

PERFORMANCE PREDICTION FOR MULTI-EFFECT DISTILLATION (MED) PLANTS

By

F.S. GREYVENSTEIN

B.Eng. (NWU)

Dissertation submitted in partial fulfilment of the requirements for the
degree

Master of Engineering

In the School of Nuclear Science and Engineering at the
North-West University
POTCHEFSTROOM



PROMOTER: Dr. B.W Botha

November 2007

TITLE: Performance Prediction for Multi-Effect Distillation (MED) plants

AUTHOR: Fritz Greyvenstein

PROMOTER: Dr B.W. Botha

ABSTRACT

Many countries worldwide experience water shortages on a daily basis and this water crisis is expected to increase even more in the near future due to limited fresh water resources. Alternative sources of fresh water such as desalinated seawater are becoming an attractive option for many developing countries. Although various desalination technologies exist today, interest in multi-effect distillation (MED) is growing rapidly worldwide. Today various energy power sources are utilized in MED plants, but the use of nuclear power as a clean and effective heat source for the MED process seems to be gaining interest. Implementation of HTGR technology, such as the Pebble Bed Modular Reactor being developed in South Africa is ideal for MED desalination purposes. In these types of reactors high temperature water is available as waste heat as opposed to high temperature steam from conventional steam power plants. Currently conventional MED plants utilize steam as the process heat source, to drive the MED process.

In this study a system simulation model was developed in the computer language C++. It evaluates different MED process flow configurations in order to identify an optimum MED plant configuration for both water and steam as process heat source. Simulation results indicate that a steam-heat-source (SHS) MED plant produces approximately 25-30% more product water than a water-heat-source (WHS) MED plant while utilizing less plant stages. Plant layout and economics are impacted by the available process heat source. Results also indicate that a parallel feed configuration (PFC), which incorporates preheating of feed water, seems to be the optimum process flow configuration type for both the SHS and WHS type plants. Product water costs for optimized SHS and WHS MED plants were also compared. Various system parameters influence plant performance, but the serie effect temperature difference seems to be the most influential parameter in terms of water production. Preheating of feed water increases production levels up to 30%. Results from the C++ model have been compared to results calculated with MEE-TVC, a desalination system design program and were generally in good agreement.

Keywords: Desalination, MED, nuclear, PBMR, flow configurations, MED simulation

TITEL: Vertoning Voorspelling vir Multi-Effek Distillasie (MED) aanlegte

OUTEUR: Fritz Greyvenstein

PROMOTOR: Dr B.W. Botha

OPSOMMING

Menigte lande wêreldwyd ervaar daaglik waterdood. Hierdie water krisis word verwag om te groei in die toekoms siende dat varswater bronne beperk is. Alternatiewe bronne van varswater, soos ontsoute seewater, raak al hoe meer aantreklik vir ontwikkelende lande. Alhoewel verskeie ontsoutings tegnologieë bestaan, groei die huidige belangstelling in multi-effek distillasie (MED) wêreldwyd. Huidiglik word verskeie energiebronne aangewend in MED aanlegte, maar die gebruik van kernkrag as 'n skoon en effektiewe hittebron vir die MED proses lok belangstelling. Die implementering van HTGR tegnologie, soos die Korrelbed Modulêre Reaktor (PBMR) wat tans in Suid-Afrika ontwikkel word, is ideaal vir MED ontsoutings doelwitte. In hierdie tipe reaktore is hoë temperatuur water beskikbaar as afval hitte in teenstelling met stoom van konvensionele kernkrag stasies. Huidige MED aanlegte gebruik stoom as die proses hittebron.

In hierdie studie is 'n stelsel simulasiemodel ontwikkel in die rekenaar taal C++. Die model evalueer verskillende MED proses vloei konfigurasies om sodoende 'n optimum MED aanleg, vir beide water en stoom hittebronne, te identifiseer. Simulasie resultate dui aan dat stoom-hitte-bron (SHS) MED aanlegte ongeveer 25-30% meer produk water produseer as 'n water-hitte-bron (WHS) MED aanleg, terwyl minder aanleg effekte gebruik word. Die beskikbare proses hittebron het 'n inwerking op aanleg uitleg en ekonomie. Resultate dui ook aan dat 'n parallele voer konfigurasie (PFC), met voorverhitting van voerwater, die moontlike optimum proses vloei konfigurasie vir beide SHS en WHS tipe aanlegte is. Produk water kostes vir optimeerde SHS en WHS MED aanlegte was ook ondersoek. Verskeie stelsel parameters beïnvloed aanleg vertoning, maar die serie-effek temperatuur verskil lyk die mees invloedrykbare parameter in terme van water produksie. Voerwater voorverhitting verhoog produksie met tot 30%. Resultate met die C++ model is vergelyk met resultate verkry van MEE-TVC, 'n ontsoutings stelsel ontwerp program en stem redelik goed ooreen.

Sleuteltermes: Ontsouting, MED, kernkrag, PBMR, vloei konfigurasies, simulasiemodel

ACKNOWLEDGEMENTS

“If my private world is in order, it will be because I have determined that every day will be for me a day of growth in knowledge and wisdom” – Gordon MacDonald.

Firstly I would like to thank my family for their continual support, love and guidance during this study. They have lovingly helped shape me and continually impart their knowledge and wisdom into my life. You are my inspiration and motivation.

Thank you to the M-Tech Industrial (Pty) Ltd. management who initiated this project and for their continued interest and insights. Especially I also want to thank my study leader, Dr. B. W. Botha, who guided and encouraged me throughout this study and gave editorial suggestions. Thank you to the management of the School of Nuclear Science and Engineering at the North West University for your leadership, guidance and vision regarding future technology.

I would like to thank Prof Hisham Ettouney from Kuwait University and the MEDRC for introducing me to the CAMEL® and MEE-TVC desalination software in order to perform additional system simulations.

Lastly, I would like to thank the Author of Life for allowing me to live on His earth and experience His grace. Without You none of this is possible or worthwhile. Thanks for choosing a wretch and making him a worthy vessel.

“If my private world is in order, it will be because I see myself as Christ’s steward and not as master of my purpose, my role and my identity” – Gordon MacDonald.

TABLE OF CONTENTS

ABSTRACT	ii
OPSOMMING	iii
ACKNOWLEDGEMENTS.....	iv
ABBREVIATIONS	xii
LIST OF VARIABLES.....	xiii
CHAPTER 1 INTRODUCTION	1
1.1 Introduction.....	1
1.2 Background	2
1.3 Problem statement	3
1.4 Objective of study	5
1.5 Outline of study.....	6
CHAPTER 2 LITERATURE STUDY	7
2.1 Introduction.....	7
2.2 MED plant considerations	7
2.2.1 Desalination costs.....	7
2.2.2 Number of effects.....	7
2.2.3 Effect layout and design arrangement.....	8
2.2.4 Optimum process flow configurations.....	9
2.2.5 Temperature range	9
2.2.6 Fouling and material selection.....	10
2.2.7 Coupling scheme and process heat source.....	11
2.3 Alternative MED energy sources	11
2.3.1 Geothermal desalination	12
2.3.2 Solar desalination	12
2.3.3 Fossil fuel desalination.....	13
2.3.4 Nuclear desalination	13
2.4 Current and previous MED developments	14
2.5 Economic evaluation of nuclear desalination systems	17
2.6 Previous work on MED modelling	18
2.7 Conclusion.....	20

CHAPTER 3	THEORETICAL BACKGROUND.....	22
3.1	Introduction.....	22
3.2	Principle of operation.....	22
3.3	Performance indices.....	25
3.4	Factors impacting the plant performance.....	26
3.5	Nature of process heat source.....	28
3.5.1	Heat source assumptions.....	32
3.6	Cost considerations.....	34
3.7	Conclusion.....	35
CHAPTER 4	MED PROCESS CONFIGURATIONS	36
4.1	Introduction.....	36
4.2	MED process configurations.....	36
4.2.1	Forward feed configuration (FFC).....	36
4.2.2	Backward feed configuration (BFC).....	38
4.2.3	Parallel feed configuration (PFC).....	39
4.3	MED brine utilization.....	41
4.4	MED feed water preheating.....	41
4.5	MED configurations characteristics.....	43
4.5.1	Configuration advantages.....	43
4.5.2	Configuration disadvantages.....	43
4.6	Conclusion.....	44
CHAPTER 5	MED PLANT PERFORMANCE PREDICTION.....	45
5.1	Introduction.....	45
5.2	MED analysis model.....	45
5.2.1	C++ Model overview.....	46
5.3	MED model validation study.....	50
5.4	Conclusion.....	55
CHAPTER 6	INVESTIGATION STUDIES.....	56
6.1	Introduction.....	56
6.2	Nature of heat source evaluation.....	56
6.2.1	System input parameters.....	56
6.2.2	System configuration.....	57

6.2.3	Preliminary system results	58
6.2.4	Preliminary system observations.....	59
6.3	Varying serie-effect temperature difference	60
6.4	Varying parallel-circuit temperature difference.....	65
6.5	Varying inlet feed water temperature	68
6.6	Varying exit steam temperature in last serie effect.....	69
6.7	Varying product ratio.....	72
6.8	Optimized MED plant configuration.....	74
6.9	Conclusion.....	80
CHAPTER 7	CONCLUSION AND RECOMMENDATIONS	81
7.1	Summary	81
7.2	Conclusion of study	82
7.3	Recommendations for further studies	83
REFERENCES	85
Appendix A	MEE program description.....	A-1
A.1	Validation Test Case 1 system results	A-6
Appendix B	MED plant cost	B-1
Appendix C	MED model configuration layouts.....	C-1

TABLE OF FIGURES

Figure 1-1: A three stage MED process layout [courtesy of DESWARE, 2007].	3
Figure 2-1: MED plant with horizontal tubes	8
Figure 2-2: Scaled tubes in a distillation plant (left) and an LT-MED plant (right)	11
Figure 2-3: A 2-unit MED plant (total capacity 35 000 m ³ /day), [Ophir, 2005:197]	14
Figure 3-1: MED unit sections	22
Figure 3-2: Preheating and partial evaporation of a stream of water	22
Figure 3-3: Preheating and partial evaporation of water on a T-S diagram	23
Figure 3-4: Thermodynamic process inside each effect	24
Figure 3-5: Counter flow arrangement in pipe	27
Figure 3-6: System with pinching (left) and no temperature pinching (right)	28
Figure 3-7: Condensation of 1kg steam	29
Figure 3-8: MED plant layout utilizing steam as heat source (SHS)	30
Figure 3-9: Heating water temperature profile	31
Figure 3-10: MED plant layout utilizing water as heat source (WHS)	32
Figure 3-11: MED plant layout utilizing water as heat source	33
Figure 4-1: Forward Feed Configuration (FFC) schematic illustration	36
Figure 4-2: Forward Feed Configuration (FFC) process flow diagram	37
Figure 4-3: T-S Diagram for the FFC	37
Figure 4-4: Backward Feed Configuration (BFC) process flow diagram	38
Figure 4-5: T-S Diagram for the BFC	39
Figure 4-6: Parallel Feed Configuration (PFC) schematic illustration	39
Figure 4-7: Parallel Feed Configuration (PFC) process flow diagram	40
Figure 4-8: T-S Diagram for the PFC	40
Figure 4-9: Example of preheating in the PFC	42
Figure 5-1: Mass balance of a FFC effect	47
Figure 5-2: Mass balance of a BFC effect	48
Figure 5-3: Mass balance of a PFC effect	48
Figure 5-4: Test case 1 – C++ model SHS plant (without preheating) layout	52
Figure 5-5: Test case 1 – MEE-TVC SHS plant (without preheating) layout	52
Figure 5-6: Test case 1 - Brine saturation temperature comparison	54
Figure 5-7: Test case 1 - Brine saturation pressure comparison	54
Figure 5-8: Test case 1 – Serie effect temperature differences comparison	55
Figure 6-1: Case Study 1: SHS plant layout	57
Figure 6-2: Case Study 1: WHS plant layout	57
Figure 6-3: Brine temperature distribution in FFC (SHS) MED plant	58
Figure 6-4: Brine pressure distribution in FFC (SHS) MED plant	58

