduces the water cost. • The evaporator accounts for the largest capital cost.

			• Higher sea water temperature lowers the cost and the power consumption.
[44]	√	Theoretical	• Increasing the number of effects and reducing the compression ratio results in less specific work, solar field area and water production cost. • Compression ratio reduction to a specified limit (CR = 2) may improve cycle performance while lowering SPC.
[45]	√	Theoretical	• Lower steam temperature operation results in increased MED-MVC system second law efficiency and decreased SPC and twp. • In comparison to BF and PF, the PCF and FF configurations require less work to achieve an equal amount of distillate. • PCF showed the highest second law efficiency among the other configurations and bf ranked the last in term of second law efficiency. • Increasing the number of effects and reducing the operating temperature results in less exergy destruction and less SPC and water cost. • BF has the highest water production cost while PCF and ff have the lowest value. • The evaporator units are the components with the highest investment costs.
[46]	√	Theoretical	• Using wind/PV hybrid system with storage device driven MVC desalination is found to meet the water needs in different cases studies in Morocco. • Increasing the plant capacity reduces the water production cost.
[48]	√	Theoretical	• Using external steam results in lower thermal performance and higher capital cost. • Lowering the splitter ratio of the brine recirculation results in lower product cost. • Lower compression ratio results in less cost and work.
[49]	√	Theoretical	• There is an optimum value for the compressor efficiency that results in the least freshwater cost

[50]	√	Theoretical	• Application of a DWC can drastically lower the price of producing water units by a maximum of 35% reduction in the cost. Note: In DWC the condensate is collected in the form of droplets over a hydrophobic surface
[52]	√	Theoretical	• The evaporator results in the highest exergy destruction in the MVC unit with 55.08%. • The PTC accounts for 69.53 of the exergy destruction in the startup unit. • The PV unit has 85.79% exergy destruction percentage in the plant. • PV area variation is most influenced by the change in temperature difference.
[54]	X	Theoretical	• Increasing the PV area increases the water produced. • High brine temperature reduces energy consumption. • High energy difference reduces the heat transfer area but increases the power consumption.
[55]	√	Theoretical	• The MVC powered by PV has higher water cost compared to RO-PV.
[56]	X	Theoretical	• MVC system powered by wind is found to be feasible. • The production increases as the temperature difference decreases.
[57]	√	Theoretical	• Water cost of MVC wind-powered system can be from 1.10 to 1.50 \$/m³ for proper sites.
[59]	√	Theoretical	• MVC powered by solar photovoltaic-lithium ion-diesel is found to be more costly than RO powered by the same hybrid system, but it shows more reliability than the RO.
[60]	√	Theoretical	• Increasing the number of effects results in higher product, higher brine salinity, higher pr, lower heat transfer area, lower brine flow rate and lower power consumed by the pump.

			• Lower ambient temperature lowers the power required by the sea water pump. • Increasing the temperature difference results in less heat transfer are but more power consumption
[62]	√	Theoretical	• Installing a desalination system powered by the excess energy produced by a hybrid diesel wind in winter in star island in New Hampshire is found to be technically feasible but not economically attractive.
[63]	√	Theoretical	• Increasing the PV contribution in a hybrid system of PV-wind used to drive a MVC system reduces the CO₂ emission and water unit price however it reduces the accumulated amount of water produced.
[64]	X	Theoretical	• Integrating solar with diesel is found to reduce carbon dioxide emissions by 179 ton/y for system that produces 120 m³/d.
[65]	X	Theoretical	• Integrating MVC with orc to power the compressor is feasible. • Turbine inlet pressure has an optimum value that results in the best performance. • Higher top temperature and lower ambient temperature results in better production
[66]	X	Theoretical	• SPC of less than 1 kWh/m³ for MVC system powered by supercritical organic Rankine cycle with 14 effects in FF configuration is achieved for seawater feed salinity of 42,000 ppm. • Increasing number of effects results in less SPC, less vapor temperature, less brine mass flow rate, less solar field area and more brine concentration.
[67][68]	X	Theoretical	• Increasing the number of effects resulted in less area of the solar collectors, less SPC but higher specific area of the MED system. • Increasing the high pressure of the ORC results in less solar collector area and less thermal energy consumption.

			• There is an optimum value for the high pressure in the ORC that results in the best cycle efficiency. • Increasing the feed salinity increases the specific area of the MED system. • SPC of 4 kWh/m³ for MVC system powered by supercritical organic Rankine cycle with 14 effects in FF configuration is achieved for seawater feed salinity of 100,000 ppm.
[69]	√	Theoretical	• Higher operating temperature results in lower power consumed, less heat transfer area and small compressor but results in more pre-treatment needed to prevent fouling and corrosion.
[70]	√	Theoretical	• For the CO₂ trans critical cycle there is an optimal value for the turbine inlet pressure that results in the best values for both water production and the GOR. • Lower temperature difference results in better system performance. • Lower ambient temperature results in more water production. • The combined system is found to be feasible.
[71]	X	Theoretical	• Using water injection in twin screw compressor may reduce power consumption by up to 7.3%. • The begging of the compression point is found to be the best point for water injection. • Increasing brine boiling temperature results in less mass ratio of water injected heat transfer area and power consumption. • Increasing injection pressure results in more SPC and mass ratio of water injected. • Increasing the salinity results in more compressor inlet volume flow rate, it also increases the feed to distillate ratio.
[72]	X	Theoretical	• The mass fraction of water injection is less than 5% in twin screw compressor.

			• Increasing temperature difference results in less heat transfer area and more power consumption. • Using water injection reduces power consumption.
[73]	X	Theoretical	• Using water injection in twin screw compressor increases compressor inlet volume flow rate. • Increasing temperature difference results in more power consumption.
[74]	X	Theoretical	• Using water injection increases the performance of an MRV system with a twin-screw compressor. • The isentropic and volumetric efficiency of the compressor become not too dependent on the water injection flow rate after a certain value is reached. • Increasing the rotating speed increases the freshwater production.
[76]	X	Theoretical	• Using combined centrifugal and twin-screw compressor is better than cascade two stages centrifugal compressor for high saturation temperature and also showed better system performance.
[77]	X	Theoretical	• Increasing the inlet skew angle increases the pressure ratio and efficiency of the compressor.
[79]	X	Theoretical	• Increasing the operating temperature lowers the specific heat transfer area. • Compared to the MEE-P/MVC system, the MEE-PC/MVC system uses less specific power and requires specific transfer area. • At higher operating temperatures, the MEE-P/MVC system's conversion ratio declines. • The top brine temperature has no effect on the MEE-PC/MVC systems' conversion ratio.
[80]	√	Theoretical	• Using md as a replacement for pre-heater heat exchanger in MVC unit reduces water production cost by up to 6%. • Increasing the operating temperature increases water production savings.

[81]	X	Theoretical	• Increasing the brine temperature results in less values of inlet volume flow rate to the compressor, feed to distillate ratio, specific heat transfer area and pressure ratio. Also, it results in less exergy destruction. • Increasing temperature difference results in less water production and more exergy destruction and power consumption.
[82]	√	Theoretical	• Increasing the temperature difference between the evaporator and the condenser results in less specific heat transfer area while it increases the SPC. • In a near-ZLD system increasing the feed salinity results in the increase in the specific heat transfer area, however it reduces the RR. • The economic evaluation found that NPV is 15.029 m€, IRR of 17.39% and the capital and operating expenditures are 594.93 k€ y⁻¹. • And 854.40 k€ y⁻¹ for a feed with 70 g/kg salinity.
[83]	√	Theoretical	• MEE with single vapor recompression system in ZLD application has in terms of energy consumption and operational costs, performs the best for desalinating wastewater compared to the other proposed configuration with 0.193–0.064 kWh/kg SPC. • Increasing evaporation temperature results in less required specific heat transfer area and compressor work. • Increasing temperature difference results in less required specific heat transfer area but more specific power consumption.
[84]	X	Theoretical	• Increasing the number of effects reduces the profit however it reduces the power consumption. • Increasing the outlet concentration increases freshwater production and increases the power consumption.

[85]	√	Theoretical	• Using plastic PTFE shell-tube for construction of evaporators and plate preheaters resulted in higher specific transfer area compared to using metal alloys because the low thermal conductivity but has the lowest specific cost. • Increasing the brine top temperature reduces SPC while increasing the temperature difference increases the SPC.
[86]	X	Theoretical	• The performance of parallel-connected double-effect MRV evaporation crystallization system is better than the conventional system with 82.2% and 51.5% higher COP and exergy efficiency, respectively.
[87]	√	Theoretical	• Increasing the temperature difference results in less specific heat transfer area and more power consumption. • Increasing the product flow require more total heat transfer area and more power.
[88]	√	Theoretical	• Increasing temperature difference results in more power consumption • The MVC has 37% less water production cost compared to the TVC.
[89]	√	Theoretical	• Increasing sea water temperature results in an increase in the RR. • Increasing the feed flow rate results in more distillate. • The increase in both the RR and the feed flow rate results in less SCOW.
[90]	X	Theoretical	• Increasing the water inlet temperature lowers the compressor work. • Increasing the pressure does not have a significant effect on compressor work. • Increasing the pressure increases the mass flow rate gradually.
[91]	√	Theoretical	• There is an optimum salinity value that results in the best system performance and cost for MVC system.

The review showed the instances of using twin-screw compressor with evaporation desalination units and it shows improvement in the system performance. The idea of using twin-screw compressor with evaporative distillation is implemented by few research studies on only single and dual effect systems. Hence, more research is required on this topic. To our knowledge no other work that is available in the literature studied the performance of the twin-screw compressor integrated with multi-effect desalination system. The presented research introduces a model of MED system integrated with twin-screw compressor and applies both energy and exergy-economic analysis on the system. Water injection is used to improve the isentropic efficiency of the compression process to reduce the compression work in order to improve the overall system performance. The compressed vapor in the final stage is mixed with a small amount of water to de-superheat it when using the twin-screw compressor. This thesis presents a model for multi-effect system integrated with twin-screw compressor for both parallel cross and forward feed configuration and compare the performance of the proposed system with the conventional MED system.

2.14 Objectives:

The specific objectives are as follows:

- To develop a mathematical model based on mass and energy balance to evaluate both design and the operation of the system.
- To assess MED-MVC desalination process performance.
- To compare different MED-MVC layouts in order to find the one that performs best in terms of energy consumption.
- To carry out economic and second law analysis of the systems considered.

Results and discussion for the parallel cross and forward feed configurations are presented in Chapter three and Chapter four, respectively.

CHAPTER 3

Parallel Feed Configuration

This chapter presents a design of parallel cross feed multi-effect system with a twin-screw compressor with water injection to improve the system performance. The chapter contains the mathematical equations of the system. The system has been analyzed and evaluated in terms of energy, exergy, and exergy-economic point of views and compared with the performance of the conventional configuration in terms of the specific power consumption, the exergy efficiency, and the cost of the produced water. The effects of different operating conditions including number of effects, steam temperature, compressor efficiency, and injection pressure on the system specific power consumption, exergy efficiency, exergy destruction, and final product cost are examined in this chapter. Other factors like interest rate, plant life expectancy, and electricity cost effect on the final product cost are also investigated.

3.1 System description:

In this study a parallel cross feed MED system that produces 52.616 kg/s of desalinated water is considered in two configurations i.e., configuration one: MED with normal compressor and configuration two: MED with twin-screw compressor. The selection of the parallel cross feed configuration is due to its lower power consumption compared to the other available configurations[78][79]. The system model is described using mass, energy balance and exergo-economic equations to calculate all the mass flow rates, temperatures, power consumption and the product cost. The model is solved using Engineering Equation Solver (EES) software.

3.1.1 Configuration One:

The system contains evaporators, pre-heaters, a compressor, and pumps as shown in Figure 9. The feed F is heated from T_c to T_f in brine and distillate pre-heaters. The feed F enters each stage at T_f with almost the same quantity at each stage as shown. Steam flows into the first evaporator where it condenses in the tubes. The latent heat of condensed steam heats the feed from T_f to saturation temperature of the first effect, T_1 and some of the feed evaporates into D_1 at T_{v1} . It is important to state that the vapor temperature T_{v1} is less than T_1 by the boiling point elevation, BPE. The amount that evaporates in the first effect flows into the tubes of the next effect and condenses; releasing the latent heat that heats the feed of this effect and evaporates part of it. This process is repeated until the last effect. The vapor that is generated in the last effect is compressed by using a conventional compressor to T_s and used as the heat source for the first effect. The brine in each effect is passed to the next effect and it is cooled from T_i into T_{i+1} . This causes some of the brine to flash. The flashed vapor joins the vapor generated in the effect to be used as a heat source for the next effect. The feed flow rate F_i is adjusted to maintain the salinity of the brine under the maximum allowable concentration[9]. The sensible heat in the brine and distillate are used to heat the feed before it enters the effects. Figure 11 shows the inputs and outputs for each effect.

3.1.2 Configuration Two:

In this configuration the conventional compressor is replaced by a twin-screw compressor with water injection. The water for injection is taken from the distillate after the preheater as shown in Figure 10. The process of injecting water during the compression process improves the isentropic efficiency and results in less work consumption as demonstrated in Figure 12.

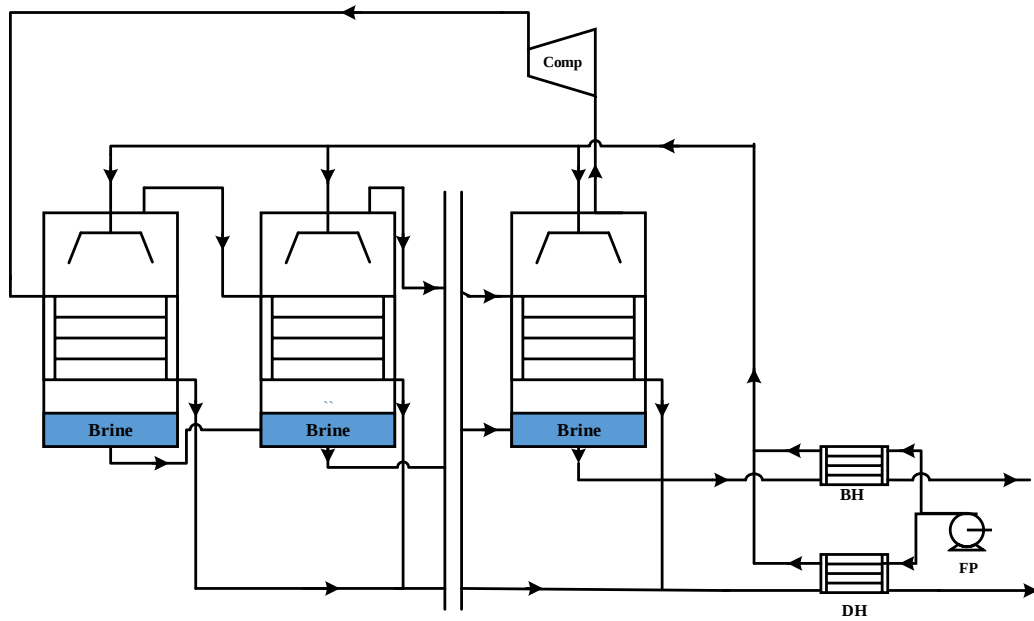


Figure 9: PCF MED with normal compressor.

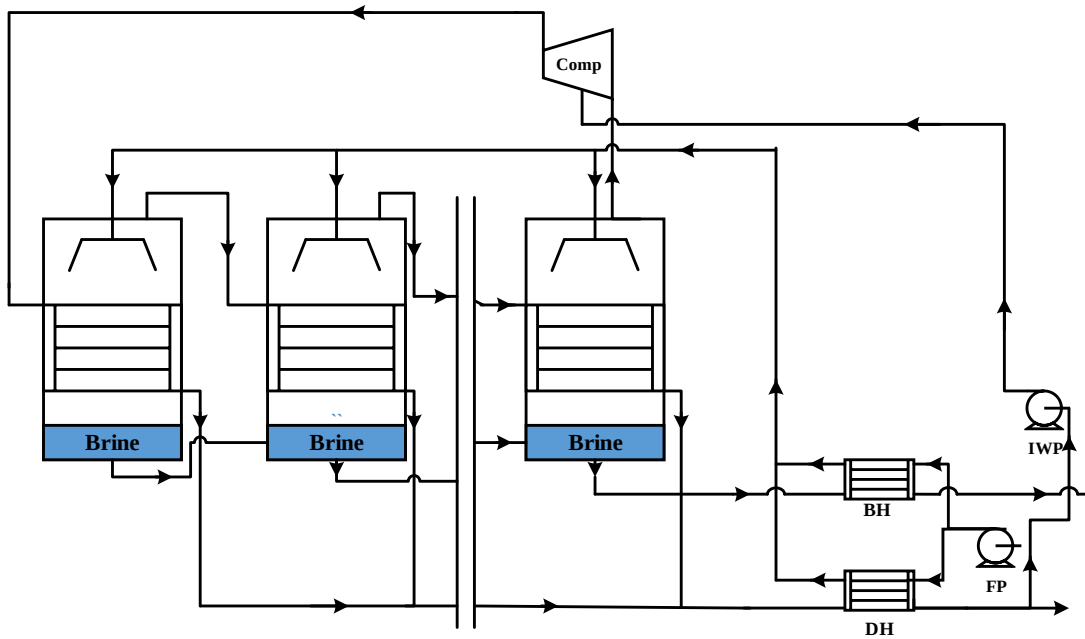


Figure 10: PCF MED with twin-screw compressor.

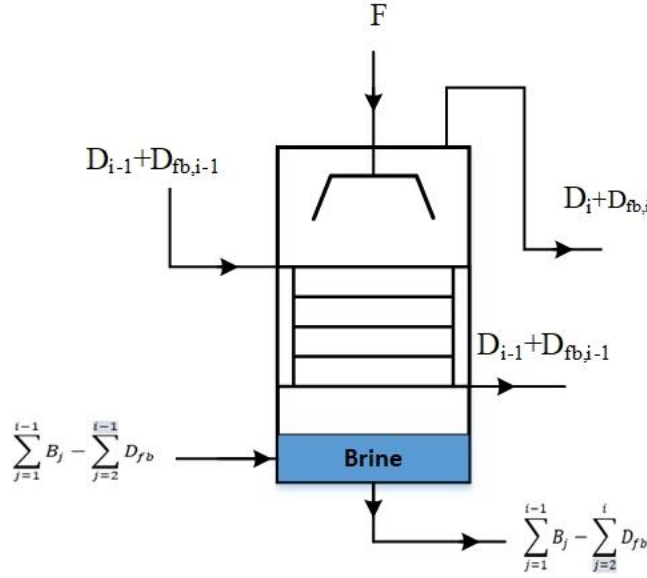


Figure 11: Inlet and outlet streams of the i th effect for PCF.

3.2 Mathematical Model:

3.2.1 Assumptions:

- Steady state conditions.
- Heat loss to the environment is negligible.
- Kinetic and potential energies are neglected in the energy balance.
- The dead state is taken at the atmospheric temperature and pressure of 20 °C and 101.3 kPa.
- The efficiency of pumps is 80% [92].
- Sea water has a cost of 0 \$ [93].
- The price per unit for electricity is 0.06 \$/kWh [12].
- Plant annual availability is 90% [94].
- Interest rate is 5% [95].
- Amortization period, t , 25 years [95].
- Specific labor cost 0.1 \$/m³ [96].
- Maintenance cost is 15% of the capital cost.

The above-described systems are modelled and analyzed using the following equations.

3.2.2 Mass, Energy, and Exergy analysis:

Vapor generated to form distillate:

$$D=D_1+D_2+D_3...+D_n \quad (1)$$

Temperature drops across the evaporator.

$$\Delta T = \frac{T_s - T_n}{N} \quad (2)$$

Vapor temperature

$$T_{vi} = T_i - \text{BPE} \quad (3)$$

Where i is the effect number, i= 1, 2.... n

Fraction of the flashed vapor from the brine

$$y = \frac{C_p \times \Delta T}{h_{fg}} \quad (4)$$

Energy and mass balance

$$D_{fi} = y. B_{i-1} \quad (5)$$

$$\frac{S_B}{S_B - S_F} = \frac{F}{D} = R \quad (6)$$

$$F_1 = D_1 + B_1 \quad (7)$$

The following equation describes energy and mass balance of the effects shown in Figures (10,11)

First stage:

$$(D_n + D_{f,n} + m_{injection}) \times h_{fg,steam} = D_1 \times h_{fg,1} + F_1 \times C_p \times (T_1 - T_f) \quad (8)$$

2nd stage:

$$D_1 \times h_{fg,1} = D_2 \times h_{fg,2} + F_2 \times C_p \times (T_2 - T_f) \quad (9)$$

3rd to the n stage:

$$(D_{i-1} + D_{f,i-1}) \times h_{fg,i-1} = D_i \times h_{fg,i} + F_i \times C_p \times (T_i - T_f) \quad (10)$$

Where:

i=1,2, 3...n

The mentioned equation from (1) to (10) describes the mass and energy balance for the twin-screw compressor by removing the term $m_{injection}$ from these equations this gives mass and energy balance for the conventional MED system.

System performance:

The specific power consumption is defined as the power consumed to produce a unit of fresh water; it can be expressed as:

$$SPC = \frac{W}{m_d \times 3.6} \quad (11)$$

Where W is the real consumed power in kW described in the $T-s$ diagram shown in Figure 12 and can be calculated as:

1- Conventional compressor

$$W = \frac{(D[n] + D_f[n]) \times (h_{ss} - h_v[n])}{n_s \times n_c} \quad (12)$$

2- Twin-screw compressor:

$$W = \frac{(d[n] + D_f[n]) \times (h_{2s} - h_v[n]) + (d[n] + D_f[n] + m_{injection}) \times (h_{3s} - h_{MP})}{n_s \times n_c} \quad (13)$$

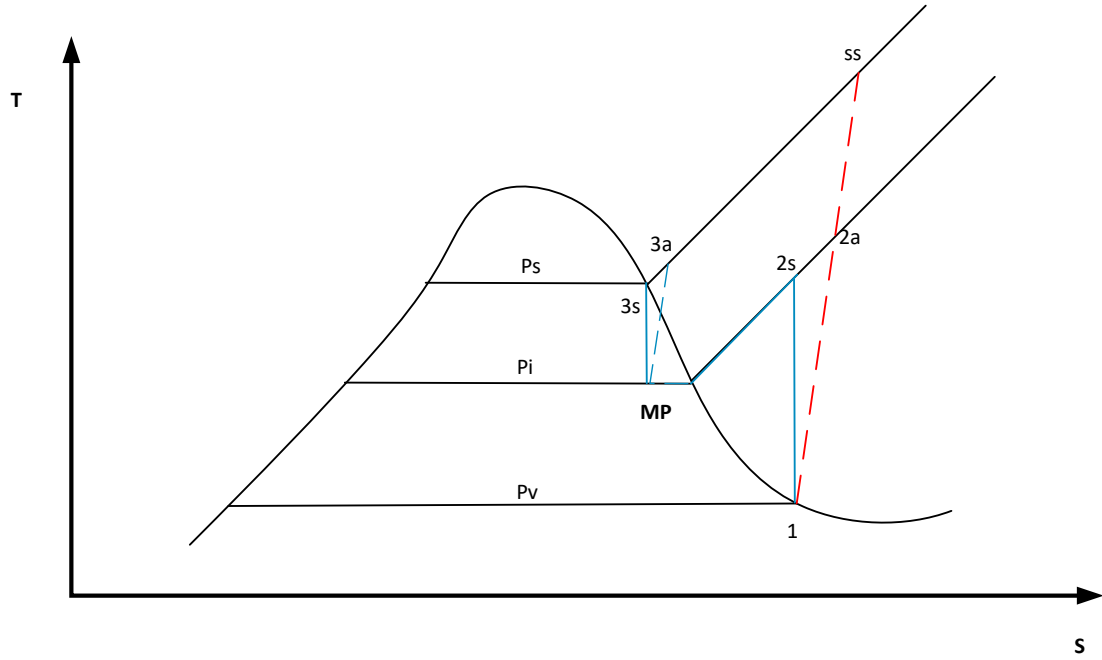


Figure 12: T-s diagram of the compression process.

The Second Law Analysis is based on the exergy balance and indicates that the difference between the sums of the exergy in the fuel and the exergy in the product equals the total of the exergy loss and destruction. This gives the following general equation.

$$\sum \dot{X}_{product} = \sum \dot{X}_{fuel} - \dot{X}_D - \dot{X}_L \quad (14)$$

While the exergy efficiency is defined as the exergy of the system useful exergy output to the system exergy input and can be expressed as:

$$\eta_{exergy} = \frac{\dot{X}_D}{\dot{W}} \times 100 \quad (15)$$

Applying equation (14) for each component in the system gives the following set of equations:

first effect:

$$\text{Exergy destruction} = D_n \times ex_{\text{steam}} + F \times ex_{\text{feed}} - D_1 \times ex_{D,i} - B_1 \times ex_{B,i} - D_n \times ex_{\text{cond}} \quad (16)$$

Second effect:

$$\begin{aligned} \text{Exergy destruction} &= D_1 \times ex_{D,1} + F \times ex_{\text{feed}} - D_2 \times ex_{D,2} - B_2 \times ex_{B,2} \\ &\quad - D_1 \times ex_{\text{con},1} \end{aligned} \quad (17)$$

3rd to the n effect:

$$\begin{aligned}
& \text{Exergy destruction} \\
& = D_{i-1} \times ex_{D(i-1)} + F \times ex_{feed} + D_{fb,i-1} \times ex_{fb,i-1} \\
& - D_i \times ex_{D,i} - B_i \times ex_{B,i} - (D_{i-1} + D_{fb,i-1}) \times ex_{con,i-1}
\end{aligned} \tag{18}$$

3.2.3 Exergo-Economic analysis:

Exergoeconomic analyses are conducted for each component for both abovementioned configurations. The cost flow approach is used to analyze the system. By combining the fixed cost and stream cost, this technique determines the cost of each flow stream that passes through all system components. The correlations in Table 3 are used to compute the fixed cost, often known as the current cost or capital cost. The fixed cost is then converted to fixed cost rate using the equations summarized in Table 4.

Table 3: Capital cost correlations.

Correlation	NO.	Description	Reference
Z_{ev} $= 250 \times Q$ $\times \Delta T m^{-1}$ $\times \Delta P t^{-0.01}$ $\times \Delta P s^{-0.1}$	(19)	Evaporator/Condenser Cost	[97]
Z_{pump} $= 13.92 \times \dot{m}_{feed}$ $\times \Delta P^{0.55} \times e^{1.05}$	(20)	Pump cost	[45]
where:			
$e = \frac{n_{pump}}{1 - n_{pump}}$			
Z_{PH} $= 1000$ $\times (12.86 \times A_{HT}^{0.8})$	(21)	Pre-heaters cost	[98]

Z_{comp}	(22)	Compressor cost	[99]
$= 794.68 \times \dot{W}$ $+ 66.11$			

Table 4: Fixed cost rate equations.

Equation	Description	Equation NO.
$Z_{annual} = Z_{component} \times CRF$	Annual fixed cost	(23)
$\dot{Z}_{annual} = \frac{Z_{annual}}{365 \times 24 \times 3600 \times availability}$	Fixed cost rate	(24)
$CRF = \frac{i \times (i + 1)^n}{(i + 1)^n - 1}$	Capital recovery factor	(25)

After calculating the fixed cost rate, then the stream cost is calculated by using the following general equation:

$$\dot{C}_{product} = \dot{C}_{fuel} + \dot{Z}_{component} \quad (26)$$

According to the above equation, the product cost is equal to the fuel cost rate plus the fixed cost rate. All system components' stream costs are assessed using this equation. The following equations are obtained by applying the general stream cost equation.

The cost of the feed stream after the feed pump is calculated using the following equation.

$$\dot{C}_{sw} = \dot{Z}_{pump} + (\dot{C}_{elect} \times \dot{W}_{FP}) \quad (27)$$

Where $\dot{W}_{FP}$ is the feed pump work and can be calculated by:

$$\dot{W}_{FP} = F \times \Delta P \times \dot{V}_{feed} \quad (28)$$

The stream after the feed pump is divided into two streams passing through the pre-heaters. The stream cost of the flow after the pre-heaters is calculated as:

Distillate pre-heater:

$$\dot{C}_{FD} = \dot{C}_{sw,D} + \dot{C}_{D,in} - \dot{C}_{D,out} + \dot{Z}_{PH,dis} \quad (29)$$

There are two outlets from the distillate pre-heater and one auxiliary equation is needed. This equation is based on the equality of the average cost of the distillate entering and exiting the distillate pre-heater and can be expressed as:

$$\frac{\dot{C}_{D,i}}{\dot{X}_{D,i}} = \frac{\dot{C}_{D,o}}{\dot{X}_{D,o}} \quad (30)$$

Brine pre-heater:

$$\dot{C}_{FB} = \dot{C}_{sw,B} + \dot{C}_{B,in} - \dot{C}_{B,out} + \dot{Z}_{PH,brine} \quad (31)$$

The brine pre-heater has two outlets, and one auxiliary equation is needed based on average cost of the inlet and outlet brine to the brine pre-heater and can be expressed as:

$$\frac{\dot{C}_{B,i}}{\dot{X}_{B,i}} = \frac{\dot{C}_{B,o}}{\dot{X}_{B,o}} \quad (32)$$

Both streams are then added together, and the stream is then divided between the system effects.