Figure 6-5: Case study 2: Comparison of product capacities in SHS mode.....	61
Figure 6-6: Case study 2: Comparison of product capacities in SHS mode.....	61
Figure 6-7: Case study 2: Comparison of product capacities in WHS mode.....	62
Figure 6-8: Case study 2: Comparison of product capacities in WHS mode.....	62
Figure 6-9: Case study 2: Gained Output Ratios for SHS plant.....	62
Figure 6-10: Case study 2: Gained output ratio vs plant capacity (SHS).....	63
Figure 6-11: Case study 2: Relative performance ratios in SHS mode.....	63
Figure 6-12: Case study 2: Relative performance ratios in WHS mode.....	64
Figure 6-13: Case study 2: AU-values for water-to-steam effects/HX (WHS).....	64
Figure 6-14: Case study 2: Comparison of AU-values for pre-heaters (WHS).....	65
Figure 6-15: Case study 3: Product capacities in SHS mode.....	65
Figure 6-16: Case study 3: Product capacities in SHS mode.....	66
Figure 6-17: Case study 3: Comparison of product capacities in WHS mode.....	66
Figure 6-18: Case study 3: Comparison of product capacities in WHS mode.....	66
Figure 6-19: Case study 3: Relative performance ratios in SHS mode.....	67
Figure 6-20: Case study 3: Relative performance ratios in WHS mode.....	67
Figure 6-21: Case study 3: AU-values for water-to-steam effects/HX (WHS).....	67
Figure 6-22: Case study 3: Comparison of AU-values for pre-heaters (WHS).....	68
Figure 6-23: Case study 4: AU-values for water-to-steam effects in WHS-mode.....	69
Figure 6-24: Case study 4: Comparison of AU-values for pre-heaters (WHS).....	69
Figure 6-25: Case study 5: Comparison of product capacities in SHS mode.....	70
Figure 6-26: Case study 5: Comparison of product capacities in SHS mode.....	70
Figure 6-27: Case study 5: Comparison of product capacities in WHS mode.....	70
Figure 6-28: Case study 5: Comparison of product capacities in WHS mode.....	71
Figure 6-29: Case study 5: Relative performance ratios in SHS mode.....	71
Figure 6-30: Case study 5: Relative performance ratios in WHS mode.....	71
Figure 6-31: Case study 5: AU-values for water-to-steam effects in WHS mode.....	72
Figure 6-32: Case study 5: AU-values for pre-heaters (WHS).....	72
Figure 6-33: Case study 6: Plant product capacities in SHS mode.....	73
Figure 6-34: Case study 6: Plant product capacities in WHS mode.....	73
Figure 6-35: Case study 6: Relative performance ratios in SHS mode.....	73
Figure 6-36: Case study 6: Relative performance ratios in WHS mode.....	74
Figure 6-37: Case study 6: AU-values for water-to-steam effects (WHS).....	74
Figure 6-38: Optimized SHS plant.....	76
Figure 6-39: MED plant costs for different size SHS plants.....	77
Figure 6-40: MED plant costs for different size WHS plants.....	77
Figure 6-41: Optimized SHS saturated brine plant data.....	78

Figure 6-42: Optimized WHS plant.....	79
---------------------------------------	----

TABLE OF FIGURES – APPENDIX A

Figure A-1: Schematic of MEE stand-alone layout	A-1
Figure A-2: Schematic of MEE thermal vapour compression (TVC) layout.....	A-2
Figure A-3: Steam jet ejector including suction chamber, nozzle and throat.....	A-2
Figure A-4: Evaporator layout including shell, tube bundle and spray nozzles	A-3
Figure A-5: MEE-TVC Design data input sheet	A-4
Figure A-6: MEE-TVC System results	A-5
Figure A-7: Test Case 1 system input data	A-6
Figure A-8: Test Case 1 system results (1)	A-7
Figure A-9: Test Case 1 system results (2)	A-8
Figure A-10: Test Case 1 system profile	A-9

TABLE OF FIGURES – APPENDIX C

Figure C-1: Analysis model of FFC layout.....	C-2
Figure C-2: Analysis model of BFC layout.....	C-3
Figure C-3: Analysis model of PFC layout.....	C-4

TABLES

Table 5-1: MED model definitions	45
Table 5-2: Model input parameters.....	46
Table 5-3: Test case 1 – C++ model evaluation system parameters	51
Table 5-4: Test case 1 – MEE-TVC system parameters.....	53
Table 5-5: Test case 1 – Validation comparison.....	53
Table 6-1: System input parameter assumptions for Case Study 1	56
Table 6-2: Production capacity levels (Case Study 1, FFC).....	59
Table 6-3: Production capacity levels (Case Study 1, BFC)	59
Table 6-4: Production capacity levels (Case Study 1, PFC)	59
Table 6-5: System parameters for the different plant performance analyses	60
Table 6-6: Optimized PFC-MED plant specifications	75
Table 6-7: Optimized PFC-MED plant costs.....	77

ABBREVIATIONS

This list contains the abbreviations as used in this study.

Abbreviation	Definition
AHPAM	<i>Absorption Heat Pump Analysis Model</i>
BFC	<i>Backward Feed Configuration</i>
BOC	<i>Beginning of Cycle</i>
BPE	<i>Boiling Point Elevation</i>
CAMEL	<i>Calculation by modular elements</i>
CC	<i>Combined Cycle</i>
CPC	<i>Compound Parabolic Concentrator</i>
DEAHP	<i>Double Effect Absorption Heat Pump</i>
DEEP	<i>Desalination Economic Evaluation Program</i>
DPPDP	<i>Dual Purpose Power and Desalination Plant</i>
EES	<i>Engineering Equation Solver</i>
EOC	<i>End of Cycle</i>
FF0	<i>Forward Feed Configuration without preheating</i>
FF1	<i>Forward Feed Configuration with preheating</i>
FFC	<i>Forward Feed Configuration</i>
GT	<i>Gas Turbine</i>
GT-MHR	<i>Gas Turbine Modular Helium Reactor</i>
GOR	<i>Gained Output Ratio</i>
HTGR	<i>High Temperature Gas cooled Reactor</i>
HTME	<i>Horizontal Tube Multiple Evaporator</i>
HT-MED	<i>High Temperature Multiple Effect Distillation</i>
HTTF	<i>Horizontal Tube Thin Film</i>
HX	<i>Heat Exchanger</i>
IAEA	<i>International Atomic Energy Agency</i>
KAERI	<i>Korea Atomic Energy Research Institute</i>
LT-MED	<i>Low Temperature Multiple Effect Distillation</i>
LWR	<i>Light Water Reactors</i>
MBT	<i>Maximum Brine Temperature</i>
MED	<i>Multi Effect Distillation</i>
MEDAM	<i>Multi Effect Distillation Analysis Model</i>
MEDRC	<i>Middle East Desalination Research Centre</i>
MEE-TVC	<i>Multiple Effect Evaporation Thermal Vapour Compression</i>
MSF	<i>Multi Stage Flash</i>
MW	<i>Mega Watt</i>
NHR	<i>Nuclear Heating Reactor</i>
PBMR	<i>Pebble Bed Modular Reactor</i>
PCU	<i>Power Conversion Unit</i>
PF0	<i>Parallel Feed Configuration without preheating</i>

PF1	<i>Parallel Feed Configuration with preheating</i>
PFC	<i>Parallel Feed Configuration</i>
PPM	<i>Parts per million</i>
PSA	<i>Platforma Solar de Almería</i>
PWR	<i>Pressurized Water Reactor</i>
RO	<i>Reverse Osmosis</i>
SHS	<i>Steam Heat Source</i>
SMART	<i>System-integrated Modular Advanced Reactor</i>
TBT	<i>Top Brine Temperature</i>
TVC	<i>Thermal Vapour Compression</i>
UA	<i>Overall heat transfer coefficient</i>
VC	<i>Vapour Compression</i>
WHS	<i>Water Heat Source</i>

LIST OF VARIABLES

This list contains the variables as used in this study.

α	-	<i>Relative Performance Ratio</i>
A	$[m^2]$	<i>Heat transfer area</i>
C_{ca}	$[\$]$	<i>Annual capital worth</i>
C_{cp}	$[\$]$	<i>Present capital worth</i>
C_{p_c}	$[kJ.kg/k]$	<i>Specific heat capacity of the cold fluid</i>
C_{p_h}	$[kJ.kg/k]$	<i>Specific heat capacity of the hot fluid</i>
cpw	$[kJ/kg.K]$	<i>The specific heat capacity of heating medium</i>
CRF	-	<i>Capital recovery factor</i>
D_i	$[m]$	<i>Pipe inlet diameter</i>
D_o	$[m]$	<i>Pipe outlet diameter</i>
h_f	$[kJ/kg]$	<i>Saturated liquid enthalpy</i>
h_{ff}	$[kJ/kg]$	<i>Fluid enthalpy at 10°C below t_1</i>
h_g	$[kJ/kg]$	<i>Saturated Vapour enthalpy</i>
h_i	$[kJ/kg]$	<i>Enthalpy at exit of i^{th} effect</i>
h_{in}	$[kJ/kg]$	<i>Inlet enthalpy for each effect/stage</i>
LF	-	<i>Load factor</i>
m_c	$[kg/s]$	<i>Mass flow of cold fluid</i>
m_h	$[kg/s]$	<i>Mass flow of hot fluid</i>
mm_i	$[kg/s]$	<i>Feed water mass flow in the i^{th} effect.</i>
m_{pp}	$[kg/s]$	<i>Total product flow</i>
MS	$[kg/s]$	<i>Equivalent heating steam mass flow</i>
ms_i	$[kg/s]$	<i>Steam mass flow generated in the $(i-1)^{th}$ effect.</i>
MW	$[kg/s]$	<i>Heating water flow rate</i>
mw_i	$[kg/s]$	<i>Waste mass flow generated in the i^{th} effect</i>
N_1	-	<i>Number of effects in serie</i>
N_2	-	<i>Number of parallel circuits</i>

N_{sum}	-	Total number of effects in given MED plant configuration
P_{avg}	$[m^3]$	Annual average production rate
p_i	$[Pa]$	Pressure at exit of i^{th} effect
P_N	$[m^3/d]$	Nominal production rate
PR	-	Product ratio
Q	$[W]$	Heat transfer rate
q_1	$[W]$	Driving heat required for a mass flow of 1 kg/s in 1 st effect. It is the total heat needed to pre-heat and evaporate the water.
qh	$[W]$	Heat available to drive the circuit
qr	$[W]$	Heat recovered from product streams
r_s	-	Ratio of heat available to heat required for evaporation of 1kg feed water, when SHS is used.
r_w	-	Ratio of heat available to heat required for evaporation of 1kg feed water, when WHS is used.
ΔT_1	$[^\circ C]$	Temperature difference across each effect
ΔT_2	$[^\circ C]$	Temperature difference in each parallel circuit
ΔT_{pinch}	$[^\circ C]$	Temperature difference allowed for pinching in the HX
t_i	$[^\circ C]$	Temperature at exit of i^{th} effect
T_{in}	$[^\circ C]$	Temperature of feed water at the inlet of 1 st effect.
T_{ci}	$[^\circ C]$	Cold fluid inlet temperature
T_{co}	$[^\circ C]$	Cold fluid outlet temperature
T_{feed}	$[^\circ C]$	The inlet feed water temperature
T_{hi}	$[^\circ C]$	Hot fluid inlet temperature
T_{ho}	$[^\circ C]$	Hot fluid outlet temperature
T_{max}	$[^\circ C]$	Maximum available heat source temperature
T_{min1}	$[^\circ C]$	Exit steam temperature in last effect.
T_{min2}	$[^\circ C]$	Temperature at the exit of last parallel circuit
U	$[W/m^2-k]$	Overall heat transfer coefficient
x_i	-	Quality at exit of effect. Indicates the amount of evaporation.

Chapter 1

Introduction

"The whole of science is nothing more than a refinement of everyday thinking." - Albert Einstein.

"Any darn fool can make something complex; it takes a genius to make something simple." - Pete Seeger

CHAPTER 1 INTRODUCTION

1.1 Introduction

Seventy percent of the planet is covered with water, but only 2.5% of that is fresh water. Nearly 70% of this fresh water is frozen in the icecaps of Antarctica and Greenland [WATERAID, 2007]. Fresh water resources are poorly distributed across the globe since the majority of fresh water is contained in the ice-caps and in the unreachable rivers of the world. Uneven rainfall leads to devastating floods in some regions while arid conditions may remain for several years in other countries. Less than 0.08% of the world's water is thus readily accessible for direct human use. Many regions of the world already face water shortages and many others are expected to experience the same water crisis in the near future. It is estimated that by 2025 about two thirds of the world population will be lacking access to clean water [Colak, 2005:427]. This predicted situation could become more problematic with rising population growth, uncertainties in fossil fuel supplies, escalating energy prices and growing concern over carbon emissions and global warming.