The cost of the compressed steam equals the cost of the vapor generated in the last effect added to cost of electricity, and the fixed cost rate of the compressor and can be expressed as:

$$\dot{C}_s = \dot{C}_{v,n} + \dot{W} \times C_{elect} + \dot{Z}_{comp} \quad (33)$$

The input cost in the evaporators includes the feed cost and the steam cost. Thus, the cost of the vapor coming out from the evaporator can be expressed as:

$$\dot{C}_{v,1} = \dot{C}_{f,1} + \dot{C}_{steam} - \dot{C}_{cond} - \dot{C}_{b,1} + \dot{Z}_{EV,1} \quad (34)$$

Since there are three outlets from the evaporator including vapor, steam condensate and brine, two additional auxiliary equations based on the equality of the average cost between the steam and the condensate as well as between the feed and the brine of the first effect are needed. These equations are expressed as:

$$\frac{\dot{C}_{steam}}{\dot{X}_{steam}} = \frac{\dot{C}_{cond}}{\dot{X}_{cond}} \quad (35)$$

$$\frac{\dot{C}_{b,1}}{\dot{X}_{b,1}} = \frac{\dot{C}_{f,1}}{\dot{X}_{F,1}} \quad (36)$$

The general stream cost for the 2nd to the N effect can be calculated using the generalized equation expressed as follow:

$$\dot{C}_{v,i} = \dot{C}_{F,i} + \dot{C}_{v,i-1} + \dot{C}_{b,i-1} - \dot{C}_{v,cond,i-1} - \dot{C}_{b,i} + \dot{Z}_{EV,i} \quad (37)$$

Vapor is the product of the evaporator, and the input parameters are feed seawater, vapor generated in the previous effect and brine from the previous effect. and as mentioned the evaporator has three outlets, including the generated vapor, condensed vapor of the previous effect and brine. That mean two auxiliary equations are needed and can be expressed as:

$$\frac{\dot{C}_{v,i-1}}{\dot{X}_{v,i-1}} = \frac{\dot{C}_{cond,i-1}}{\dot{X}_{D,i-1}} \quad (38)$$

$$\frac{\dot{C}_{b,i}}{\dot{X}_{b,i}} = \frac{\dot{C}_{f,i}}{\dot{X}_{F,i}} \quad (39)$$

The product stream cost equal to the sum of the distillate stream cost, brine cost, chemical cost, maintenance cost and labor cost and can be expressed as:

$$\dot{C}_D = \dot{C}_{B,n} + \sum_{i=1}^n \dot{C}_{D,i} + OM \quad (40)$$

And hence the product cost in \$/m³ can be expressed as:

$$\dot{C}_P = \frac{\dot{C}_D}{\dot{V}} \quad (41)$$

Compressor work:

$$W = \frac{(D_n + D_{f,n}) \times (C_p \times T_{avg}) \times (PR^{\frac{k-1}{k}} - 1)}{n_{comp}} \quad (42)$$

3.3 Results:

In this chapter, MED driven with twin-screw compressor performance is studied and compared to the performance of MED system with conventional compressor without water injection. The results and findings from performing the analysis are demonstrated in this section.

3.3.1 Model validation:

The mathematical model presented in section three is validated by comparing the SPC for configuration one, obtained by using equation 42 with the results reported in [78] using data in Table 5 as the inputs. Figure 13 shows a very good agreement between the two sets of variables.

Table 5 : Input data for model validation.

Parameter	Value
Distillate flowrate kg/s	35
Steam temperature T_s °C	72
Sea water temperature T_{sw} °C	21
Evaporation temperature in the last effect °C	40
Feed temperature T_f °C	36
Feed salinity g/kg	35
Brine salinity g/kg	70

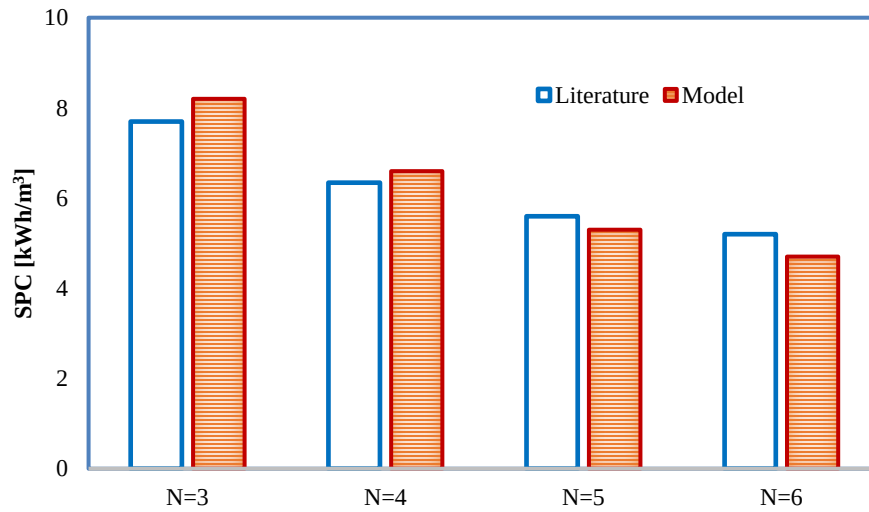


Figure 13: Validation of configuration one against the data obtained from Jamil and Zubair [78].

3.3.2 Energy and exergy analysis:

The model is implemented to predict the performance of system in terms of the SPC and exergy efficiency additionally the twin-screw compressor is compared with the results of the conventional configuration using normal compressor. The results from this analysis are shown in Figures (14-20). Figure 14 shows the impact of the number of effects on the specific power consumption for both configurations. The results from the figure demonstrate that increasing number of effect results in lower specific power consumption for both configurations. Increasing the number of effects results in less vapor in the last effect which requires less compression work and hence less specific work. For example, increasing the number of effects from 3 to 8 effects results in lowering the specific power consumption from 30.87 and 35.94 to 13.36 and 15.77 kWh/m³ for twin-screw and normal compressor configurations, respectively. The figure also demonstrates that the configuration with twin-screw compressor has less specific work compared to the conventional configuration. The injection of water during the compression process improves the isentropic efficiency of the compression processes and results in less specific work. The twin-screw compressor configuration has 14.11 and 15.28 % less specific power consumption at 3 and 8 number of effects, respectively compared to the conventional configuration at the same number of effects.

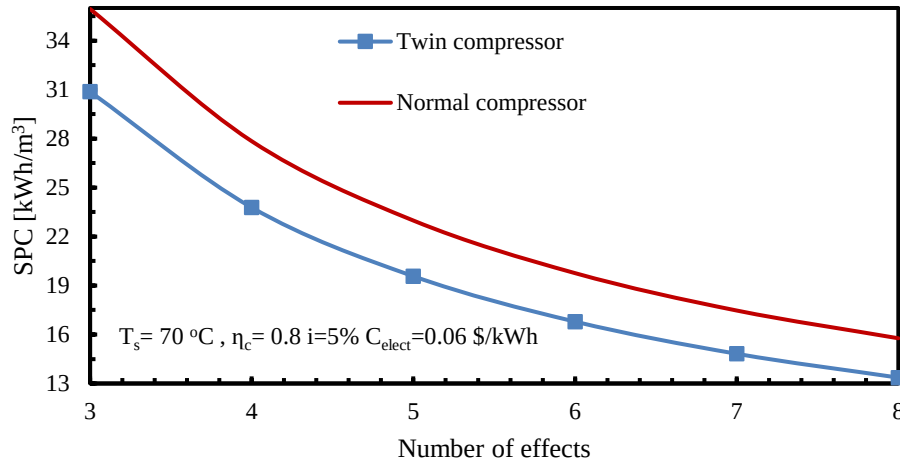


Figure 14: The influence of the number of effects on the specific power consumption PF.

Meanwhile, Figure 15 illustrates how the exergy efficiency is affected by the number of effects for both configurations. The figure shows that increasing the number of effects results in higher exergetic efficiency. This is because increasing the number of effects results in less energy requirements as demonstrated in Figure 14. Increasing the number of effects from 3 to 8 effects results in increasing the exergetic efficiency from 9.308 and 9.016 to 18.79 and 18.03 % for the twin-screw and normal compressor configurations, respectively. The figure also depicts that the twin-screw compressor configuration has higher exergetic efficiency compared to the normal compressor configuration. This is because as explained earlier the twin-screw compressor has less power requirements compared to the conventional compressor because of the better isentropic efficiency regarding the compression process.

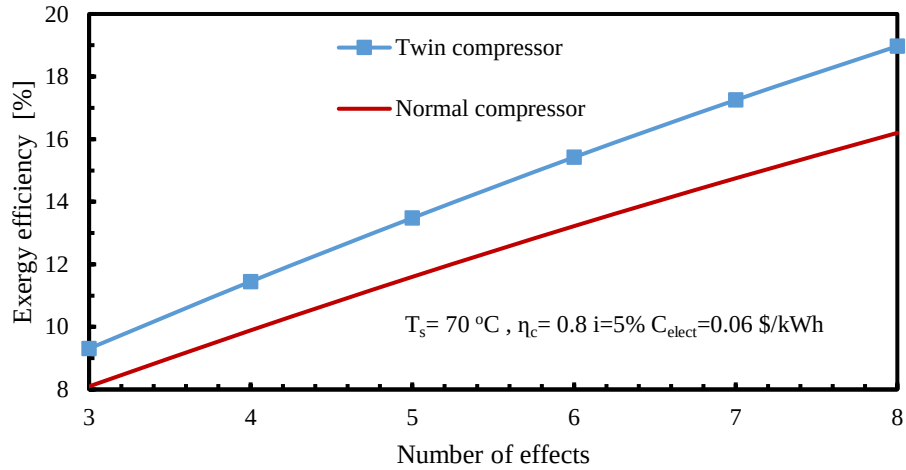


Figure 15: Number of effects vs exergy efficiency for PF.

Figure 16 illustrates the influence of the number of effects on the exergy destruction on both configurations. The figure shows that increasing the number of effects results in less exergy destruction in the system, the figure also shows that the twin-screw compressor configuration has less total exergy destruction compared to the normal compressor configuration which supports the results demonstrated in Figure 15. Increasing the number of effects reduces the exergy destruction from 5592.24 and 6554.39 to 2155.4 and 2613.91 kW for the twin-screw compressor configuration and the normal compressor configuration, respectively.

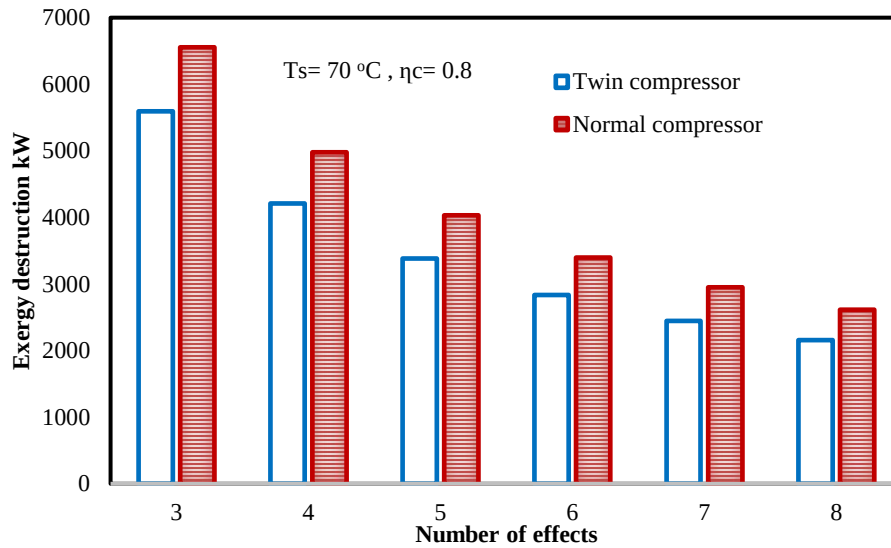


Figure 16: The impact of the number of effects on the exergy destruction PF.

Illustrated in Figure 17 is the response of the specific power consumption to the steam temperature for both configurations. The figure depicts that increasing the steam temperature results in higher specific power consumption for both configurations. Increasing the steam temperature requires a higher compression ratio which requires more power and hence results in higher specific power consumption. the figure also shows that the twin-screw compressor has less specific power consumption compared to the normal compressor configuration and this difference in the specific power consumption increases with increasing the steam temperature. At lower steam temperatures the process tends to be close to the saturation line compared to higher temperatures thus the effect of water injection on the compression process is more noticeable at higher steam temperatures. For example, the difference between the twin-screw compressor and normal compressor configurations in term of the specific power consumption increases from 10.39 to 26.09 % when increasing the steam temperature from 60 to 105 °C.

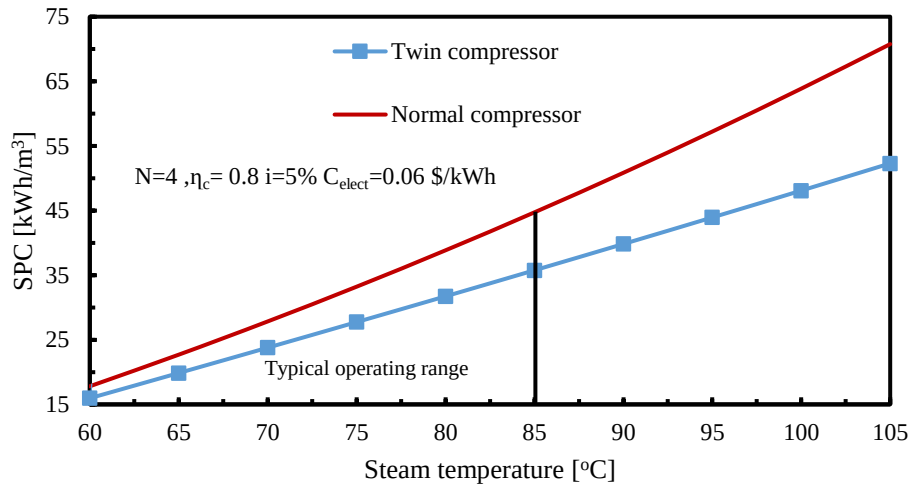


Figure 17: The effect on the steam temperature on the specific power consumption PF.

Shown in Figure 18 is the effect of the steam temperature on the exergy destruction in both configurations. The figure shows that increasing the steam temperature results in higher exergy destruction in both configurations. The figure also depicts as expected the configuration with the normal compressor has higher exergy destruction when compared to the twin-screw compressor configuration. As an example, increasing the steam temperature from 60 to 105 °C increases the exergy destruction from 2797 to 9243 kW in the twin-screw compressor configuration while it increases the exergy destruction in the normal compressor configuration from 3148 to 12760 kW for the same temperature range.

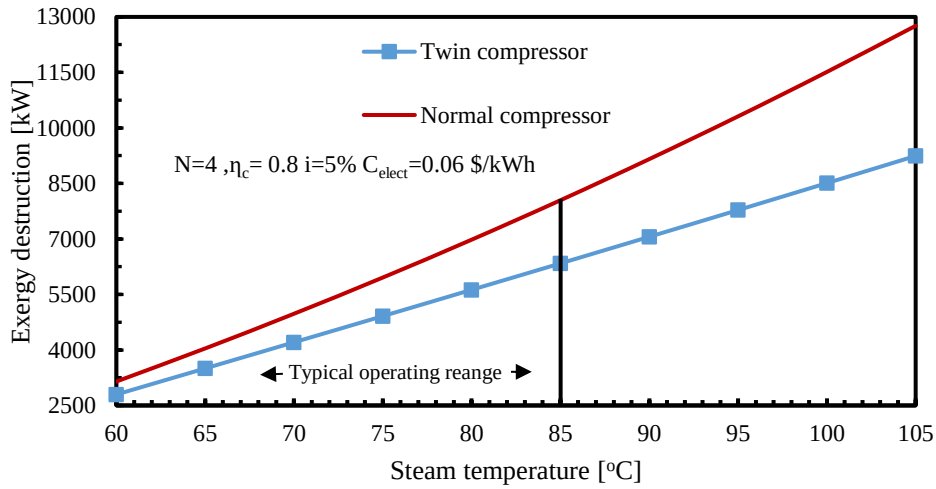


Figure 18: The effect of the steam temperature on exergy destruction PF.