Currently about 2.3 billion people live in water-stressed areas and among them 1.7 billion [Misra, 2004:1] live in water-scarce areas where the water availability per person is less than 1000 m³/year [Ingersoll, 2004:1]. Water shortage is a global issue and every year new countries are affected by growing water problems. Possible solutions to these water stress levels include better water conservation, water management and pollution control. To meet this ever-increasing demand for fresh water, desalination offers one of the most promising alternatives for the required supply of potable water in many countries. This is because seawater is the biggest source of water available and can be considered as unlimited when compared with all natural fresh water resources. In addition to this, seawater can be considered a relatively unpolluted source of water.

With the removal of salinity, seawater can become an immense water resource and provide a possible solution to this growing water crisis. Many countries will have an increased dependency on alternative sources of water which include seawater desalination. Certain regions of the world already use seawater as a dependable resource to produce drinkable water. Desalination technologies have been well established since the mid 20th century and are widely deployed in the Middle East and North Africa. Today more than 17 000 plants with various capacities produce more than 37 million m³/day of drinkable water worldwide. These plants mainly utilize

fossil fuel energy sources such as coal, oil and natural gas [IAEA, 2000a:25]. Different desalination technologies have been developed and are either based on evaporation and condensation or are membrane technologies. In either case the desalination process is an energy intensive process and it must be supplied with a clean and effective energy source [Colak, 2005:428]. Various energy sources are utilized in desalination plants today, but interest in using nuclear energy for producing drinkable water has been growing worldwide in the past decade. This has been motivated by a wide variety of reasons such as economic competitiveness of nuclear energy to energy supply diversification, from conservation of limited fossil fuel resources to environmental protection.

1.2 Background

Commercial seawater desalination processes that are proven and reliable for large scale freshwater production includes multi-stage flash (MSF) and multi-effect distillation (MED) for evaporative desalination and reverse osmosis (RO) for membrane desalination. Vapour compression (VC) plants based on thermal and mechanical vapour compression are also employed for small and medium capacity ranges. These processes have their respective advantages and disadvantages. The selection of a particular desalination process depends on the saline feed water quality, product water quality requirement, reactor type (heat source availability) and process economics. Thermal desalination plants provide pure water that is directly usable for industrial process applications whereas RO plants provide drinking quality water [Colak, 2005:428]. The advantages of MSF plants are a high quality distillate and a long operating history with easy operation, but high quality materials are needed and MSF is generally not suited for a single purpose plant. Reverse osmosis plants require lower capital costs than thermal processes and are more flexible due to variable sizes and modules, but requires pre-treatment of feed-water and leads to short membrane lifetimes [IAEA, 2000a:32].

Studies conducted by the IAEA with the code DEEP in 2002 suggests that desalination water product costs range from 0.40 \$/m³ to about 1.90 \$/m³ depending on the water plant type and size, energy source, specific regions and economic scenarios. Water production costs from MSF appear to be higher than those from RO or MED. Capital costs for MSF range from \$1000- \$3000 per m³/d, for MED \$900 - \$2000 per m³/d and for RO \$900 - \$1700 per m³/d capacity. The advantages of MED plants are fast start-up and shutdown with low power consumption. MED has a short operation history, but it is superior to MSF plants in terms of evaporation process

efficiency mainly because of higher heat transfer coefficients. Distillation is the process with the largest installed capacity in the world - almost two-thirds of the world's capacity. Saline water is heated to produce water vapour that is then condensed to form fresh water. For a desalination plant to be economical the boiling point is controlled by adjusting the atmospheric pressure of the water being boiled. As the ambient pressure above the water decreases it leads to a reduction in the water boiling temperature. Reduction of the boiling point is important in the desalination process for two major reasons namely multiple boiling and scale control. To significantly reduce the amount of energy needed for vaporization the distillation desalting process usually utilizes multiple boiling points in successive vessels each operating at a lower temperature and pressure [DESWARE, 2007].

1.3 Problem statement

Conventional MED plants utilize steam as a process heat source to produce clean water in a desalination plant, consisting of a number of stages (effects) in serie. Many options are available today for generating the steam for conventional MED plants and this steam heat source is usually generated in the boilers of fossil-fired type steam power stations. Nuclear power could also be harnessed to generate steam, cleanly, in Generation II and III type reactors, whether by means of a single-purpose heating nuclear reactor or by a dual-purpose nuclear plant (water and electricity production).

In Figure 1-1 a three stage MED process layout utilizing steam as external heat source is illustrated. In a conventional MED plant the seawater enters the first effect and is raised to the boiling point after being preheated in tubes. Seawater is either sprayed or otherwise distributed onto the surface of evaporator tubes in a thin film to encourage rapid boiling and evaporation. Steam, supplied from a boiler, heats the tubes and is then condensed on the opposite sides of the tubes while the condensate from the boiler steam is recycled to the boiler for reuse [DESWARE, 2007].

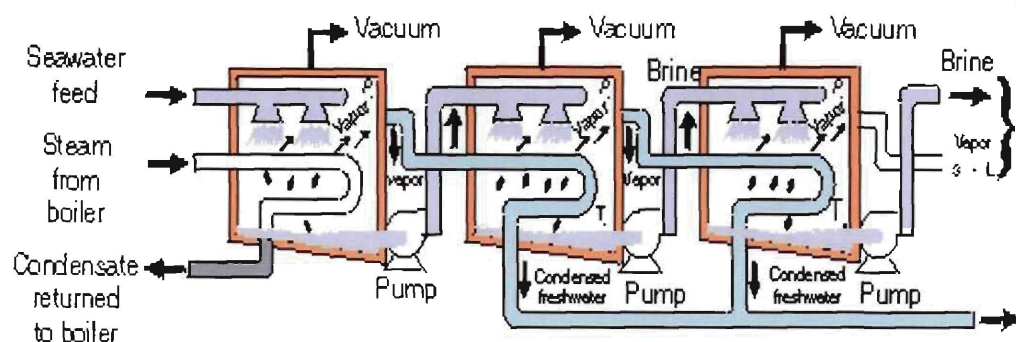


Figure 1-1: A three stage MED process layout [courtesy of DESWARE, 2007].

Only a portion of the seawater applied to the tubes in the first effect is evaporated. The remaining feed water is collected and fed to the second effect where it is again applied to a tube bundle. These tubes are in turn being heated by the vapour created in the preceding effect. This vapour is condensed to form fresh water product while giving up heat to evaporate a portion of the remaining seawater feed in the next effect. This continues for several effects with 8 or 16 effects found in a typical large plant. Usually the remaining seawater in each effect must be pumped to the next effect so as to apply it to the next tube bundle. Additional condensation takes place in each effect on the tubes that transport the feed water from its source through the plant to the first effect. Pre-heating of feed water occurs before it is evaporated in the first effect.

Generation IV type reactors, such as the Pebble Bed Modular Reactor (PBMR), which is currently being developed in South Africa, could also provide a clean source of energy to drive the MED process. The PBMR is a helium-cooled, graphite-moderated High Temperature Reactor (HTR). Helium is used as the coolant and energy transfer medium to a closed cycle gas turbine and generator system. To remove the heat generated in the core, helium flows to the reactor vessel at a temperature of 500°C and a pressure of 90 bars. It then moves down between the hot fuel spheres, after which it leaves the bottom of the vessel having been heated to a temperature of about 900°C. The hot gas then enters the first of three gas turbines in a series, the first two of which drive compressors and the third of which drives the electrical generator. The coolant leaves the last turbine, after which it is cooled, recompressed, reheated and returned to the reactor vessel. The process cycle used is a standard Brayton cycle with a closed circuit water-cooled inter-cooler and pre-cooler. This cycle consists of two water-cooled heat exchangers (pre-cooler and intercooler), which have gas inlet temperatures of 159°C and 119°C respectively. By changing the heat exchanger size and water flow rates, a water outlet of 220 MW with a temperature of 80-90°C is possible with minor impact on the electrical output. The PBMR thus leads to a good desalination product, but water as waste heat is now available instead of a steam heat source. Having this free waste heat source, the option of using high temperature process water in a MED plant needs to be investigated. However, when water is available as process heat source, such as in High Temperature Gas-cooled Reactor (HTGR) nuclear power plants, the MED plant design differs from conventional MED plants due to the nature of the heat source.

The economics of a desalination process is impacted by various factors such as the number of plant effects, desalination costs, process flow configurations and the temperature range of operation. These factors should be evaluated individually and as part of an integrated system in order to gain understanding into the performance of desalination and the impact of different parameters on system design. Economic aspects such as water production rates, capital cost and water specific cost play a major role in decision making. Overall safety, product water quality, the power-to-water ratio and operational flexibility and availability of a desalination plant are crucial factors. These factors also influence the choice of reactor type and coupling technique used in the plant.

Research and development (R&D) in modern-day desalination designs tend to focus on optimizing the number of effects (stages) which determines the plant efficiency (performance ratio) and plant cost. Practical operating temperature ranges determine both the size of components, such as the heat exchangers, as well as the amount of scale control needed. Stage layout (horizontal or vertical tubes) determines the material cost and plant capacity whereas fouling and material selection plays a role in the plant specific performance.

Based on the above mentioned R&D activities, it can be seen that simulation models are needed to evaluate and simulate MED plant parameters. Development of generic tools, which determine the temperature and pressure of the brine and product streams in the MED plant, is needed to optimize and determine MED desalination plant capacities. Currently there are limited system simulation tools available which allow the use of water and steam as process heat sources. However, these tools are usually only available for commercial simulation purposes. The modelling and simulation of a MED desalination unit will lead to a greater understanding and personal knowledge of MED desalination technology for further local development. These tools will be helpful in selecting the number of stages needed and sizing of the plant components as well as investigating the impact of different process heat sources and flow configurations on MED plant design.

1.4 Objective of study

The objective of this study is to develop a system simulation model that will be able to predict the impact of different design parameters and process layouts on the performance of the plant. This model will be used for optimizing the plant design.

1.5 Outline of study

In Chapter 2 an extensive literature survey is documented which includes a look at alternative energy sources employed in MED desalination plants today, current and previous MED plant development, economic evaluations of nuclear desalination systems as well as previous work done on the modelling and simulation of MED plants. Chapter 3 indicates the fundamental thermodynamic process which occurs inside each effect in order to show which system parameters influence system efficiency. The impact of external heat sources on plant layout, cost and efficiency are also shown in order to gain understanding into MED system performance.

Different practical MED process flow configurations are identified in Chapter 4 which could be utilized to produce drinking water in actual plants. Each flow configuration is discussed according to operation, layout motivation and characteristics. The option of preheating in MED plants is also proposed. Chapter 5 introduces the simulation model and model validations in order to perform different investigation studies in Chapter 6. Fixed system parameters are used in Chapter 6 to evaluate product capacities of the different process flow configurations when steam and water is used as external heat source. The effect on plant product capacity is shown when preheating is incorporated. System parameters are then varied to perform system simulations of all the different process flow configurations in order to evaluate the sensitivity of different system parameters on plant performance. This allows the identification of an optimized MED plant configuration.

In Chapter 7 recommendations are made, conclusions are drawn and future work is mentioned.

Chapter 2

Literature Study

"I believe that every right implies a responsibility; every opportunity, an obligation; every possession, a duty." John D. Rockefeller, Jr.

"Smooth seas do not make skilful sailors." - African Proverb

CHAPTER 2 LITERATURE STUDY

2.1 Introduction

A number of technologies has been associated with MED desalination and are largely related to the increased desalination system efficiency, practical conditions in countries and the choice of the energy source for the process. Firstly the aim of this chapter is to provide an overview of alternative MED process energy sources utilized in desalination plants today. Secondly the aim of this chapter is to provide an overview of past and current operating experiences with MED desalination and design approaches followed. Models are very useful and efficient tools for investigating system performance over a wide range of operating conditions as well as evaluating the performance of existing plants. Thirdly the aim of this chapter is to provide information on previous work done on MED modelling.