While Figure 19 illustrates the impact of the compressor efficiency on the specific power consumption for both configurations. Again, as shown in the previous figures configuration one has higher specific power consumption compared to configuration two due to higher superheated steam. The figure shows that higher compressor efficiency lowers the specific power consumption. Increasing the compressor efficiency results in less power requirements to achieve the specified compression ratio. To illustrate, increasing the compressor efficiency from 40 to 90% lower the SPC from 55.68 to 24.75 kWh/m³ for configuration one which is more than 55 % reduction in the specific power consumption. This also lowers the SPC in configuration two from 47.56 to 21.14 kWh/m³ which is 55.60 % reduction.

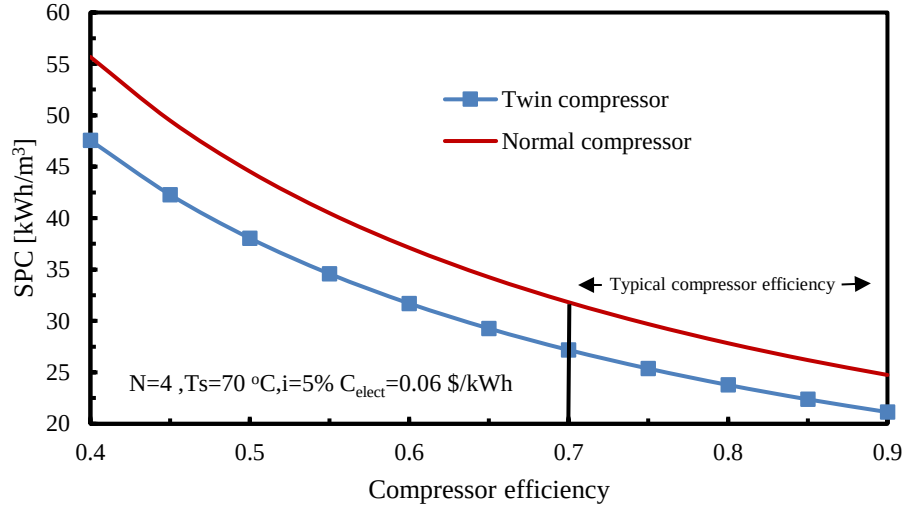


Figure 19: The impact of the compressor efficiency on specific power consumption PF.

Additionally, Figure 20 shows the effect of the compressor efficiency on the exergetic efficiency for both setups. Increasing the compressor efficiency as explained in Figure 19 lowers the energy requirements and hence results in better exergetic efficiency as illustrated in Figure 20. Increasing the compressor efficiency from 40 to 90% increases the exergy efficiency from 4.95 to 11.13 % in setup one and from 5.72 to 12.88 % for configuration two.

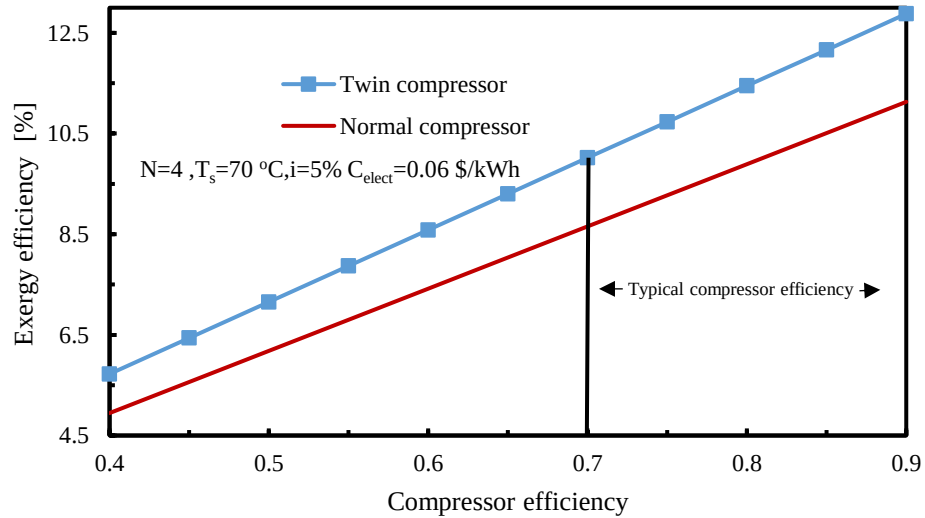


Figure 20: The effect of the compressor efficiency on the exergy efficiency PF.

3.3.3 Exergo-Economic analysis:

The results from using equations [19-41] are presented and discussed in this section. The mentioned equations are used to calculate the product cost by using the cost-flow method. Each stream is represented as a flowing cost in this study, much as flowing energy and exergy. The cost of each stream entering or leaving each component is assessed after a separate analysis of each component has been conducted. The flow cost of each stream in a six-effect system is shown in Table 6.

Table 6: Flow cost of each stream entering and leaving each effect.

Effect _i	$\dot{C}_{f,i}$ \$/s	$\dot{C}_D$ \$/s	$\dot{C}_{b,i}$ \$/s	$\dot{C}_{v,i}$ \$/s
1	0.01025	0.003834	0.06427	0.02825
2	0.007857	0.001101	0.09136	0.00794
3	0.007476	0.0002717	0.1051	0.001435
4	0.007346	0.00004228	0.1096	0.00438
5	0.007449	0.0001083	0.1079	0.01352
6	0.008762	0.00027	0.105	0.0252
Final product cost	2.413 \$/m ³			

The collected findings are shown in Figures (21-27). Figure 21 shows how the final product cost is influenced by changing number of effects. The figure shows that increasing the number of effects from 3 to 8 effects results in lower final product cost for both setups this because as explained from the results illustrated in Figure 14 ; increasing the number of effects lower the power requirements in the system which consequently results in less cost associated with electricity, it also lower the size of the compressor and hence less capital cost. This is translated to a lower overall final product cost as shown in the figure. For example, in configuration one increasing the number of effects from 3 to 8 lower the final product cost from 4.86 to 2.3 \$/m³ which is 52.76 % reduction. While, for configuration two this lowers the cost from 4.185 to 1.97 \$/m³.

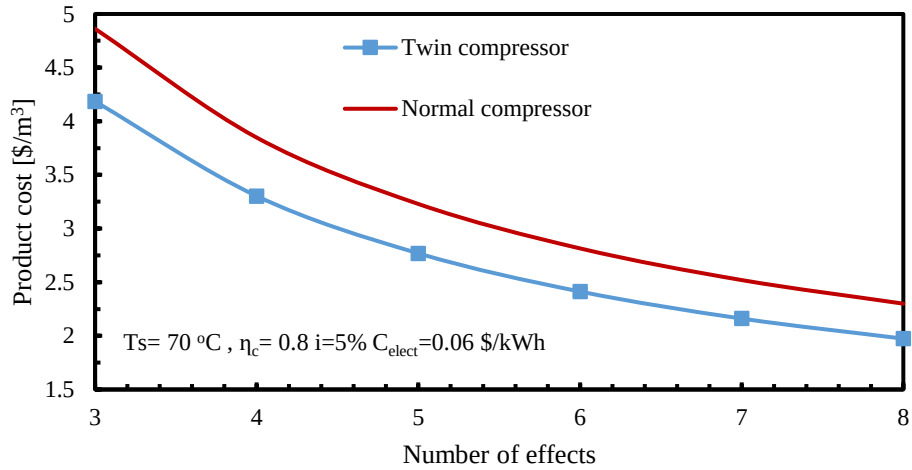


Figure 21: The impact of number of effects on the product cost PF.

Figure 22 shows the effect of the steam temperature on the final product cost for both configurations. The figure illustrates that increasing the steam temperature results in higher final product cost. The figure also demonstrates that increasing the steam temperature increases the difference between the two configurations in terms of the unit cost of the freshwater produced. This is best explained by the results found in Figure 17, which shows that increasing the steam temperature results in higher SPC and also it increases the difference in the SPC between the two setups. Increasing the SPC results in higher cost of power and larger compressor size. Increasing the steam temperature from 60 to 105 °C increases the freshwater cost by 71.47 and 65.12 % for setup one and setup two, respectively.

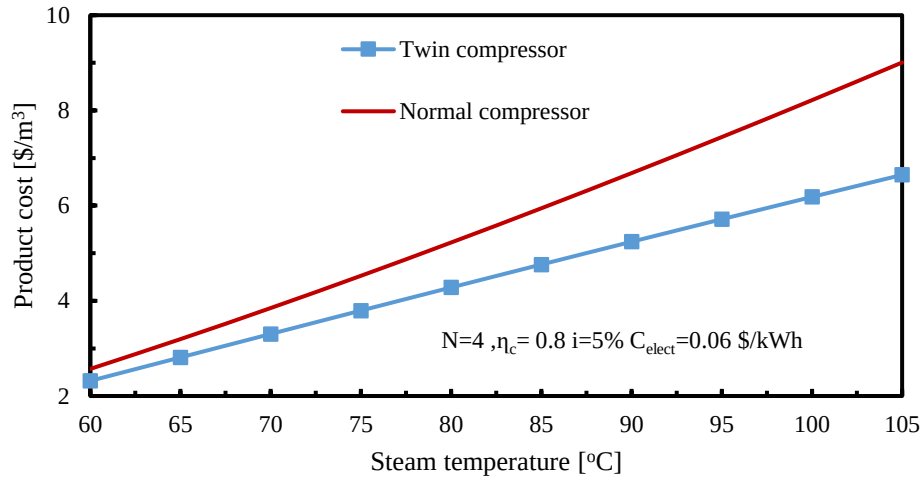


Figure 22: Effect of steam temperature on the product cost PF.

On the other hand, Figure 23 depicts the effect of the compressor efficiency on the final product cost. Increasing the compressor efficiency results in less final product cost. This is because higher compressor efficiency results in less cost associated with power input and capital cost as explained from the results given in Figure 19 and hence lower final product cost. The figure shows that increasing the compressor efficiency from 40 to 90 % lower the unit cost from 7.54 to 3.44 \$/m³ for the configuration with the normal compressor. Similarly, this lowers the product cost for the twin-screw compressor configuration from 6.45 to 2.95 \$/m³ at the same conditions.

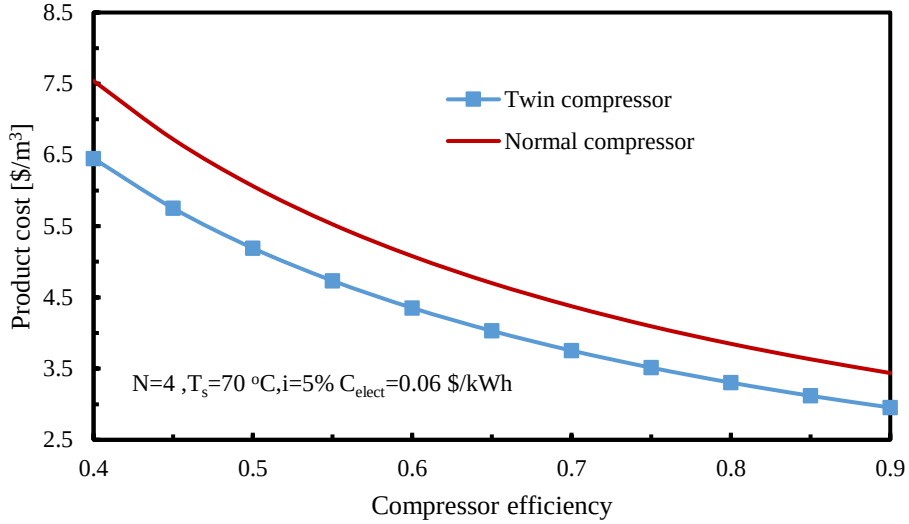


Figure 23: Effect of compressor efficiency on the product cost PF.

Figure 24 shows the effect the electricity price has on the final product cost for both configurations for 3 and 6 number of effects at the same conditions. As discussed, earlier configuration one has higher specific power consumption compared to configuration two. The increased energy requirements result in higher final product cost for the same number of effects as illustrated in Figure 24. The figure demonstrates that increasing the electricity cost from 0.01 to 0.1 \$/kWh increases the final product cost for configuration one from 1.38 to 7.65 \$/m³ at 3 number of effects which is higher by more than five folds. while it increases the final product cost for configuration two from 1.20 to 6.57 \$/m³ at the same conditions. The figure also shows that increasing the number of effects from 3 to 6 effects lowers the final product costs by 74.5 and 75.47 % for configuration one and configuration two, respectively. This result shows that the electricity price plays a crucial role in determining whether this technology is economically feasible or not and should be considered when studying different possible locations for applying this technology.

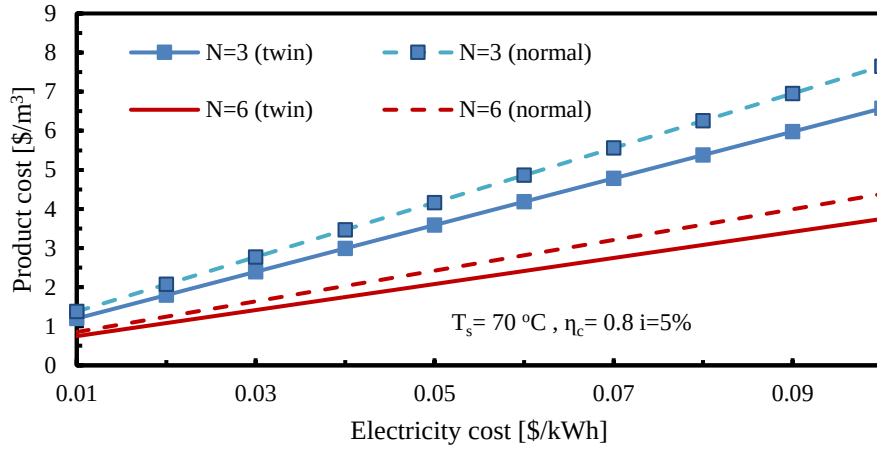


Figure 24: Effect of the electricity cost on the product cost PF.

While Figure 25 demonstrates the impact of plant life on the final price of the freshwater produced from both setups. The figure shows that increasing the life of the system expectancy results in lower freshwater price for both configurations. Increasing the life of the plant from 15 to 30 years lowers the final product cost from 4.01 to 3.81 $\$/\text{m}^3$ for configuration one. However, under the same conditions it lowers the final product cost for configuration two from 3.45 to 3.27 $\$/\text{m}^3$. Comparing these results with the findings in Figure 24 it can be concluded that the electricity price has more impact on the final product cost when compared to the life expectancy of the system.

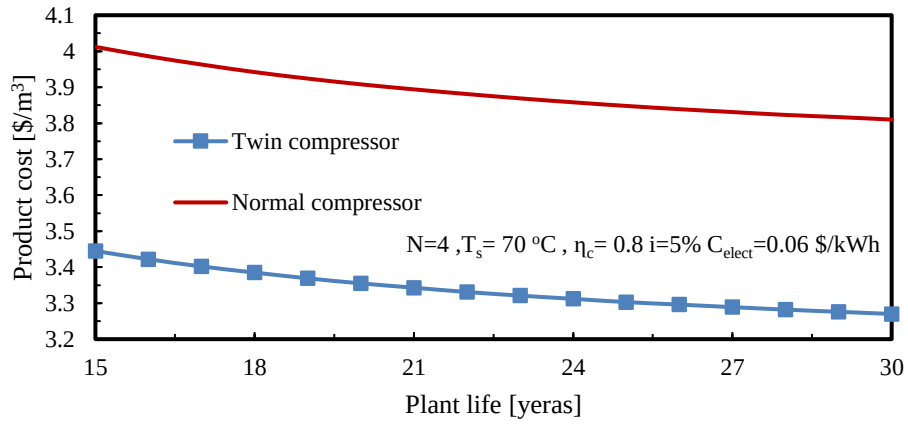


Figure 25: Effect of plant life on the product cost PF.