2.2 MED plant considerations

Various factors influence the choice for a suitable desalination process and it requires understanding of the processes, knowledge of the interaction effects and an approach to optimal integration. Some factors to consider during the design phase of a MED desalination plant are (according to [IAEA, 2000a:75-106]):

2.2.1 Desalination costs

One of the most important factors influencing the choice for a suitable desalination process is process economics. There should be a balance between costs and benefits. The costs depend on the capacity and type of plant, the region, the quality of raw and product water and capital and labor costs [Faibish, 2003:244]. Cost comparisons of current desalination plants have been conducted with DEEP and found that desalination costs are currently declining worldwide [IAEA, 2000b, 14-17].

2.2.2 Number of effects

For conventional MED the Gained Output Ratio (GOR) is the ratio of the mass of potable water generated to the mass of steam consumed. The energy efficiency of the MED plant can be increased by increasing the number of effects and increasing the heat transfer area [Methnani, 2007]. In the ideal limit where each effect evaporates a mass of steam equal to the mass condensed, the GOR value approaches the number of effects. However, as the number of effects increase, the total heat exchanger surface area required increases as well. Plant production capacities also increase with increasing number of effects. The capital cost of MED systems is proportional to the total heat exchanger area. Thus the optimal number of

stages depends upon the relative cost of energy to generate steam versus capital cost of the heat exchanging equipment. As the cost of energy increases, the optimal value of the GOR also increases. The choice for the optimal amount of MED plant effects becomes a trade-off between product capacity and capital cost.

2.2.3 Effect layout and design arrangement

MED plants are built in *vertical tube* or *horizontal tube* arrangements. The main differences are in the arrangement of the evaporation tubes, the side on which evaporation takes place and the materials used for the evaporation tubes.

In the Vertical Tube Evaporator (VTE) the seawater boils in a thin film flowing inside the tubes and steam condenses on the heat transfer tubes. VTE processes include falling film evaporators, rising film evaporators and evaporators with forced and natural circulation. A significant improvement in heat transfer is achieved by using double fluted tubes to extend the surface and reduce the film thickness. Normally several effects are used in series along the direction of vapour flow in a desalination plant [Ophir, 2005:190].



Figure 2-1: MED plant with horizontal tubes

In the Horizontal Tube Thin Film (HTTF) evaporator the seawater feed is sprayed onto the outer surface of the tubes and vapour flows inside the horizontal tubes where it condenses and supplies product water. The advantage is that the overall heat transfer coefficient is about three times that of a submerged tube desalination plant. However the evaporation of seawater in a HTTF evaporator is sensitive to the distribution of brine on the tubes. Seawater supply to each effect should also be large enough to prevent dry spots. Significant improvements in heat transfer are achieved by using oval tubes for distribution and film thinning.

A low temperature (up to 70°C) version of the HTTF is the LT-MED which is used for low and medium capacity desalination plants. The advantages of LT-MED include high heat transfer coefficients, increased thermodynamic efficiency, lower pressure drops, utilization of economical and durable tube materials (aluminium alloy) because of low temperature operation and the increase of the heat transfer area per ton of water produced in the desalination plant for the same investment costs. The thermodynamic superiority of MED over the MSF process results in a very low temperature drop per effect (1.5-2.5°C) which enables the incorporation of a large number of effects (10-16) even with the Maximum Brine Temperature (MBT) as low as 70°C. This results in favourable economics.

A high temperature (up to 130°C) version of the HTTF is the HT-MED which uses expensive materials. HT-MED plants can incorporate a larger number of effects and therefore have a greater GOR. The number of effects in HT-MED generally varies from 2 to 24. Current MED plants usually have a GOR in the range of 6 to 12 with some HT-MED plants having a GOR of 20 or higher. The HT-MED and LT-MED only differ in terms of temperature range and number of plant effects.

Thin film Horizontal Tube Multiple Evaporation (HTME) distillation technology is presently considered the most promising for the production of fresh water from seawater. The process has all the main features of the MED process described above with the evaporator being the centrepiece of the process. This is where heating steam condenses inside horizontal tube bundles while a thin film of seawater is sprayed over the external surface of the tubes. Low-pressure saturated steam is used as the heat source. This is typically supplied by steam boilers in dual-purpose plants co-generating electricity and steam.

2.2.4 Optimum process flow configurations

Based on the direction of the feed water, vapour and brine flow, available heat source and thermodynamic considerations, MED plants may be further divided into various process flow configurations which impact the capital cost (amount of evaporators and piping) and performance ratio (product capacity) of the plant. The evaluation of the optimum process flow configuration usually occurs during the preliminary design phase in order to evaluate the plant production capacity and cost of desalinated product water. Different process flow configurations or plant layouts lead to different advantages and disadvantages.

2.2.5 Temperature range

Temperature ranges of distillation processes have an effect on the prime energy consumption and capital cost. The objective in MED designs is to provide for the

largest possible practical temperature range in order to utilize more effects in the plant. More plant effects lead to higher production levels. Restrictions on the bottom and top temperature range influence this objective. Bottom temperature should be above the available heat sink temperature which in the case of the Pebble Bed Modular Reactor is the seawater. Large volume vapour and gasses are attained at low saturated pressure and this leads to large bottom stage and duct dimensions. Therefore the limitation for the sea temperature for design purposes is not below 40°C. When seawater at a lower temperature is available pre-heating of the seawater is needed. Top temperature ranges also cause some limitations. Although most substances dissolve more readily in warmer water, some dissolve more readily in cooler water. Unfortunately some of these substances, like carbonates and sulphates, are found in seawater. One of the most important is calcium sulphate (CaSO₄) which precipitates the solution when seawater approaches 115°C (203°F). This material forms a hard scale that coats the tubes or surfaces present. Scale creates thermal and mechanical problems and, once formed, is difficult to remove. One way to avoid the formation of scale is to control the seawater salinity and to control the top temperature of the process. Another way is to add special chemicals to the seawater that reduce scale precipitation and permit the top temperature to reach 110°C.

2.2.6 Fouling and material selection

Fouling is the deposition of any material on the heat exchanging surfaces (tubes) which increase the resistance to heat transfer. This decreases the performance ratio and plant production rates [DESWARE, 2007]. Fouling factors vary in each plant section and should be accounted for in the plant design phase and the calculation of the optimum operating point. Compared to MSF, LT-MED is a more recently developed process and the selection of material for the evaporators has not yet been fully established. The most common material for large plants is solid stainless steel of type 316L. The highly alloyed 254 SMO has also been used for several plants in Saudi Arabia [Olson, 2005:223]. However, the possibility to utilize the strength of a duplex grade such as 2205, or even SAF 2507, should enable an even higher cost saving potential since the cylindrical cross section of the evaporators is more advantageous from a design point of view. Duplex stainless steels of type 2205 can be combined with other duplex grades to optimize the demands for corrosion resistance and costs. HTME systems are technically well developed, but research on new low-cost construction materials is in progress. Aluminium for heat exchangers and carbon steel shell material are presently used, though high-grade stainless steel

and titanium are proposed for future use. In addition, polymeric materials are being considered for the tube bundles; a promising possibility given the very low pressure difference between the inside and outside of the tubes.

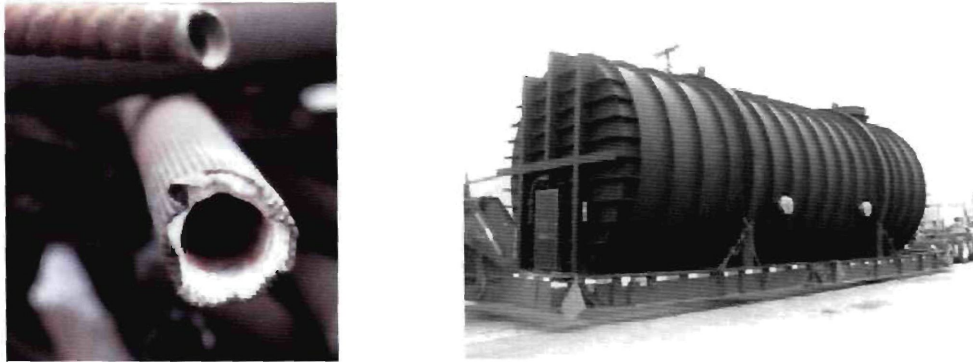


Figure 2-2: Scaled tubes in a distillation plant (left) and an LT-MED plant (right).

2.2.7 Coupling scheme and process heat source

The coupling configuration and choice of the process heat source play a major role in the choice and size of the desalination plant. Desalination plants can be coupled with a variety of single purpose nuclear plants to produce only water or with co-generation nuclear plants to produce water and electricity [Dardoura, 2005:232]. When a nuclear reactor is used to supply steam for desalination the method of coupling has a significant technical and economical impact. For optimum coupling the size and type of reactor, the specific characteristics of the desalination process and the desirability and value of electricity generation as a co-product should be assessed.

For meaningful production with MED the heating fluids (usually water vapour) are required at temperatures between 70°C and 110°C. In a conventional coupling scheme the vapour is extracted from one of the low pressure turbine stages. After exchanging heat in the process heat exchanger (or the second condenser) of the intermediate circuit this vapour is sent back to the main condenser of the plant. This vapour extraction naturally leads to the loss of some electrical power since a fraction of it has not been used for electricity production. In order to optimize the coupling scheme it is necessary to determine the conditions which lead to effective heat transfer in the process which does not affect plant performance.

2.3 Alternative MED energy sources

As mentioned in Chapter 1 the MED process is an energy intensive process utilizing heat sources in many different configurations. Many alternative energy sources are employed in MED systems today. The following section describes some of the main alternative energy sources found in MED systems today:

2.3.1 Geothermal desalination

Geothermal desalination is an experimental process under development for the production of fresh water using heat energy extracted from underground rocks [Wikipedia, 2007]. Advantages of this process include less maintenance and a low environmental impact source of energy. A number of prototypes, since 1995, indicated that with process water approaching 100°C and a chill source of 2°C a full size device will deliver 600 m³ per day. This renewable energy source could lead to a less expensive method of providing clean water. Geothermal desalination would only be useful where the region allows it. For example, favourable geological and volcanic conditions in certain regions in Europe lead to large geothermal fields which provide high temperature heat (fluids) at a depth of 700-1400 m with fairly good flow (50-120m³/h). In the case of a geothermal driven MED unit, additional energy is required for pumping, transporting and re-injecting the geothermal fluid [Wikipedia, 2007].

2.3.2 Solar desalination

Several reviews of the status of solar desalination have been published by different authors. One study by Blanco indicates that among low capacity production systems, solar ponds represent the best alternative in case of both low fresh water demand and land price. For higher desalting capacities it is necessary to choose conventional distillation plants coupled to a solar thermal system. Conventional MED seawater desalination plants coupled to a thermal solar system is known as indirect solar desalination. Several small size systems and pilot plants have been implemented. The solar field could drive the desalination plant by both heating the seawater and brine which are pre-heated at the plant or by generating steam. Scale formation and corrosion are minimal leading to high plant availabilities of 94% to 96%.

Spain had two pilot plant experiences of solar thermal desalination. The solar-pond-powered configuration seems to be the most cost effective solar desalination process. Technological improvements that could be applied to indirect solar desalination are the use of flat plates instead of tubular heat exchangers, selection of materials and coupling of heat pumps together with the design of solar heat pumps. This technology can't compete, on produced water cost basis, with conventional thermal distillation technologies, but there seems to be room for improvement of MED systems using solar thermal energy. In 2002 a new project named "Enhanced Zero Discharged Seawater Desalination using Hybrid Solar Technology" (AQUASOL) was approved by the European Commission and the activities were initiated in 2002.

First order analyses showed that the new concept proposed will be fully competitive if the total solar system cost is around 300 €/m³.

2.3.3 Fossil fuel desalination

Heat to be used for desalination purposes may also be produced by burning fossil fuels. Several power plant options are applicable and some of them are presently used to produce the majority of desalted water in the world. The main options, based on industrial maturity and economical production rates, are fossil fuelled steam boiler electric power plants and combined cycle electric power plants. The averaged water costs using a fossil fuel plant coupled with MED units are much higher than with nuclear plants.

2.3.4 Nuclear desalination

The IAEA (2000b:3) has defined a nuclear desalination system:

Nuclear desalination is defined to be the production of potable water from seawater in a facility in which a nuclear reactor is used as the source of energy for the desalination process. Electrical and/or thermal energy may be used in the desalination process. The facility may be dedicated solely to the production of potable water, or may be used for the generation of electricity and the production of potable water, in which case only a portion of the total energy output of the reactor is used for water production.