While Figure 26 shows how is the final product cost is affected by the interest rate. The interest rate affects the per capita cost of the plant and hence the final product cost. Increasing the interest rate from 1 to 10 % increases the final product cost from 3.68 to 4.10 \$/m³ for setup one and from 3.16 to 3.52 \$/m³ for configuration two which is 10.2 % increase in the produced freshwater unit cost.

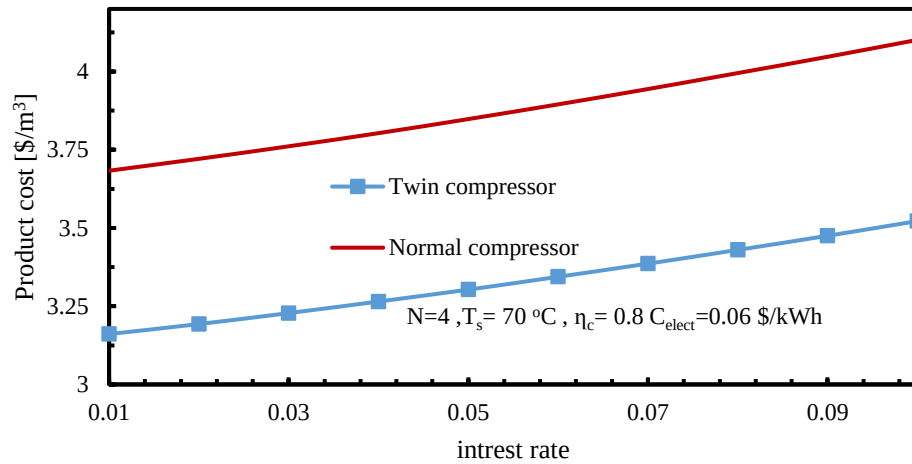


Figure 26: The influence of the interest rate on the product cost PF.

The purpose of using twin-screw compressor with water injection is to reduce the power consumption and obtain lower final product cost. One of the important factors that influence the amount of power reduced in the twin-screw compressor is the pressure of the injected water. Figure 27 shows the effect of the injection pressure on the specific power consumption, exergy efficiency and the final product cost at 4 number of effects. The figure shows that increasing the pressure at which that water is injected results in higher specific power consumption. This increase in the power requirements results in less exergy efficiency and higher final product costs. From these results it can be concluded that that the injection of water should be at the begging of the compression process to ensure the least power consumed, higher exergy efficiency and the least unit cost of the produced freshwater.

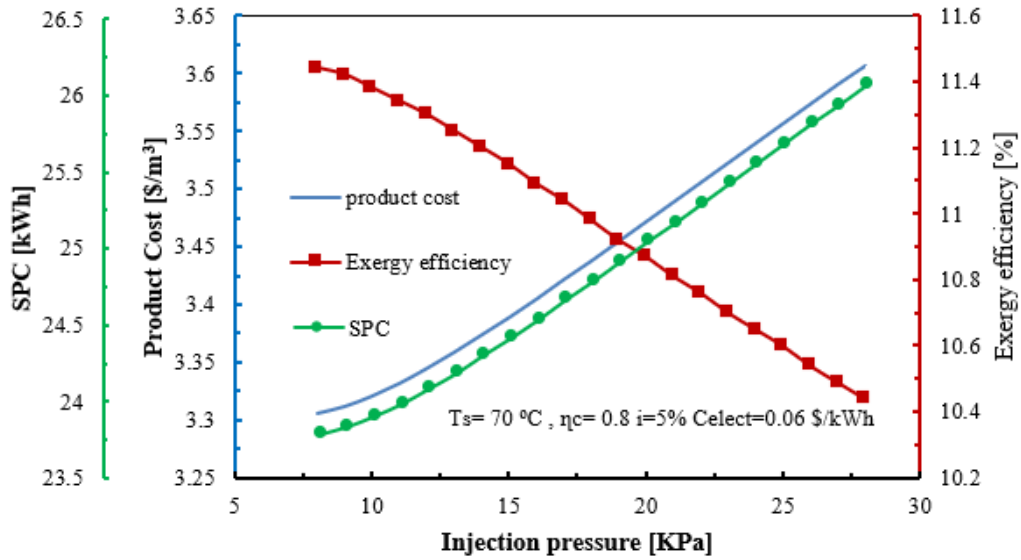


Figure 27: The effect of injection pressure on the SPC, Product cost and Exergy efficiency PF.

3.3.4 Sensitivity analysis:

In this section, an extensive sensitivity analysis is conducted to assess the impact of key operational parameters on a system's performance. This analysis is crucial for identifying the parameters that have the most pronounced effects on the system's efficiency, energy consumption, and cost-effectiveness. The selected parameters for this study, namely compressor efficiency, number of effects, and temperature, were chosen due to their

fundamental roles in system operation and potential influence on critical performance metrics. Compressor efficiency is systematically varied within the realistic range of 0.7 to 0.9, reflecting typical efficiencies achievable in such systems. The number of effects is considered across a range representing different stages in multi-effect processes, tailored to the specific configurations and operational settings. Temperature is analyzed over a span from 60°C to 80°C, covering operational temperatures commonly encountered in these systems. Each parameter is explored at five levels to comprehensively span the chosen range. The focus of the sensitivity analysis is on three primary output variables: Specific Power Consumption (SPC), Exergy, and Cost. SPC directly measures the system's energy efficiency, Exergy provides insights into the quality and utility of the energy used, and Cost is vital for assessing economic feasibility. Systematically varying these input parameters within their defined ranges and observing their impacts on SPC, Exergy, and Cost allows us to determine the most influential factors. This understanding is pivotal for prioritizing optimization efforts, leading to enhanced overall performance and cost-efficiency. Upon analyzing the operational parameters across SPC, Exergy, and Cost, distinct trends emerge, with compressor efficiency consistently standing out as the most influential factor in each case. Figure 28 shows the effect of the input parameters on the SPC. On the other hand, the exergy trend is shown in Figure 29. Additionally Figure 30 shows how the cost is influenced by the input parameters.

3.3.4.1 Compressor Efficiency:

Efficiency of the compressor shows a profound impact across all parameters. As efficiency increases from 0.7 to 0.9, there is a significant decrease in SPC (from approximately 18.57 to 29.16), indicating a strong inverse relationship. Simultaneously, Exergy shows an increase with better efficiency, illustrating its positive correlation. In terms of Cost, a similar trend is observed as efficiency improves, Cost decreases, reinforcing efficiency's role in enhancing operational economy.

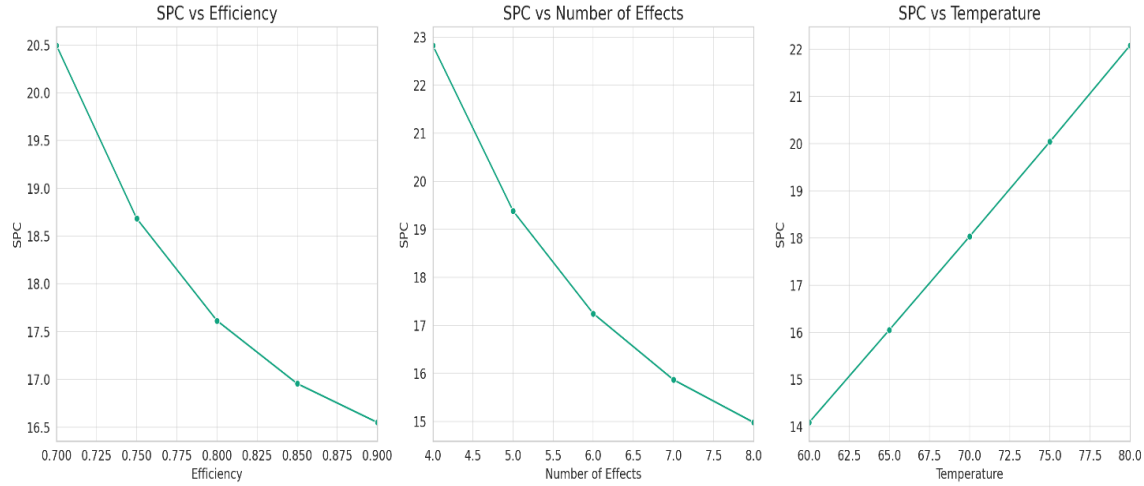


Figure 28: SPC trend.

3.3.4.2 Number of Effects:

The number of effects demonstrates a moderate influence. In the context of SPC, an increase in the number of effects correlates with a decrease in power consumption, albeit to a lesser degree than efficiency. Its impact on Exergy and Cost is less marked, suggesting that while it contributes to system performance, its influence is secondary to efficiency.

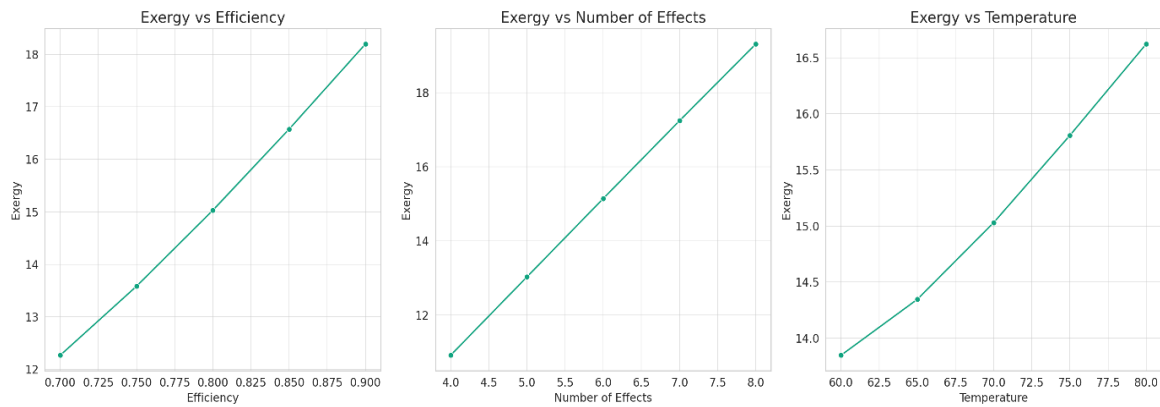


Figure 29: Exergy trend.

3.3.4.3 Temperature:

Temperature's role is the least pronounced. An increase in temperature leads to a mild increase in SPC and Cost. For instance, a rise in temperature from 60°C to 80°C might be associated with a slight increase in these parameters. In the case of Exergy, the increase

with temperature is also observed but is comparatively modest next to the impact of efficiency.

Overall, these numerical trends underscore compressor efficiency as the key driver in optimizing system performance, particularly in reducing SPC and Cost while enhancing Exergy. The number of effects and temperature, while influential, have a less significant impact within the examined ranges. This analysis is crucial for informed decision-making in system design and operation, especially in energy-intensive processes where efficiency, cost-effectiveness, and optimal energy utilization are essential.

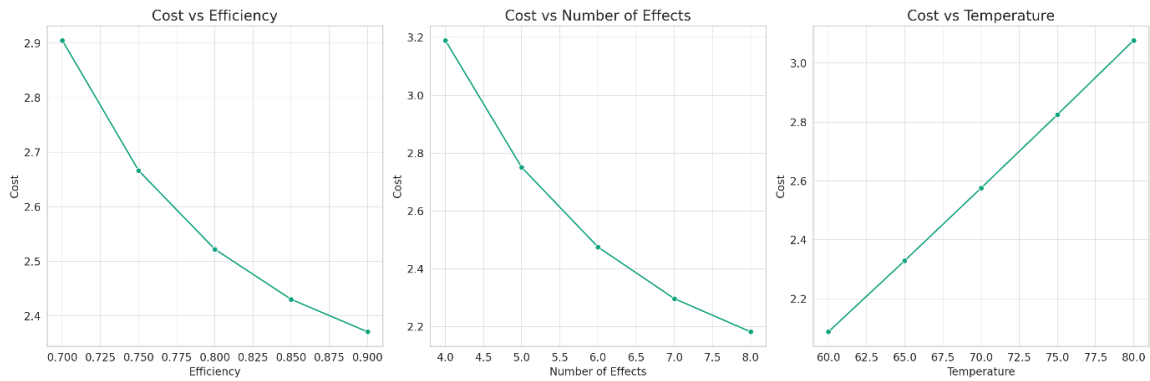


Figure 30: Cost trend

CHAPTER 4

Forward Feed Configuration

This chapter presents the design of a forward feed multi-effect system equipped with a twin-screw compressor featuring water injection for enhanced performance. The chapter encompasses the mathematical equations describing the system. An in-depth analysis and evaluation of the system are conducted from energy, exergy, and exergy-economic perspectives similar to the analysis done in chapter Three. A comparison is made between this system's performance and that of the conventional configuration, focusing on specific power consumption, exergy efficiency, and the cost of the produced water. The impact of various operational conditions, such as the number of effects, steam temperature, compressor efficiency, and injection pressure, on specific power consumption, exergy efficiency, exergy destruction, and final product cost is examined. Additionally, the chapter investigates the influence of factors like interest rate, plant life expectancy, and electricity cost on the ultimate product cost.

4.1 System description:

In this chapter a forward feed MED system is considered for analysis. The system has been analyzed in two configurations i.e., configuration one: MED FF system integrated with normal compressor and configuration two: MED FF system integrated with twin-screw compressor with water injection. The main objective of this research is to compare the performance between the two configurations in terms of specific power consumption, exergy efficiency and the final product cost. The system model is described using mass, energy balance and exergo-economic equations to calculate all the mass flow rates, temperatures, power consumption and the product cost. The model is solved using Engineering Equation Solver (EES) software.

4.1.1 Configuration One:

The main parts of the system are evaporators, pre-heaters, compressors, and pumps. The stream of feed at temperature T_c is first heated from T_c to T_f in brine and distillate pre-heaters. The feed then enters the first effect at T_f . The compressed steam loses its latent

heat in the tube side of the heat exchanger in the evaporator. The feed is heated in the first effect to the saturation temperature of the first effect, T_1 , and part of it evaporates, referred to as D_1 . The rest is passed to the next stage as the feed of that stage. The part that has evaporated in the previous stage is passed to the next stage as the source of heat. This process is repeated for all the following effects. However, in the last effect, the generated vapor is passed to the compressor to generate the steam that enters the first effect at a temperature T_s . Steam flows into the first evaporator, where it condenses in the tubes. The latent heat of the condensed steam heats the feed from T_f to the saturation temperature of the first effect.

4.1.2 Configuration Two:

In this configuration the conventional compressor is replaced by a twin-screw compressor with water injection. The water for injection is taken from the distillate after the preheater as shown in Figure 31. The process of injecting water during the compression process improves the isentropic efficiency and results in less work consumption.

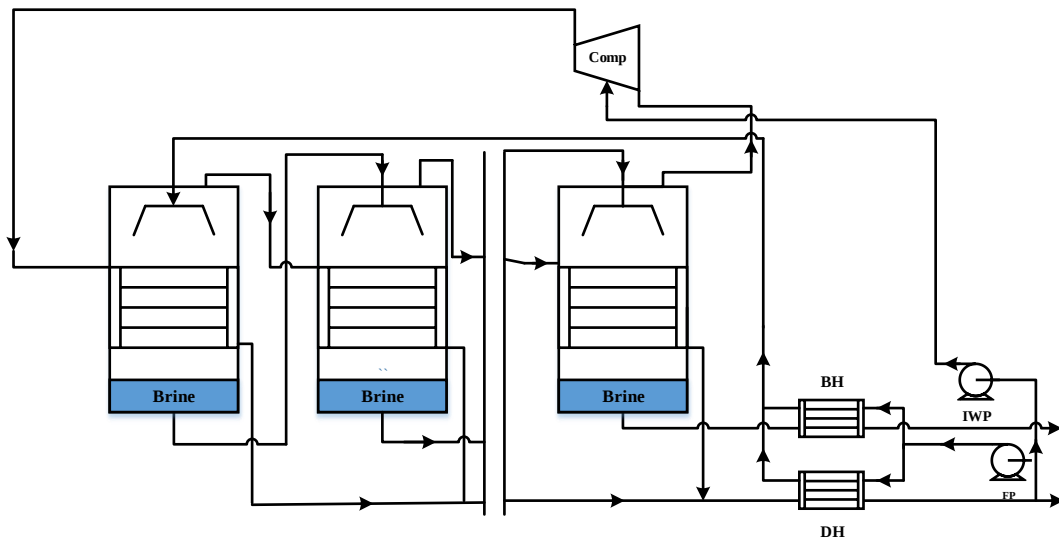


Figure 31: FF integrated with twin-screw compressor.

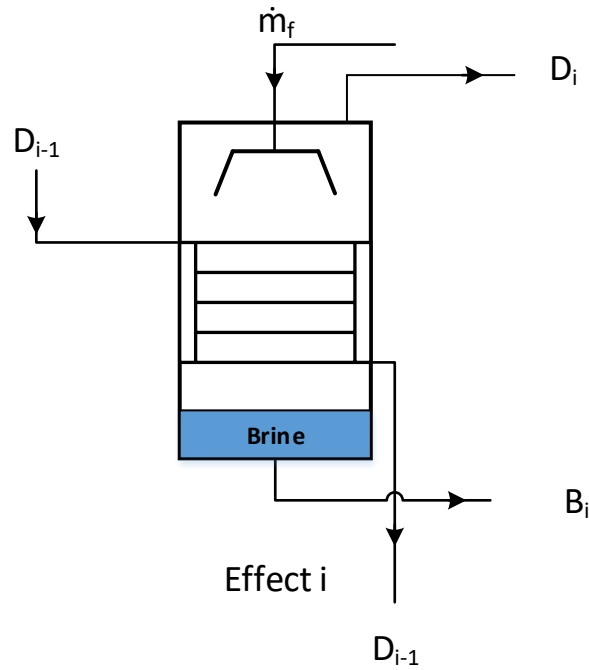


Figure 32: Inlet and outlet streams of the i_{th} effect for FF.

4.2 Mathematical Model:

4.2.1 Assumptions:

The same assumption in Chapter Three in the subsection 3.2.1 are implemented in this chapter.

4.2.2 Mass, Energy, and Exergy analysis:

In this section mass and energy equation of the system are provided in the following equations.

Vapor generated to form distillate:

$$D = D_1 + D_2 + D_3 \dots + D_n \quad (1)$$

Temperature drops across the evaporator:

$$\Delta T = \frac{T_s - T_n}{N} \quad (2)$$

Vapor temperature

$$T_{vi} = T_i - \text{BPE} \quad (3)$$

Where i is the effect number, i= 1, 2.... n

Mass and energy balance at the first stage:

$$\dot{m}_{f1} = D_1 + B_1 \quad (43)$$

$$(D_n + m_{injection}) \times h_{fg} = m_f \times c_p (T_1 - T_f) + D_1 \times h_{fg,Tv(1)} \quad (44)$$

$$\dot{m}_f \times X_f = B_1 \times X_{b,1} \quad (45)$$

Mass and energy balance 2nd stage to n stage (i = 2 to n):

$$B_{i-1} = B_i + D_i \quad (46)$$

$$D_{i-1} \times h_{fg,Tv(i)} = B_i \times h_{b(i)} + D_i \times h_{g,Tv(i)} - B_{i-1} \times h_{b(i-1)} \quad (47)$$

$$B_{(i-1)} \times X_{b(i)} = B_i \times X_{b(i-1)} \quad (48)$$

System performance:

The specific power consumption is defined as the power consumed to produce a unit of fresh water; it can be expressed as:

$$SPC = \frac{W}{m_d \times 3.6} \quad (11)$$

Where W is the real consumed power in kW and can be calculated as:

3- Conventional compressor

$$W = \frac{(D[n]) \times (h_{ss} - h_v[n])}{n_s \times n_c} \quad (49)$$

4- Twin-screw compressor:

$$W = \frac{(D[n]) \times (h_{2s} - h_v[n]) + (D_{f[n]} + m_{injection}) \times (h_{3s} - h_{MP})}{n_s \times n_c} \quad (50)$$

The Second Law Analysis is based on the exergy balance and indicates that the difference between the sums of the exergy in the fuel and the exergy in the product equals the total of the exergy loss and destruction. This gives the following general equation.

$$\sum \dot{X}_{product} = \sum \dot{X}_{fuel} - \dot{X}_D - \dot{X}_L \quad (14)$$

While the exergy efficiency is defined as the exergy of the system useful exergy output to the system exergy input and can be expressed as:

$$\eta_{exergy} = \frac{\dot{X}_D}{\dot{W}} \times 100 \quad (15)$$

Applying equation (56) for each component in the system gives the following set of equations:

1st effect:

$$\begin{aligned} \text{Exergy destruction} = & D_n \times ex_{steam} + \dot{m}_f \times ex_f - D_1 \times ex_{D,1} - B_1 \times ex_{B,1} \\ & - D_n \times ex_{cond} \end{aligned} \quad (51)$$

2nd to the n effect:

$$\begin{aligned} \text{Exergy destruction} \\ = & D_{i-1} \times ex_{D,i-1} + B_{i-1} \times ex_{B,i-1} - D_i \times ex_{D,i} - B_i \times ex_{B,i} \\ & - D_{i-1} \times ex_{cond,i-1} \end{aligned} \quad (52)$$

Compressor:

$$\text{Exergy destruction} = W + m_{inj} \times ex_{inj} + D_n \times ex_{D,n} - (D_n + m_{inj}) \times ex_{steam} \quad (53)$$

Distillate pre-heater:

$$\text{Exergy destruction} = (1 - \alpha) \times m_f \times (e_c - e_f) + m_d \times (e_{con[n-1]} - e_{d_{final}}) \quad (54)$$

Brine pre-heater:

$$\text{Exergy destruction} = \alpha \times m_f \times (e_c - e_f) + m_b \times (e_{b[n]} - e_{b_{final}}) \quad (55)$$

4.2.3 Exergo-Economic analysis:

Exergoeconomic assessments are carried out for each component in both of the aforementioned configurations. The same equation in Table 3 and Table 4 are used in this section.

After determining the fixed cost rate, the stream cost is computed using the general equation below:

$$\dot{C}_{product} = \dot{C}_{fuel} + \dot{Z}_{component} \quad (26)$$

According to the preceding equation, the product cost is equal to the fuel cost rate plus the fixed cost rate. With this equation, the stream costs of all system components are calculated. The general stream cost equation yields the following equations.

The cost of the feed stream after the feed pump is calculated using the following equation.

$$\dot{C}_{sw} = \dot{Z}_{pump} + (\dot{C}_{elect} \times \dot{W}_{FP}) \quad (27)$$

Where $\dot{W}_{FP}$ is the feed pump work and can be calculated by:

$$\dot{W}_{FP} = F \times \Delta P \times \dot{V}_{feed} \quad (28)$$

Following the feed pump, the stream is separated into two streams that pass through the pre-heaters. The flow cost after the pre-heaters is estimated as follows:

Distillate pre-heater:

$$\dot{C}_{FD} = \dot{C}_{sw,D} + \dot{C}_{D,in} - \dot{C}_{D,out} + \dot{Z}_{PH,dis} \quad (29)$$

The distillate pre-heater has two outlets, and only one auxiliary equation is required. This equation, which can be stated as, is predicated on the equality of the average cost of the distillate entering and departing the distillate pre-heater:

$$\frac{\dot{C}_{D,i}}{\dot{X}_{D,i}} = \frac{\dot{C}_{D,o}}{\dot{X}_{D,o}} \quad (30)$$

Brine pre-heater:

$$\dot{C}_{FB} = \dot{C}_{sw,B} + \dot{C}_{B,in} - \dot{C}_{B,out} + \dot{Z}_{PH,brine} \quad (31)$$

The brine pre-heater has two outlets, and one auxiliary equation based on the average cost of the inlet and outlet brine to the brine pre-heater is required, which can be stated as:

$$\frac{\dot{C}_{B,i}}{\dot{X}_{B,i}} = \frac{\dot{C}_{B,o}}{\dot{X}_{B,o}} \quad (32)$$

Both streams are then added together, and the stream is then divided between the system effects.

The compressed steam cost is equal to the cost of the vapor generated in the last effect plus the cost of power and the fixed cost rate of the compressor and can be stated as:

$$\dot{C}_s = \dot{C}_{v,n} + \dot{W} \times C_{elect} + \dot{Z}_{comp} \quad (33)$$

The input cost in the evaporators includes the feed cost and the steam cost. Thus, the cost of the vapor coming out from the evaporator can be expressed as:

$$\dot{C}_{v,1} = \dot{C}_f + \dot{C}_{steam} - \dot{C}_{cond} - \dot{C}_{b,1} + \dot{Z}_{EV,1} \quad (34)$$

Because the evaporator has three outputs, vapor, steam condensate, and brine, two more auxiliary equations based on the equality of the average cost between the steam and the condensate, as well as the feed and the brine of the first effect, are required. These equations are written as:

$$\frac{\dot{C}_{steam}}{\dot{X}_{steam}} = \frac{\dot{C}_{cond}}{\dot{X}_{cond}} \quad (35)$$

$$\frac{\dot{C}_{b,1}}{\dot{X}_{b,1}} = \frac{\dot{C}_{f,1}}{\dot{X}_{F,1}} \quad (36)$$

The general stream cost for the 2nd to the N effect can be calculated using the generalized equation expressed as follow:

$$\dot{C}_{v,i} = \dot{C}_{v,i-1} + \dot{C}_{b,i-1} - \dot{C}_{v,cond,i-1} - \dot{C}_{b,i} + \dot{Z}_{EV,i} \quad (56)$$

The evaporator produces vapor, and the input parameters include feed seawater, vapor produced in the previous effect, and brine produced in the preceding effect. As previously stated, the evaporator has three outlets: produced vapor, condensed vapor from the preceding effect, and brine. That means two auxiliary equations are required, which can be written as:

$$\frac{\dot{C}_{v,i-1}}{\dot{X}_{v,i-1}} = \frac{\dot{C}_{cond,i-1}}{\dot{X}_{D,i-1}} \quad (38)$$

$$\frac{\dot{C}_{b,i}}{\dot{X}_{b,i}} = \frac{\dot{C}_{b,i-1}}{\dot{X}_{b,i-1}} \quad (39)$$

The product stream cost equal to the sum of the distillate stream cost, brine cost, chemical cost, maintenance cost and labor cost and can be expressed as:

$$\dot{C}_D = \dot{C}_{B,n} + \sum_{i=1}^n \dot{C}_{D,i} + OM \quad (40)$$

And hence the product cost in \$/m³ can be expressed as:

$$\dot{C}_P = \frac{\dot{C}_D}{\dot{V}} \quad (41)$$

4.3 Results:

In this section, the performance of a MED system driven by a twin-screw compressor is evaluated and compared to the performance of a forward feed MED system driven by a normal compressor without water injection. This section displays the results and findings of the analysis.

4.3.1 Energy and exergy analysis:

The model is employed to evaluate system performance in terms of SPC and exergy efficiency; additionally, the results of the twin-screw compressor are compared with those of the conventional configuration employing a normal compressor. Figures (33-44) depict the findings of this analysis. Figure 33 Shows the effect of the number of effects on the specific power consumption for the two configurations. The figure shows that increasing the number of effects results in lower power consumption for both configurations. This is because a higher number of effects results in lower vapor in the last effect compared to lesser number of effects which require less compression work, and this is translated to lower specific power consumption as seen in the figure. For example, increasing the number of effects from 3 to 8 lower the specific power consumption from 38.7 to 19.62 kWh/m³ for the normal compressor configuration while this lower the specific power consumption for the twin-screw compressor from 33.17 to 16.58 kWh/m³ the figure also shows that the twin-screw compressor configuration has lower specific power consumption compared to the normal compressor configuration at the same conditions. This is as explained earlier using the twin-screw compressor with water injection results in higher isentropic efficiency which lower the required work by the compressor. To illustrate at 8 number of effects the SPC for configuration one is 19.62 kWh/m³ while it is 16.85 kWh/m³ for configuration two at the same number of effects which is 14.12% reduction.

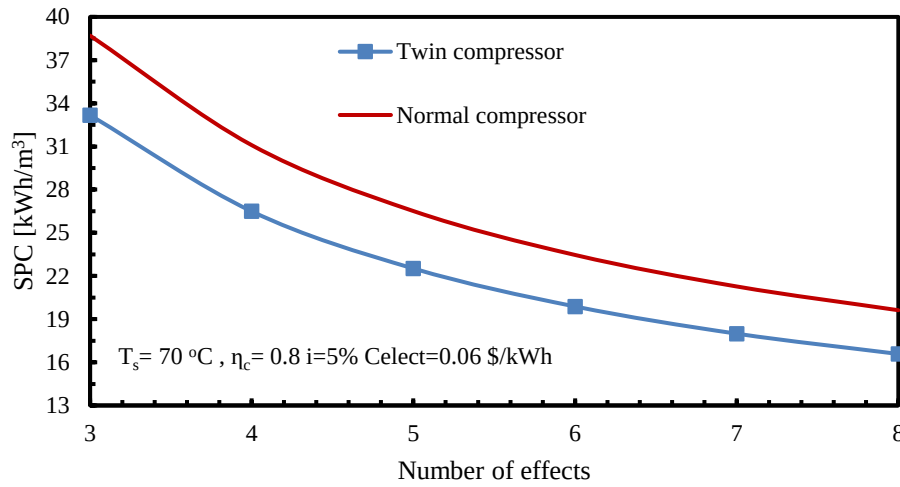


Figure 33: The impact of number of effects on a specific power requirement FF.

While Figure 34 illustrate how the exergy efficiency is affected by the number of effects in the MED system for both setups. The figure depicts that increasing the number of effects increases the exergy efficiency. The exergy efficiency depends on the power consumption of the system (lower power consumption results in higher exergy efficiency) and by looking at the results in Figure 33 this explains why higher number of effects results in higher exergy efficiency. For example, increasing the number of effects from 3 to 8 increases the exergy efficiency from 7.66 to 12.38% for configuration one while it increases from 8.82 to 14.49% for the twin compressor configuration. the figure also shows that configuration two has better exergy efficiency compared to configuration one and this is also explained by the results in Figure 33 (implementing twin-screw compressor lower the power consumption in the system compared to the normal compressor) which results in higher exergy efficiency. For example, at 8 number of effects this is 14.6 % increase in the exergy efficiency.