Based on this definition nuclear desalination MED units utilize waste process heat from dual purpose plants or heat from the reactor in single purpose heating reactors, depending on the water-power ratio in the specific region. In the distillation system, such as MED, the objective is to deliver the reject heat at an appropriate temperature without much impact on the power production level. In a PWR this requires steam bleeding at different stages of the turbine which leads to loss of electrical power. In the case of the GT-MHR (General Atomics design) heat is available at 80-105°C compared to 35°C at turbine outlet for the PWR. The emphasis is therefore placed on coupling with GT technologies which effectively use higher temperatures for increased water production [Peterson, 2006:2-3].

A special feature of the Brayton cycle optimized for the GT-MHR operating conditions is the release of heat at the cold side via the pre-cooler and intercooler at more than 100°C. Normally this heat is released only through a cooling tower or to a river, but with proper adaptation it can be converted to useful heat to be used, for example to heat the feed water of a MED desalination unit. Technically any reactor can be used for nuclear desalination although the current interest lies in gas cooled reactor

technology [Colak, 2005:429]. This interest is due to the inherent safety characteristics, low cost and the short construction time expectations of such reactors. Higher thermal efficiency and fuel utilization are other advantages of such reactors. The High Temperature Gas cooled Reactor (HTGR) design, one of the leading reactor concepts currently under consideration for future nuclear power plant deployment, is one of the candidate reactor designs well suited for process heat applications. Traditionally emphasis has been on HTGR suitability for high temperature applications such as hydrogen production, but its potential for low temperature applications such as nuclear desalination is attracting interest with the provision of virtually cost free waste heat at the cycle sink boundary and at the desired range of temperatures (100-120°C) needed for desalination.

2.4 Current and previous MED developments

By the beginning of the year 2004 a worldwide total of 17,348 desalination units with a total capacity of 37 million m³/day had been installed or were under construction. That represents a more than 30-fold increase in global capacity over three decades. Roughly 60% of this capacity is for seawater desalination, 25% for brackish water desalination and the remaining for river water treatment and other applications. Around 60% of desalting plants are located in the Middle East, followed by North America (20%) and Europe and Asia (around 8 to 10% each). This includes several MED seawater desalination plants with 5000 m³/d capacity range being built in a number of countries. A few countries have also ordered MED plants of 20,000 – 50,000 m³/d capacity in recent years.



Figure 2-3: A 2-unit MED plant (total capacity 35 000 m³/day), [Ophir, 2005:197]

In Ashdod (Israel) an integrated plant was designed and built to simulate the coupling of a MED plant with a nuclear reactor. A low temperature, horizontal tube, multi-effect (LT-MED) unit with a production capacity of 17 400 m³/day was coupled to an old 50

MW (e) oil fired power plant. The Ashdod unit operated continuously for over a year as a demonstration plant and fulfilled its design goals. In particular, the behaviour of the specially designed coupling system was investigated. Its flexibility, partial load, transients and modes of operation (single purpose, dual purpose and changing from single to dual purpose operation) was found to be satisfactory. Also no problems of corrosion and scaling deposition were detected in the power plant condenser which operated at increased seawater concentration levels at above 60°C [IAEA, 2002:15].

Korea initiated specific programmes on nuclear desalination in 1997 which will lead to the construction of mainly small and advanced nuclear reactors coupled to a desalination plant. The Korea Atomic Energy Research Institute (KAERI), as the lead organization with governmental support and participation, is carrying out the work with various industries. The central part of the integrated system is a 330 MW (Th) SMART reactor for dual-purpose application. The integrated nuclear desalination plant with SMART aims to produce both electricity and water. The capacity of the desalination system under design is 40 000 m³/day using the MED process, but it can be adjusted for various demands. This amount of product water is assessed to be sufficient for a population of about 100,000. For the SMART integrated nuclear desalination plant two types of preliminary economic evaluation were carried out to assess the cost of water production and electricity generation. The IAEA Desalination Economic Evaluation Program (DEEP) was used for the evaluation [IAEA, 2002:15].

Lowest water production costs of 0.83 \$/m³ were obtained at a Maximum Brine Temperature (MBT) of 65°C and at the Gain Output Ratio (GOR) of about 13. The plant also generates electricity of about 90 MW (e). The amount of electricity generation remains nearly the same over the entire MBT range. Results indicate that the optimum value of MBT with respect to economic use of energy lies in the range of 60–70°C for the current coupling arrangement. From this result it was also found that approximately 10% of the energy produced by the SMART is consumed for the target water production of 40 000 m³/day. In 2005, KAERI applied for a construction permit for a one-fifth scale 65 MW (Th) prototype of a SMART with a desalination unit [IAEA, 2006:32]. In the Russian Federation the NIKA-70, a Pressurized Water Reactor (PWR), utilizes either RO or MED for a desalination plant currently under investigation. The most acceptable distillation technology for coupling with NIKA-70 is multi-stage distillation. MSF plants can also be coupled with the NIKA-70, but preliminary economic estimations have shown that the cost of desalted water is too

high. This type of desalination plant was therefore not further considered for desalination purposes.

It seems reasonable to use distillation desalination plants with a horizontal-tube film MED apparatus. Those MED water plants are facilities characterized by high cost efficiency and productivity of desalination process, quality and stability of produced distillate, low consumption of energy resources, low need for metal and occupied area, enhanced reliability and flexibility, simplicity of control, maintenance and repair. As an additional benefit, the cost of these plants is not very high and rather competitive in the international market. The following options of these plants are offered: 240, 600, 1200, 2400, 3600, 16800 and 20000 m³/day. Combined (hybrid) desalination plants consisting of membrane (RO) and distillation (MED) plants can be of special interest for consumers. In this case one can obtain very pure fresh water from the distillation plant as well as fresh water with a higher level of salt, but at a lower cost from the membrane water plant.

An economic evaluation of seawater desalination complexes using NIKA-70 reactors was performed with the IAEA software package, DEEP, for the economic comparison of seawater desalination plants [IAEA, 2006]. Water costs are 0.99–1.09 \$/m³ for a distillation plant, 0.83–1.01 \$/m³ for a membrane plant with pre-heat and 0.88–0.97 \$/m³ for a hybrid plant. For a distillation plant the average daily water production optimized by cost equals 32 324 m³/d of fresh water and 7.7 MW(e) of net saleable power at a water cost of 0.99 \$/m³. The hybrid plant seems most attractive because it allows production of both very pure freshwater by the MED process and fresh water with increased salinity in the reverse osmosis process at a rather low cost.

India is proceeding with a nuclear desalination demonstration plant at Kalpakkam to demonstrate the multi-stage flash (MSF) process and the plant has already been set up. In 2004 India also commissioned a low temperature evaporation plant at the CIRUS heavy water research reactor at Trombay utilizing moderator waste heat to produce clean water. Argentina has identified a site for its small reactor (CAREM), which could be used for desalination. Depending on financing, construction could begin in the near future (2007-2009 timeframe). CAREM-25 is an advanced, but simple project for a small nuclear power plant. This project contains new design solutions, after having obtained significant worldwide experience with light water reactors. This design involves the electrical and thermal coupling of desalination technology. The size of the plant makes it ideal for nuclear desalination of seawater.

The CAREM is an indirect cycle plant with some distinctive features such as passive safety systems and unique coupling systems to minimize risk of water contamination. An analysis of coupling a CAREM plant with a thermal desalination system was performed within the framework of supporting IAEA's activities on nuclear desalination. This was due to general interest shown by Member States in coupling of nuclear power plants with MED systems. In addition, a conceptual safety analysis of a nuclear desalination plant (NDP) with thermal coupling was developed, and found to be a safe option. A generic MED Plant, most likely LT-MED, was suggested.

2.5 Economic evaluation of nuclear desalination systems

Little work has been published on the economics of nuclear desalination systems since a nuclear renaissance has only recently become a reality. A study worth mentioning is Nisan and Dardour [2006:255] who conducted detailed analyses of water costs for several nuclear reactors operating in a cogeneration mode. The reactors under consideration were the 900 MW (e) French PWR, the advanced PWR, the AP-600 and high temperature gas cooled reactors such as the GT-MHR and the PBMR. These reactors were coupled to two desalination processes namely MED and RO. It was shown that desalination costs could be further reduced by utilizing waste heat from the GT-MHR and PBMR type of reactors. Comparisons were made with desalination costs from the cheapest of energy based systems namely the 600 MW (e) gas turbine combined cycle plant (CC-600) [Nisan, 2006:234].

Compared to the CC-600, the construction costs of the integrated MED plants with nuclear reactors is slightly higher because of the necessity of including the cost of the intermediate circuit between the reactors and the desalination plant. The MED desalination cost with PWR systems such as the PWR-900 and the AP-600 are respectively 46 and 42% lower than the corresponding cost by the CC-600 plant. The lowest costs with the MED plants are obtained by the GT-MHR and the PBMR which could utilize approximate free waste heat. Compared to the cost by the CC-600+MED system, these reactors, coupled to MED, give desalination costs which are respectively 62% and 44% lower. The GT-MHR + MED system lead to 42% lower costs than the PWR-900+MED system. Compared to the corresponding AP-600 based system, this cost is 51% lower. The cost of PBMR + MED system is 4% higher than the PWR+MED system. The four nuclear options lead to much lower desalination costs as compared to those by the CC-600 plant.

Another study conducted by Colak [2005:432,433] also deals with possible coupling schemes for desalination plants. A number of possible plant combinations were taken into account and economical analyses were obtained with DEEP. The PBMR MED-RO hybrid type plant is found to be the best in terms of cost of water produced.

2.6 Previous work on MED modelling

Some of the earliest work on MED modelling was done by Vidali and Kousi [Vidali et al] who developed a modelling and simulation program based on the design parameters of the MED plant installed in the PSA (Platforma Solar de Almeria). The model is based on mass and energy balances for the streams flowing through each stage of the MED unit to predict the performance of the unit in terms of energy requirements. This unit uses a multiple effect stacked horizontal tube film evaporator design. Low pressure steam is provided to the first cell at 70°C and 0.35 bar generated by a low pressure boiler. MED plant simulation software has been developed since 1993 by the University of Bremen and Munich. The models named MEDAM (Multiple Effect Distillation Analysis Model) and AHPAM (Absorption Heat Pump Analysis Model) were developed in the FORTRAN 77 code and have many design and simulation options.

Since this code was too complex for further developments by researchers, Vidali proposed to create a simpler environment to model the installed MED plant through implementing Microsoft EXCEL worksheets instead of the FORTRAN code. Each cell of the MED plant is composed of real or virtual components according to the assumptions of the model. Vidali evaluated the effect of power input in the first cell on the energy exchange in each evaporator and on the performance ratio. Sensitivity analyses were performed to include fouling effects due to scaling. This model was developed, extended and modified without significant effort due to the simplicity of EXCEL. Rashad and Hawlader [Rashad et al] conducted a single phase heat transfer performance study of a submerged vertical tube evaporator for MED application. The performance study of the evaporator has been made with different feed flow rates, feed water temperatures and heating medium temperatures. Various overall heat transfer coefficients and heat flux were presented. Four experiments were conducted, with variable system parameters, to determine the efficiency of the single phase heat transfer. It was found that the overall heat transfer coefficients in the evaporator increases significantly with the increase in heating medium flow rate and temperature and that the lower the feed flow rate, the better the evaporator performance.

Ashour [2002:193] performed a thermodynamic analysis of two LT-MED units of 5000m³/d capacity recently commissioned by General Electricity Company at Tripoli West plant. A computer program was written based on the mathematical models of the different plant components and a study on the effect of the different process variables on the plant performance was carried out. The purpose of this model was to mathematically describe the various mass and heat transfer processes in the MED plant, with a parallel feed system. A control volume approach was followed where balance equations were developed for each component. The model predictions were tested against available plant data and the results showed good agreement with actual plant data.

El-Fiqi [2003:140] developed a steady-state mathematical model to analyze MED desalination systems. The effect of the process variables on the performance of a "forward-feed" multi-effect boiling falling film was carried out. This included the effect of number of effects and top brine temperature on the performance ratio. The author also investigated the influence of these two factors on the specific heat transfer area and the effect of seawater inlet temperature on the performance ratio. The effect of the TBT and temperature difference per effect on performance ratio and specific heat transfer area were also investigated. It was found that the performance ratio is completely dependent on the number of effects, and slightly dependent on the TBT.