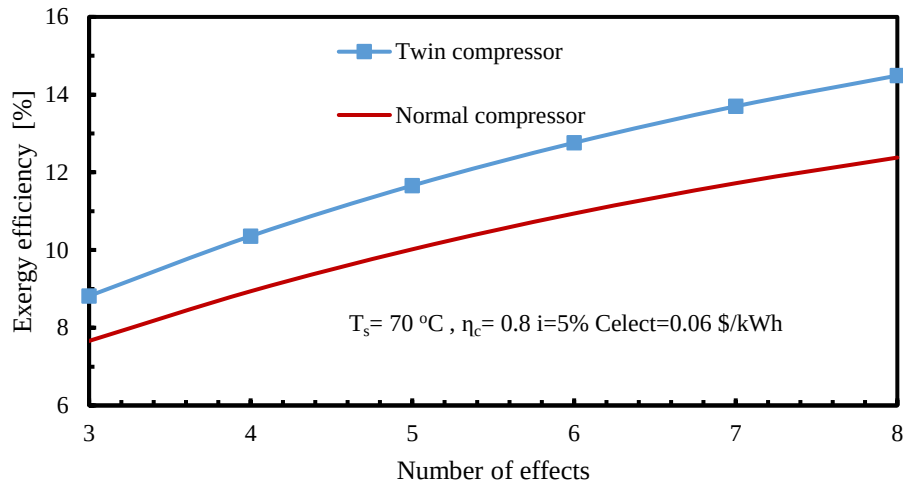


Figure 34: The influence of Number of effects on the exergetic efficiency FF.

However, Figure 35 illustrate the response of the specific power consumption to the steam temperature for the two configurations. The figure shows that increasing the steam temperature results in higher specific power consumption for both configurations. increasing steam temperature results in higher compression ratio and hence higher power consumption by the compressor the figure also shows that the twin compressor configuration has lower specific power consumption compared to the normal compressor configuration. This difference increases with the increase in the steam temperature. This is because at lower temperature the compressor steam tends to be closer to the saturation line while at higher temperature the steam becomes more superheated. For example, at 60 °C steam temperature the SPC power consumption is 19.4 and 17.36 kWh/m³ for configuration one and configuration two respectively which is 10.51 % reduction in SPC while at 105 °C the SPC is 84.98 and 62.37 kWh/m³ for setup one and setup two respectively which is 26.6 % reduction in the power consumption.

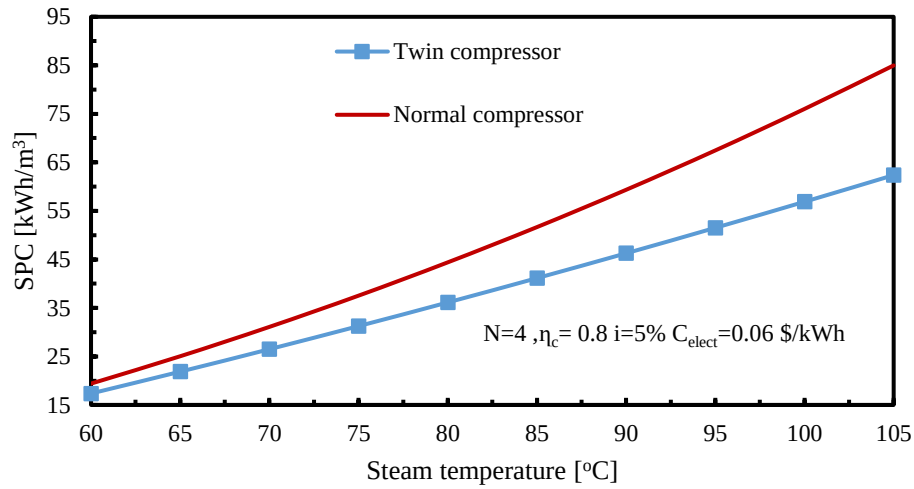


Figure 35: The specific power consumption response to the steam temperature FF.

Figure 36, on the other hand, shows how the compressor efficiency affects the specific power consumption for the two layouts. Again, as seen in the preceding figures, configuration one uses more specific power than configuration two since the amount of superheated steam is higher. The graph demonstrates that a more efficient compressor uses less specific power. Less power is needed to achieve the desired compression ratio when the compressor efficiency is increased. As an example, the SPC is lowered from 62.17 to 27.63 kWh/m³ for configuration one by improving the compressor efficiency from 40 to 90% represents a reduction in the specific power consumption of more than 55%. Moreover, this reduced the SPC in configuration two by 55.60%, from 52.98 to 23.55 kWh/m³.

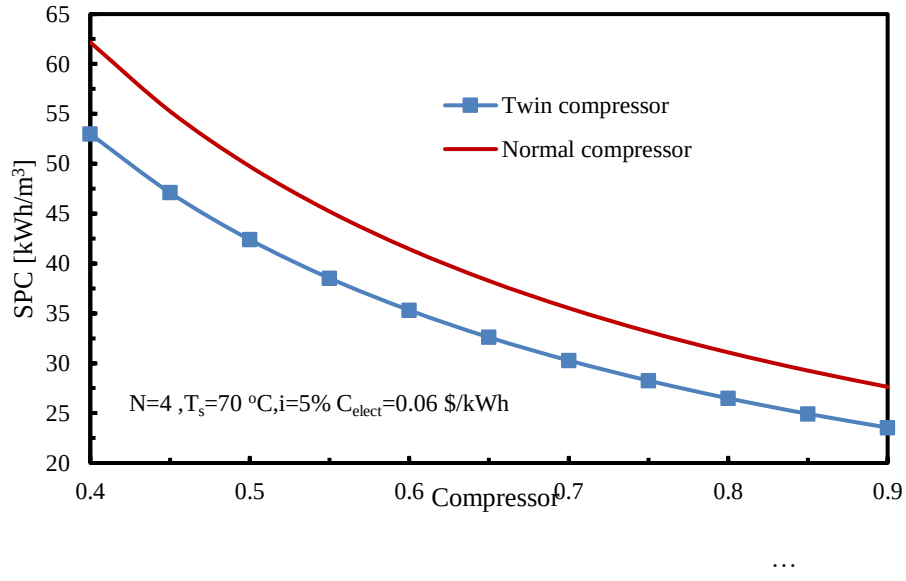


Figure 36: The impact of the compressor efficiency on the specific power consumption FF.

Figure 37 also depicts the influence of compressor efficiency on exergetic efficiency in both settings. Improving compressor efficiency, as shown in Figure 36, reduces energy requirements and, as a result, improves exergetic efficiency, as shown in Figure 37. Increasing the compressor efficiency results in less wasted energy in form of heat which leads to a higher proportion of useful work output. Raising the compressor efficiency from 40 to 90% raises the exergy efficiency in setup one from 4.47 to 10.06% and in configuration two from 5.18 to 11.65%. Choosing a compressor with higher efficiency yields to less specific power consumption and hence better exergy efficiency.

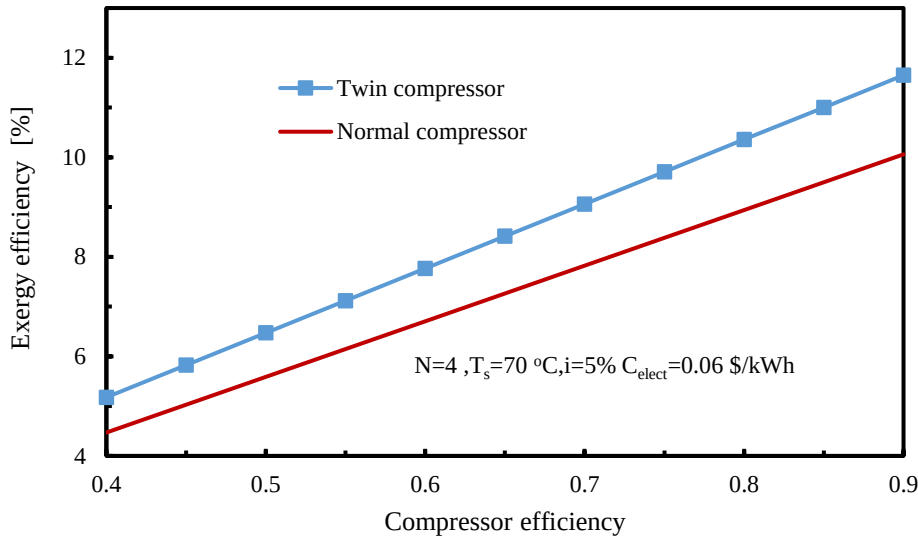


Figure 37: The effect of compressor efficiency on the exergy efficiency FF.

4.3.2 Exergo-Economic analysis:

Similar to the analysis done in Chapter Three, the outcomes of using the exergy-economic equations were presented and discussed in this section. The cost-flow approach was used to compute the product cost using the equations provided. Each stream was viewed as a flowing cost, in the same way as flowing energy and exergy were. Following a thorough examination of each component, the cost of each stream entering or exiting the component was calculated and the results are presented and discussed in Figures (38-44). Figure 38 depicts how the number of affects influences the ultimate product cost. The figure shows that increasing the number of effects from 3 to 8 effects results in a lower final product cost for both setups. This is because, as explained in Figure 33, increasing the number of effects reduces the power requirements in the system, resulting in less cost associated with electricity. It also reduces the size of the compressor, resulting in less capital cost, as seen in the figure, this translates to a cheaper overall product cost. In configuration one, for example, increasing the number of effects from 3 to 8 reduces the final product cost from 7.43 to 4.23 \$/m³, a 43.07% savings. Configuration two, on the other hand, increasing the effects number from 3 to 8 reduces the cost from 4.99 to 3.19 \$/m³.

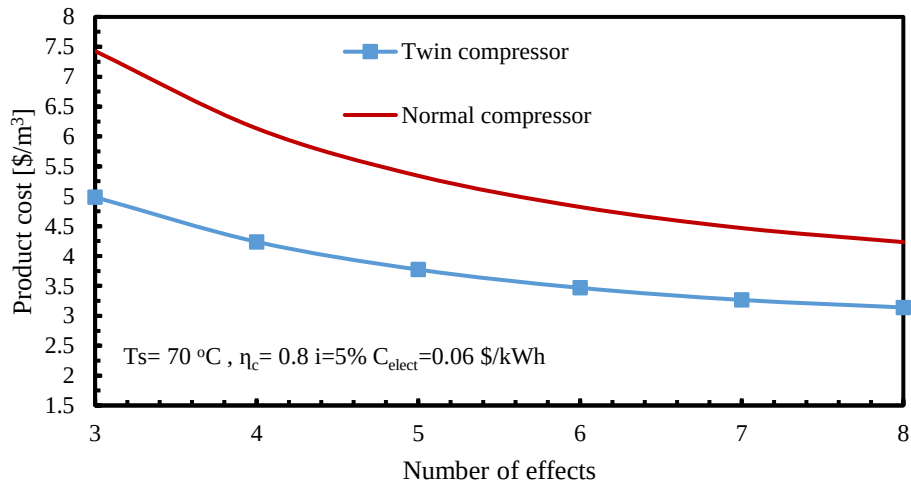


Figure 38: The impact of number of effects on the freshwater production cost FF.

Figure 39 depicts the impact of steam temperature on end product cost in both configurations. The graph shows that increasing the temperature of the steam results in a higher final product cost. The figure also shows that increasing the steam temperature increases the difference in the unit cost of freshwater produced between the two setups. This is best explained by the results in Figure 35, which demonstrate that increasing the steam temperature resulted in higher SPC as well as a larger difference in SPC between the two settings. Increased SPC results in greater power costs and larger compressor size. Raising the steam temperature from 60 to 105 °C increases the freshwater production cost from 3.67 to 31.36 \$/m³ for configuration one while it increases from 2.91 to 9.46 \$/m³.

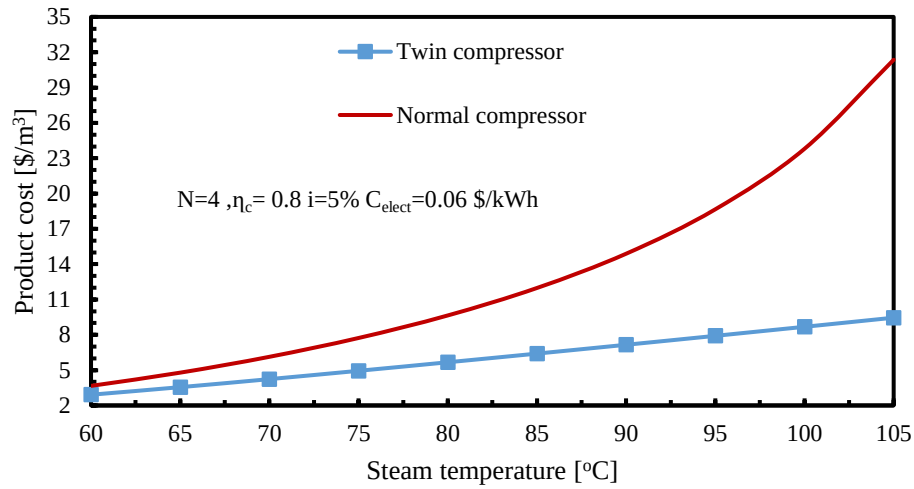


Figure 39: The product cost response to the steam temperature FF.

Figure 40, on the other hand, demonstrates the influence of compressor efficiency on final product cost. Improving compressor efficiency leads to lower final product costs. This is because increased compressor efficiency results in reduced power input and capital costs, as demonstrated by the results in Figure 36, and thus lower final product cost. According to the graph, increasing compressor efficiency from 40 to 90% reduces unit cost from 12.06 to 5.48 \$/m³ for the setup with the conventional compressor. Similarly, for the same conditions, this reduces the product cost for the twin-screw compressor design from 8.29 to 3.79 \$/m³.

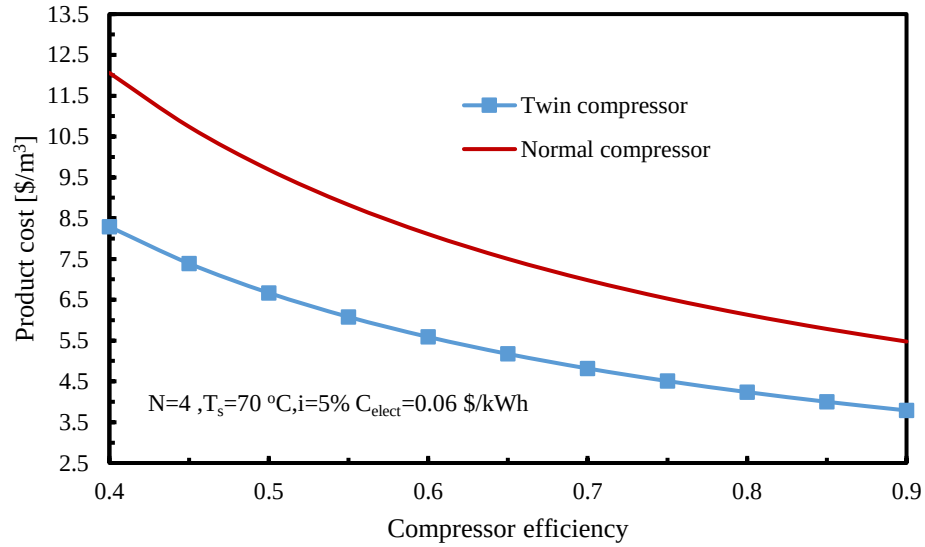


Figure 40: Effect of the compressor efficiency on the product cost FF.

Figure 41 depicts the influence of the electricity price on the final product cost for both configurations for three and six effects under the same conditions. As previously stated, configuration one has a larger specific power usage than configuration two. As seen in Figure 41, greater energy cost result in higher final product cost for the same number of effects. The chart shows that increasing the electricity cost from 0.01 to 0.1 \$/kWh raises the final product cost for configuration one from 3.13 to 11.73 \$/m³ at three effects, while raising the final product cost for configuration two from 1.46 to 7.51 \$/m³ at the same conditions. The figure also shows that increasing the number of effects from 3 to 6 effects lowers the final product costs by 30 and 23 % for configuration one and configuration two, respectively at 0.01 \$/kWh electricity cost. This result shows that the electricity price plays a crucial role in determining whether this technology is economically feasible or not and should be considered when studying different possible locations for applying this technology.

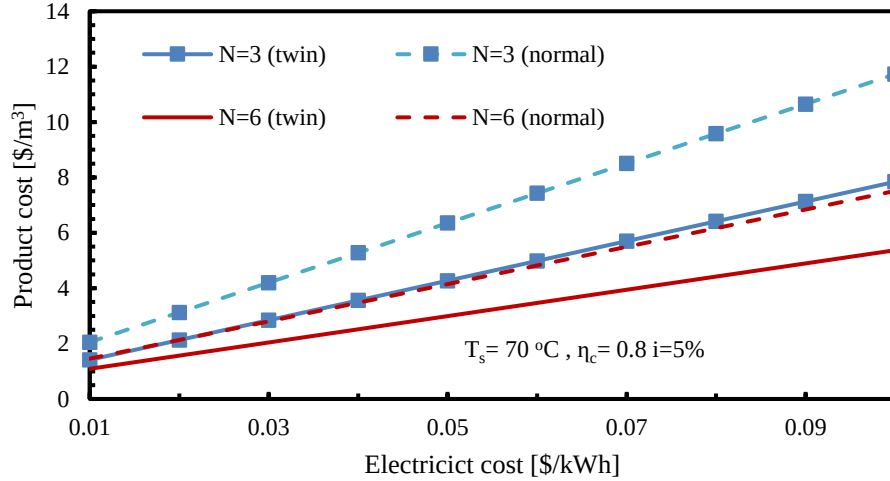


Figure 41: The effect of the electricity cost on the final product cost for different number of effects FF.

Figure 42 depicts the effect of the plant life on the final price of freshwater provided by both setups. The graph indicates that increasing the life expectancy of the system results in lower freshwater prices for both configurations. Extending the plant's life from 15 to 30 years reduces the final product cost for configuration one from 6.4 to 6.07 $\$/\text{m}^3$. Under the same conditions, however, it reduces the end product cost for configuration two from 4.40 to 4.20 $\$/\text{m}^3$. When these results are compared to the data in Figure 41, it can be inferred that the power price has a greater impact on the final product cost than the system's life expectancy.

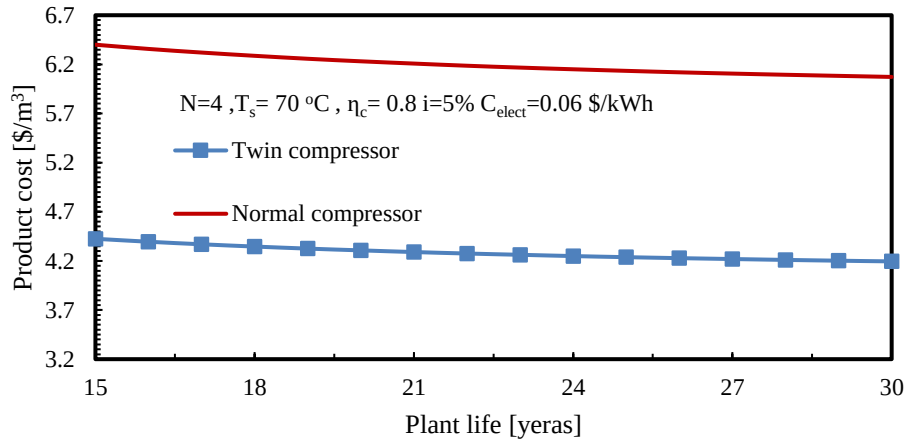


Figure 42: The influence of the plant life expectancy on the product cost FF.

Figure 43 depicts how the interest rate affects the final product cost. The interest rate influences the financial cost of the plant, and thus the end output cost. Raising the interest rate from 1% to 10% raises the end product cost from 5.87 to 6.54 \$/m³ for setup one and from 4.05 to 4.53 \$/m³ for configuration two. These numbers show that the interest rate is a significant factor in term of deciding whether or not to invest in this technology.

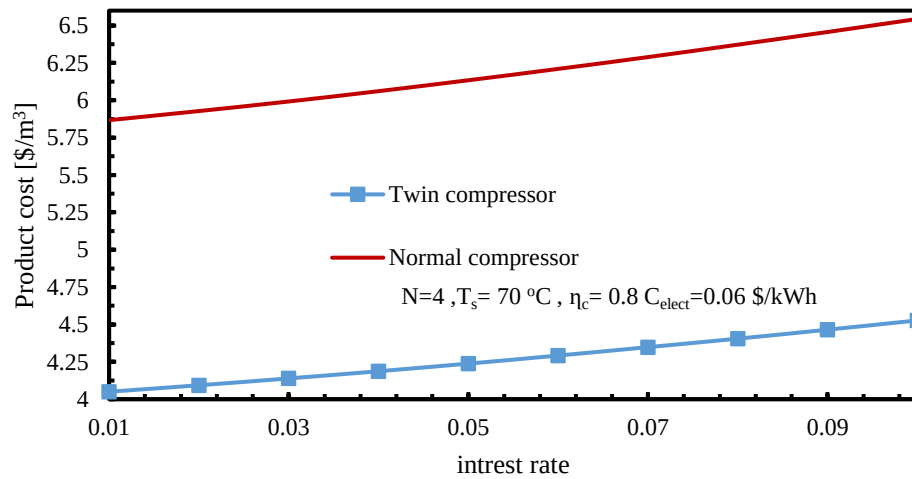


Figure 43: The effect of the interest rate on the product cost FF.

The use of a twin-screw compressor with water injection is intended to reduce power usage and lower final product costs. The pressure of the injected water is a significant aspect that

influences the amount of power reduced in the twin-screw compressor. Figure 44 depicts the influence of injection pressure on particular power consumption, exergy efficiency, and final product cost for 4 number of effects system. According to the graph, raising the pressure at which water is pumped results in a larger specific power consumption. This increase in power demand leads to lower exergy efficiency and higher end product costs. Based on these findings, it can be concluded that water injection should occur at the start of the compression process to ensure the least amount of power consumed, the highest exergy efficiency, and the lowest unit cost of the produced freshwater.

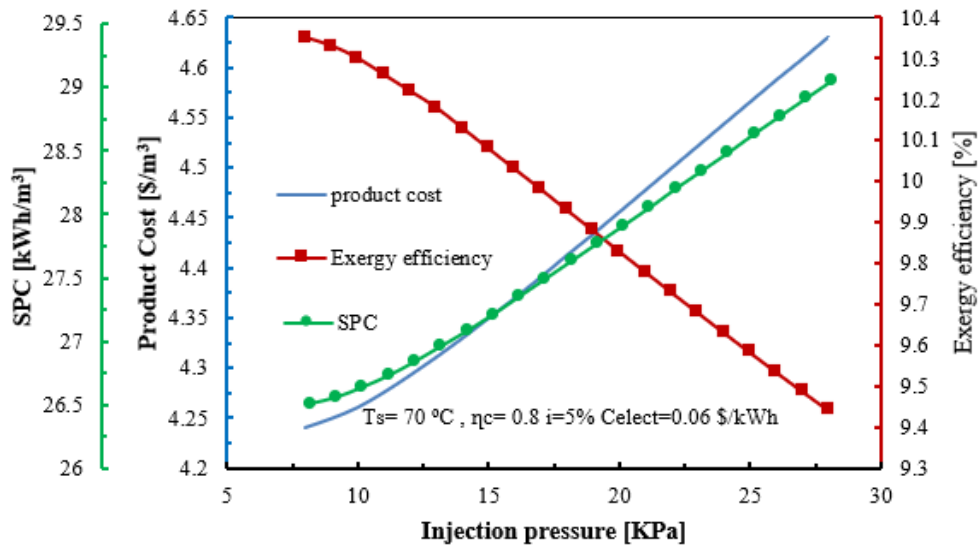


Figure 44: The impact of the injection pressure on the SPC, Exergy efficiency and the product cost FF.

4.3.3 Configurations comparison:

Figure 45 and Figure 46 show a comparison between the two configurations operated by twin-screw compressors in terms of specific power consumption and product cost. The figures show that the PF configuration has a lower specific power consumption compared to the FF configuration which aligns with the results reported in the literature. Figure 45 shows that the PF resulted in lower specific power consumption ranging from 8.1 to 12.2%, while the product cost difference between the two configurations ranges from 20.4 to 24.5%.

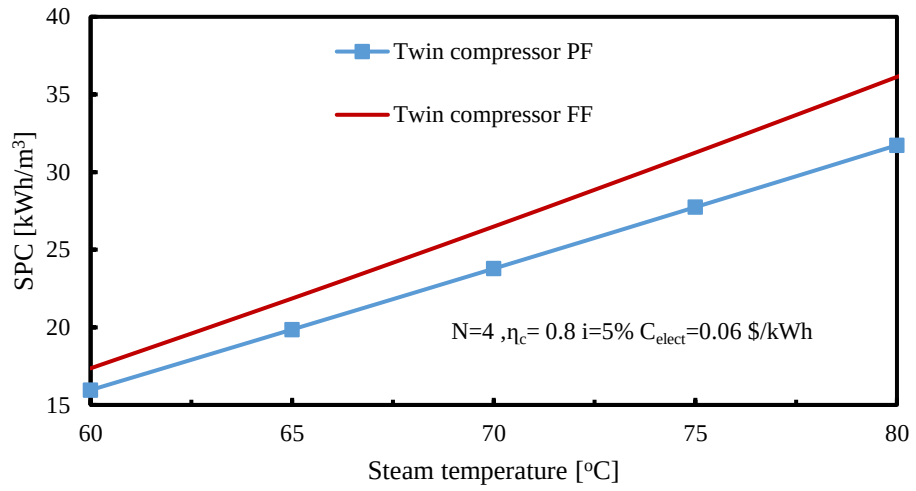


Figure 45: SPC for PF and FF configurations with twin screw compressor.

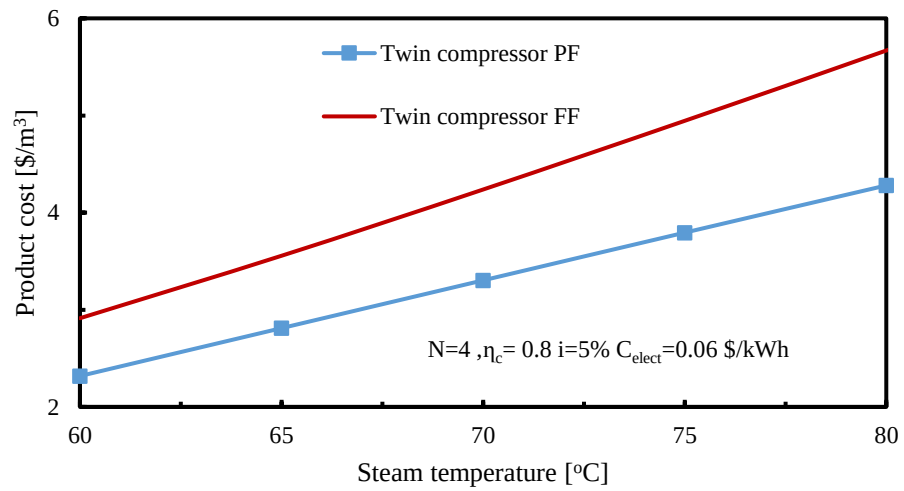


Figure 46: Product cost for PF and FF configurations with twin screw compressor.

CHAPTER 5

CONCLUSION

This chapter serves as a synthesis of the findings from Chapters 1 and 2, encapsulating the identified insights within the realm of MVC technology. Additionally, it encapsulates the outcomes of Chapters 3 and 4, highlighting the enhanced performance of the MED-MVC system when utilizing a twin-screw compressor with water injection in contrast to the conventional compressor. The multi-effect desalination system with a mechanical vapor compressor (MED-MVC) stands as a reliable and versatile technology for freshwater production. It adeptly extracts clean water from various sources, including brackish and seawater, and exhibits potential for applications beyond water scarcity, such as in oil exploration by-product separation. The pivotal component, the compressor, is typically powered by electricity, though studies propose low-grade energy from thermal cycles. Key findings from the MED-MVC research include:

The system driven by a twin-screw compressor in parallel feed configuration demonstrates superior performance compared to the conventional compressor-driven system. Specifically, the twin-screw compressor configuration exhibits an average reduction of 15.28% in Specific Power Consumption (SPC) in comparison to the conventional compressor setup, showcasing the advantages of employing twin-screw compressors in MED systems. However, in the forward feed configuration, the twin-screw compressor setup displayed a 15.5% reduction in SPC.

As for the impact of the number of effects, increasing their count in the PF system yields a notable decrease in SPC, with an average reduction of 15.29% for each additional effect. The system's exergy efficiency also sees improvements, with an 18.97% peak value achieved for an 8-effects configuration. While these values for the FF are 12.83% and 14.49%, respectively.

Further exploration highlights the significant influence of steam temperature on power requirements and exergy destruction. In the PF configuration Higher steam temperatures result in elevated power requirements, averaging an increase of 8.03% per 10°C temperature rise. Additionally, enhancing compressor efficiency proves beneficial to the system's performance, as a 1.11% decrease in SPC is realized for every 1% increase in compressor efficiency. On the other hand, these values for the FF configuration are 9.88% and 1.11% respectively.

Considering economic factors, an increase in the number of effects leads to a decrease in the final product cost, with an average cost reduction of \$0.442 per cubic meter of

freshwater produced for each additional effect in the PF configuration. Conversely, higher steam temperatures correspond to an increased cost of freshwater production, with an average cost rise of \$0.96 per cubic meter for every 10°C temperature increase.

Notably, electricity cost has a more pronounced impact on the produced water price compared to the plant lifespan. Moreover, a higher interest rate contributes to elevated final product costs, with a shift from 1% to 10% interest leading to a 11.4% cost increase for produced water.

Examining injection pressure reveals that injecting cooling water at the start of the compression process results in lower SPC, this approach also increases exergy efficiency and decreases freshwater costs.

Notably, the utilization of two twin compressors significantly reduces power consumption by 23.76% compared to the conventional compressor configuration, and an additional 11.11% reduction compared to a single twin compressor.

The sensitivity analysis highlights efficiency as the dominant factor influencing Specific Power Consumption (SPC), Exergy, and Cost in desalination systems, emphasizing the need for optimization to enhance overall performance. These insights guide the pursuit of more efficient and economically viable desalination technologies.

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1-Shamet, O., & Antar, M. (2023). Mechanical vapor compression desalination technology—A review. *Renewable and Sustainable Energy Reviews*, 187, 113757.

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Conferences:

- 1- Energy and Exergo-Economic Analysis of a Forward Feed Multi-Effect Desalination System Driven by Twin-Screw Compressor with Water Injection
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