Ettouney and El-Dessoukey [1999:280,281] also developed a computer package for design and simulation of thermal desalination processes. The MED configurations include parallel and forward feed systems. All models are based on a well developed set of materials and energy balance equations as well as correlations for evaluation of physical properties, heat transfer coefficients and thermodynamic losses. These mathematical models have been tested and validated against available industrial and literature data. All models generate the design and simulation variables which have the strongest effect on the unit product cost. These include the thermal performance ratio, specific heat transfer area, the conversion ratio, specific power consumption, and specific flow rate of cooling water.

Fiorini and Sciubba [2005:3] developed a model for the thermodynamic and thermo-economic simulation of a MED desalination plant. The code is embedded in a modular simulator, CAMEL[®] (CAlculation by Modular Elements), which makes it easy to use for different plant configurations. CAMEL[®] was developed by the Mechanical and Aeronautical Engineering department at the University of Rome. A

model for the MED stage was included in the code library and allows for detail identification of the plant losses and inefficiencies. The model can simulate all the different MED configurations. The thermodynamic model of each component is based on mass and energy balance criteria and the results have been validated with the relevant literature data. Sensitivity calculations were performed incorporating various case studies such as combined power plant configurations etc. Analysis procedures are usually comprised out of calculating the steam feeding cost to the MED plant, thermo-economic analysis by comparing product cost versus plant production costs and thermo-economic comparisons of MED configurations using different number of stages (Sciubba [2007:1-3]).

Serra and Uche [Serra et al, 2006] from Spain performed simulations and thermo-economic analyses of several configurations of gas turbine (GT) based dual purpose power and desalination plants (DPPDP). One of the investigated configurations was a combined cycle (CC) with MED and a model was developed. The results with the model showed that the GOR increases with brine salinity. High brine salinity is appropriate whenever available materials are introduced. It is shown that GOR does not rise as much when the salinity and UA are both increased.

Dardoura and Nisana [2005:230,231] developed a computer-package to simulate the dynamics of different Multi Effect Evaporator systems. The software, SIMED, is aimed at simulating different MED couplings to nuclear reactors such as GT-MHR, PBMR, PWR or fossil energy sources such as the gas turbine combined cycle or simple oil and gas burners. This package serves as an educational tool to understand the MED process better. Basic mass, energy and momentum conservation equations and heat transfer correlations form the basis for the models implemented in SIMED. Conservation laws are applied separately to fluid phases (brine pool, vapour space) in system components such as MED effects, condensers, coolers, pumps and ducts. These types of models are expensive and take time to develop. Some assumptions are necessary in order to solve the model equations. The models show promising results with PWR-MED coupled systems.

2.7 Conclusion

Different energy sources are available today for utilization in MED desalination plants. The choice of suitable energy source depends on the economic viability and local availability of the source. Main energy sources implemented today in MED desalination plants are geothermal, solar, fossil fuels and nuclear energy. HTGR type

reactor designs, which are classified as new advanced generation reactors such as the PBMR, seems to be well suited for desalination purposes.

Various MED units have been successfully installed in Israel, Korea and Japan, with new MED plants planned for China, Morocco, Canada, Argentina and Russia. The LT-MED configuration, with horizontal tube layout, seems to be the most widely used choice, since this configuration leads to a more efficient system. Various modelling and simulation approaches have been followed in the past. Common modelling approaches most widely used would be the generation of mathematical models, which is based on mass and energy balances for separate components. The modelling process generally involves making correct assumptions regarding the flow conditions inside the components. Parameters under investigation are the optimum number of effects, performance ratio and the TBT.

In order to generate suitable mathematical models and make correct assumptions, the fundamental process which occurs inside each distillation effect has to be understood well. In order to gain further understanding into the mode of MED operation, the effect of different system parameters on the MED system should be investigated.

Chapter 3

Theoretical Background

"Discovery consists of seeing what everybody has seen and thinking what nobody has thought." - Albert Szent-Györgyi (1893-92), Hungarian-born US biochemist.

"When the well is dry, we know the worth of water." Ben Franklin

CHAPTER 3 THEORETICAL BACKGROUND

3.1 Introduction

Thermal desalination plants consist of three distinct sections namely the heat source circuit, the distillation unit and a suitable coupling mechanism as shown in Figure 3-1. Efficiency of a MED plant is impacted by different flow configurations employed in the secondary circuit. It has been proved thermodynamically that the nature of the heat source available in the primary circuit influences the process flow configuration, heat transfer coefficients and layout of the plant in the secondary circuit. Chapter 3 introduces the basic principle of MED and identifies different plant performance indices. Heat source utilization, particularly steam and water, and the impact on the secondary circuit configuration are also shown.

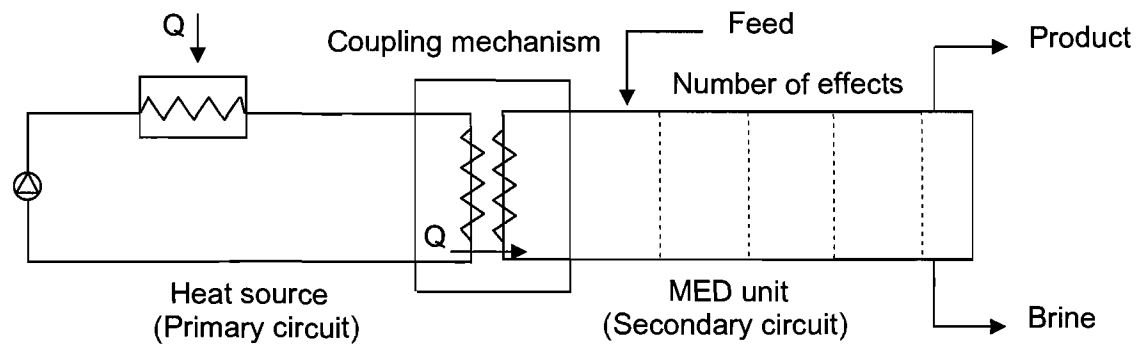


Figure 3-1: MED unit sections

3.2 Principle of operation

Effective evaporation and condensation, which occurs inside each plant stage, are the most important driving mechanisms in the MED process. This mechanism allows an external heat source to be utilized in a number of effects to produce clean water. Consider a stream of sub-cooled water being heated to saturation and then partially evaporated with further addition of heat as shown in Figure 3-2.

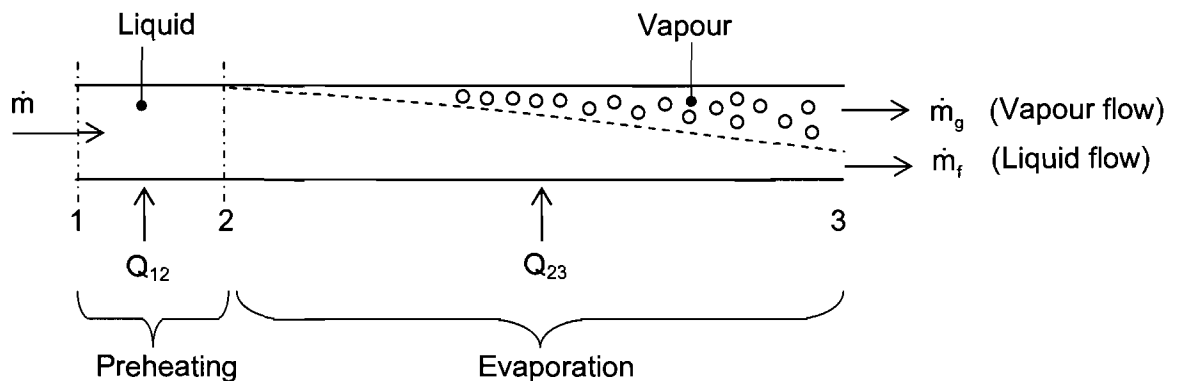


Figure 3-2: Preheating and partial evaporation of a stream of water

The process is shown on a T-S diagram in Figure 3-3, indicating the different fluid positions in the flow section.

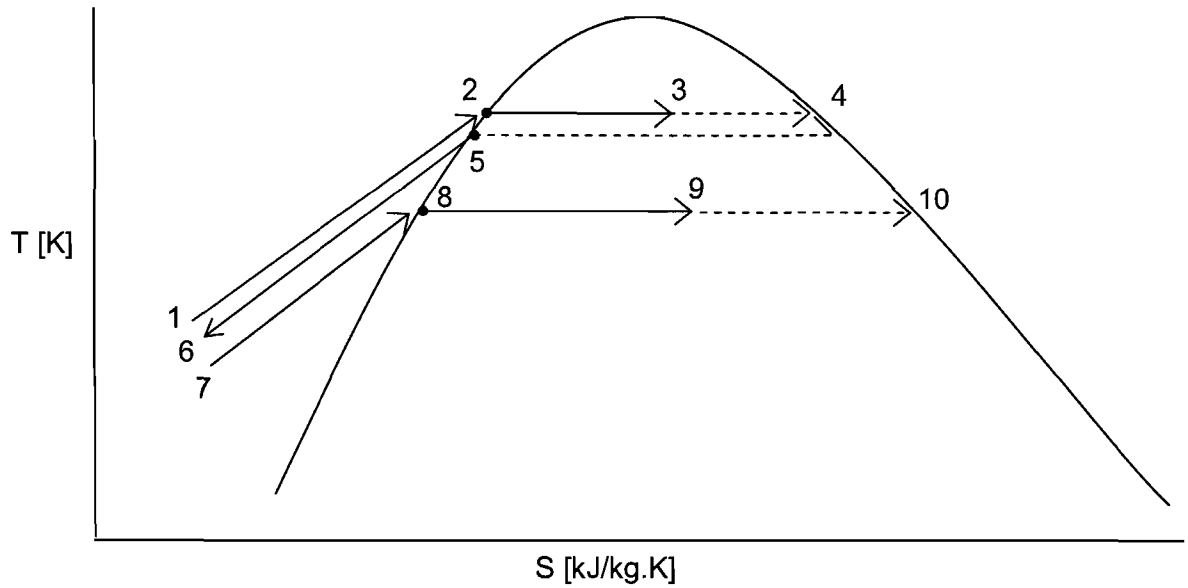


Figure 3-3: Preheating and partial evaporation of water on a T-S diagram

Applying the First Law of Thermodynamics the heat required to preheat the water from 1-2 can be written as:

$$Q_{12} = \dot{m} C_p (T_2 - T_1) = \dot{m} (h_2 - h_1) \quad (3.1)$$

where C_p is the specific heat of water.

The heat required to partially evaporate the water can be expressed as:

$$Q_{23} = \dot{m} (h_3 - h_2) \quad (3.2)$$

Introducing the definition of quality of a liquid-vapour mixture

$$x = \frac{\dot{m}_g}{\dot{m}} \quad (3.3)$$

and assuming thermodynamic equilibrium the enthalpy of a liquid-vapour mixture can be expressed as:

$$\begin{aligned} h &= h_f (1 - x) + h_g (x) \\ &= h_f + x(h_g - h_f) = h_f + x h_{fg} \end{aligned} \quad (3.4)$$

where h_f is the enthalpy of saturated liquid and h_g is the enthalpy of saturated vapour.

$$h_{fg} = h_g - h_f \quad (3.5)$$

Substitution of (3.4) into (3.2) leads to:

$$\begin{aligned} Q_{23} &= \dot{m} (h_f + x(h_g - h_f) - h_f) \\ &= \dot{m} x (h_g - h_f) = \dot{m} \left(\frac{\dot{m}_g}{\dot{m}} \right) (h_g - h_f) = \dot{m}_g h_{fg,3} \end{aligned} \quad (3.6)$$

The total amount of heat required to preheat and partially evaporate the stream of water is given by:

$$Q_{13} = Q_{12} + Q_{23} \quad (3.7)$$

The MED process is based on the principle that by separating the liquid and vapour streams and by condensing the vapour, a clean stream of desalinated water can be obtained since the solved salts remain in solution in the liquid stream. In addition to this, the heat released by the condensing vapour can be used to partially evaporate a second stream of water at a somewhat lower temperature. This process is depicted in Figure 3-4. Note that this figure is only used for conceptual purposes and doesn't depict the actual plant stages and interconnected piping.

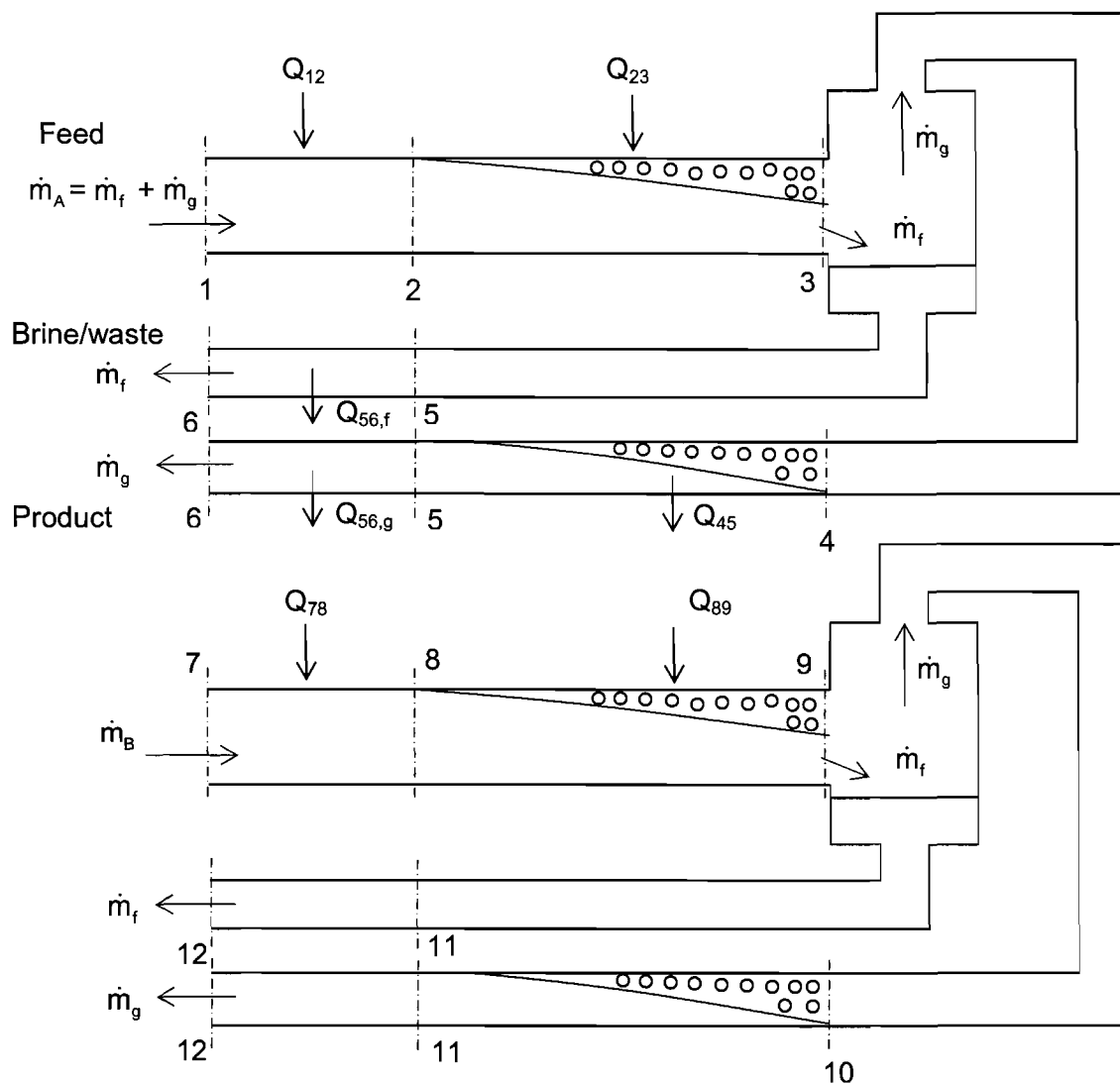


Figure 3-4: Thermodynamic process inside each effect

The heat required to condense the vapour stream $\dot{m}_{g,A}$ from 4 to 5, Q_{45} , is given by:

$$Q_{45} = \dot{m}_{g,A}(h_4 - h_5) = \dot{m}_{g,A}h_{fg,4} \quad (3.8)$$

Assuming no pressure and temperature losses between 3 and 4, it can be seen that $h_{fg,3} = h_{fg,4}$, which means that $Q_{23} = Q_{45}$. The heat required to evaporate the second feed stream \dot{m}_B from 8 to 9, Q_{89} , is given by:

$$Q_{89} = \dot{m}_{g,B} h_{fg,9} \quad (3.9)$$

Equating Q_{45} and Q_{89} we have:

$$\dot{m}_{g,A} h_{fg,4} = \dot{m}_{g,B} h_{fg,9} \quad (3.10)$$

Assuming that $h_{fg,4} \approx h_{fg,9}$, then $\dot{m}_{g,A} \approx \dot{m}_{g,B}$, which implies that $\dot{m}_A \approx \dot{m}_B$. Also interesting to note is that by further cooling both streams $\dot{m}_{f,A}$ and $\dot{m}_{g,A}$ from T_5 to T_6 with T_6 slightly higher than T_1 the heat from these two streams can be used to preheat Stream B from T_7 to T_8 where T_7 is slightly lower than T_6 and T_8 is slightly lower than T_5 . All the heat released by condensing and sub-cooling $\dot{m}_{f,A}$ to T_6 is therefore utilized to preheat and partially evaporate Stream B. Preheat feed water heat exchangers could be used to utilize the heat still available in the product and waste streams to preheat the feed water.

$$Q_{78} = \dot{m}_B C_p (T_8 - T_7) \quad (3.11)$$

$$Q_{56,f} + Q_{56,g} = (\dot{m}_{f,A} + \dot{m}_{g,A}) C_p (T_5 - T_6) \quad (3.12)$$

With $\dot{m}_A \approx \dot{m}_B$ and $(T_5 - T_6) \approx (T_8 - T_7)$ it is seen that $Q_{56,f} + Q_{56,g} = Q_{78}$.

The process can be repeated for a number of times, the only limitation being the ΔT per stage that will determine how many stages can be fit in between the temperature of the heat source and the heat sink.

3.3 Performance indices

When designing MED systems, certain system design limits exist [Methnani, 2007]. The Top Brine Temperature (TBT) should be kept below 70°C in order to control the amount of scale forming on the heat exchanging surfaces. The TBT design limit constrains the steam economy since fewer effects can be installed in the MED plant. A lower TBT, however, allows for cheaper materials such as aluminium to be used for the evaporators. The choice for TBT becomes a trade-off between cost and production. The steam economy is characterized by the Gained Output Ratio (GOR) and the Performance Ratio (PR):

$$GOR = \frac{\text{Product capacity}}{\text{Heating steam flow}} \quad (3.13)$$

$$PR = \frac{\text{product mass}}{\text{energy input}} \quad (3.14)$$

The GOR is usually used when steam is available as heat source and the PR is used when water is available as heat source in the primary circuit to drive the flow in the secondary circuit. The Gained Output Ratio (GOR) of the MED system is an important parameter since it is an indication of the efficiency of the plant. In other words the GOR indicates how effective heat is utilized in the secondary circuit to produce a certain amount of product water. Brine salinity is also a limitation and is characterized by the brine concentration factor (CF_b) which is defined as:

$$CF_b = f / (f-1) \quad (3.15)$$

where f is the feed-to-distillate ratio. This factor is constrained by material and environmental limits ($CF_b \approx 1.5 - 2$ in practice). Other limitations include brine and vapour velocities and heat transfer losses.

3.4 Factors impacting the plant performance

In order to determine the performance ratio (or GOR) of a MED system it is important to relate the total heat transfer rate in each effect to quantities such as the inlet and outlet fluid temperatures, the overall heat transfer coefficient (U) and the total heat transfer area (A). Q is defined as the total rate of heat transfer between the hot and cold fluids. The simplest heat exchanger is one for which the hot and cold fluids move in parallel or counter flow directions in a concentric tube or double pipe construction. To understand how the GOR fundamentally impacts the system configuration we first need to consider the counter flow arrangement in a pipe as seen in Figure 3-5. The fluids enter at opposite ends, flow in opposite directions and leave at opposite ends. The hot and cold fluid inlet streams are T_{hi} and T_{ci} respectively, and T_{ho} and T_{co} are the hot and cold fluid outlet streams respectively. Let \dot{m}_h and \dot{m}_c be the respective fluid mass flows and L the length of the pipe. The heat transfer rate, Q , in each fluid stream is given by:

$$Q = \dot{m}_h C_{p_h} (T_{hi} - T_{ho}) = \dot{m}_c C_{p_c} (T_{co} - T_{ci}) \quad (3.16)$$

where C_p is the specific heat capacity of each fluid stream.

The heat transfer rate, Q , between the two fluids is given by:

$$Q = AU\Delta T_{LMTD} \quad (3.17)$$

where ΔT_{LMTD} is the log mean temperature difference and given by:

$$\Delta T_{LMTD} = \frac{(T_{hi} - T_{co}) - (T_{ho} - T_{ci})}{\ln \left(\frac{(T_{hi} - T_{co})}{(T_{ho} - T_{ci})} \right)} \quad (3.18)$$

The heat transfer rate in Equation (3.17) becomes:

$$Q = AU \frac{(T_{hi} - T_{co}) - (T_{ho} - T_{ci})}{\ln \left(\frac{(T_{hi} - T_{co})}{(T_{ho} - T_{ci})} \right)} \quad (3.19)$$

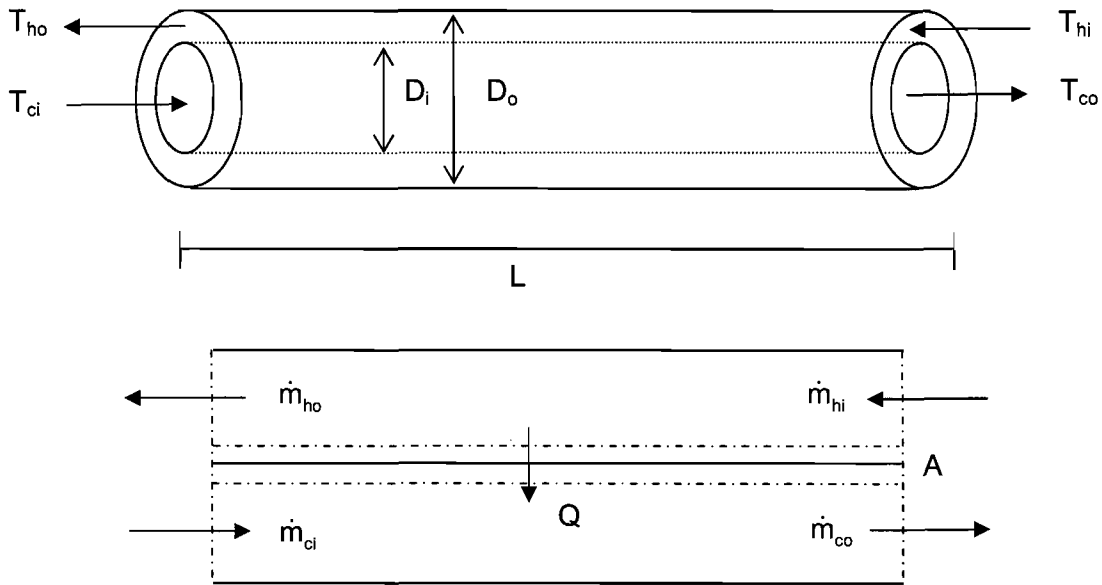


Figure 3-5: Counter flow arrangement in pipe

An essential part, and often the most uncertain part, of any heat exchanger analysis is the determination of the overall heat transfer coefficient where U is determined by:

$$\frac{1}{AU} = \frac{1}{A_c U_c} = \frac{1}{A_h U_h} \quad (3.20)$$

If we assume that AU is constant, then Q is only dependant upon ΔT_{LMTD} . It can be seen that the AU -value plays an important role in the GOR of the MED system. If the AU -value is increased, then the ΔT will decrease according to Equation (3.17) for a constant Q -value. This means that more effects could be utilized in the system leading to an increase in fresh water production. For example, when the top and bottom practical temperature range is 120°C and 30°C for the MED system, then the ΔT_{MED} for the system is 90°C . Designing for a ΔT_{STAGE} of 20°C will lead to approximately 4 plant stages whereas a ΔT_{STAGE} of 10°C will lead to 9 stages. Thus a small and acceptable ΔT_{STAGE} leads to increased water production. When the AU -value is increased infinitely, then fundamentally there is no limit to the amount of water production possible. As mentioned the efficiency of the MED system is a function of the number of effects or stages being utilized in the secondary circuit. This is valid when the different heat exchanging streams in each effect or preheat feed water heat exchanger are of the same order. However, when the mass flows in these streams differ, there is a practical limit on the ΔT_{HX} that is obtained for each effect

according to Equation (3.16). It can be seen in Figure 3-6 (left) that when this phenomena occurs, less effects can be utilized in the system leading to a decrease in water production. The fluid temperatures T_{hi} and T_{ci} are restricted by practical design considerations (for example the external heat source or the inlet sea temperature in the 1st effect) and it is seen that T_{ho} and T_{ci} “pinch” each other. This phenomenon is called *temperature pinching* and should be avoided in ideal MED systems in order to obtain maximum water production. Temperature pinching also impacts the GOR.

When equal mass flows are obtained in the heat exchangers for the same ΔT_{HX1} , more effects can be utilized as seen in Figure 3-6 (right). The increase in effects leads to an increased AU-value which increases the water production as mentioned before.

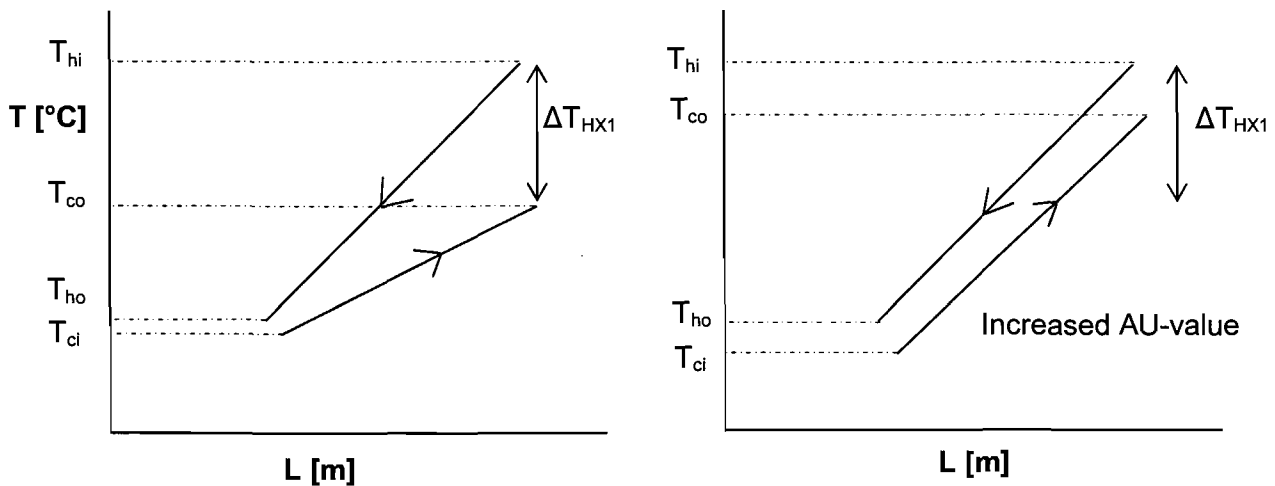


Figure 3-6: System with pinching (left) and no temperature pinching (right)

3.5 Nature of process heat source

Today both steam and water is used as heating medium in the first effect of MED plants to evaporate feed water. Layout, economics and water production of the MED plant is impacted by the choice and availability of a particular heat source in the first effect together with the utilization method of the heat source. In this section the difference between water and steam as heat source will be discussed in order to investigate how the primary heat source influences practical designs and configurations of MED systems. When a MED desalination plant is coupled with conventional steam power plants, steam is usually available as heat source to drive the MED process. This is known as latent heating utilization since the heat source undergoes no temperature changes during the heating of feed water streams. In contrast, gas-cooled high temperature reactors (HTGRs) such as the PBMR provide virtually free heat in the form of water to be used in the MED process [Dardour and

Nisan, 2006:255]. When water is available as heat source, sensible heating occurs since temperature changes in the heat source occurs during heating of feed water streams. In these designs circulating helium, which has to be compressed in two successive stages, cools the reactor core. Due to thermodynamic considerations these stages require pre-cooling of the helium to about 26°C through the use of helium-water heat exchangers. Heat (approximately 220 MW) is dissipated in the pre-cooler and intercooler and then discharged to the heat sink. Depending on the designs, the temperature ranges of the water in these heat exchangers can be between 70°C and 130°C, which is the ideal range for desalination with a MED plant. The impact of the different heat sources on MED system design, due to thermodynamic nature, needs to be investigated in order to perform techno economic studies of MED plants. Thus now, consider the scenario where 1kg/s steam is condensed at a constant temperature of 70°C as seen in Figure 3-7. The amount of heat released during the condensation process is:

$$Q = \dot{m} (h_g - h_f) = 1 (2626 - 293) = 2.3 \text{ [MW]} \quad (3.21)$$

With the assumption of a practical 5°C temperature drop after the condensation process, the amount of water that could be evaporated, and thus the product water that can be produced, with 1kg/s of steam is approximately:

$$\begin{aligned} Q &= \dot{m}_{\text{evap}} (h_g - h_f) = \dot{m}_{\text{evap}} (2617 - 272) = 2.3 \text{ [MW]} \\ \dot{m}_{\text{evap}} &= 0.9947 \text{ [kg/s]} \end{aligned} \quad (3.22)$$

The result from (3.22) shows that with 1kg of steam approximately 1kg of fresh product water can be produced.

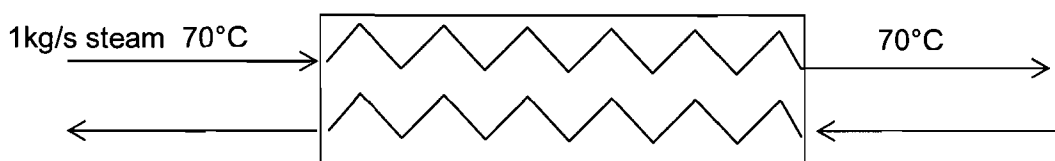


Figure 3-7: Condensation of 1kg steam

In contrast, when liquid water is used as heating medium, the temperature of the water drops considerably from 70°C to approximately 30°C, since sensible heating occurs in the heat source heat exchanger. The heating medium temperature decreases to a value close to the inlet feed water temperature. The amount of water (mass flow) needed as heating medium to produce the same amount of heat as the steam and thus the same amount of product water is approximately:

$$\begin{aligned} Q &= \dot{m} C_p (\Delta T) = \dot{m} \cdot (4.2) \cdot (70 - 30) = 2.3 \text{ [MW]} \\ \dot{m} &= 14 \text{ [kg/s]} \end{aligned} \quad (3.23)$$

The result from (3.23) shows that with 14kg of heating water, the same amount of heat is obtained as with 1 kg of steam evaporation. More relative product water could be produced when steam is used as heating medium in the first effect of the MED secondary circuit as opposed to water being utilized. The available heat source impacts the layout of the MED stages in the secondary circuit. Consider a secondary circuit layout of a LT-MED unit as seen in Figure 3-8. Steam is used as heating medium in the first effect (A to B). Inlet temperature to the first effect is approximately 70°C and the outlet of the last effect is 30°C. When using a practical effect temperature drop of 5°C, the secondary circuit then consists of 8 effects (40°C / 5) each producing 1 kg/s of product water. Thus a total of 8 kg/s product water is obtained from the unit when 1kg/s external heating steam is applied. The total heat added to the feed water is given by area a-b-c-d. Approximately 2.3 [MW] is transferred to each effect in the system. When steam is used as external heat source, a MED series layout is favourable.

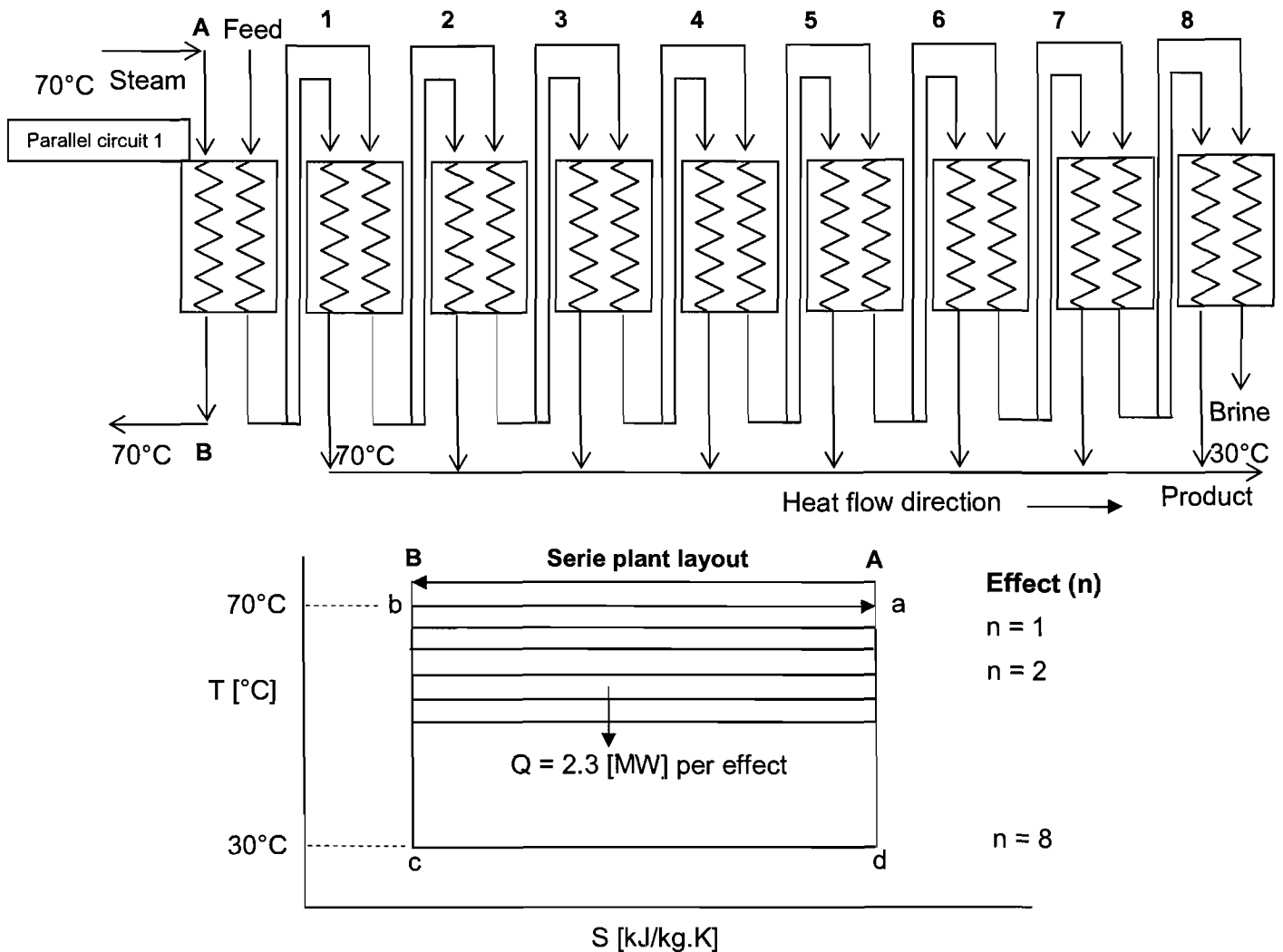


Figure 3-8: MED plant layout utilizing steam as heat source (SHS)

However, when water is used as heating medium in the first effect there are certain thermodynamic restrictions. The temperature of the heating water drops from 70°C to 30°C in the first effect as opposed to a zero temperature drop when steam is utilized as heating medium. The temperature profile of the water heat source is shown in Figure 3-9. Since the water temperature drops from 70°C to 30°C in the first effect, an incremental use of the heat source is necessary. This leads to a number of parallel circuits being installed to effectively utilize the available sensible heat in each first effect of each circuit. The total mass flow of heating water is thus not allowed to be used in the first effect to evaporate feed water (which may have been pre-heated) in the first effect. Again when using a practical circuit temperature drop of 5°C the MED plant consists of 8 parallel circuits (40°C / 5). Each parallel circuit consists of serie effects. We see that when water is used as external heat source, a MED serie-parallel layout is favourable.

Consider a complete LT-MED plant as seen in Figure 3-10 where water is the heating medium in the first effect. Only a fraction of heat ($Q/8$) is utilized in each parallel circuit's first effect. The plant consists of 8 effects in serie in the first parallel circuit, 7 effects in serie in the second parallel circuit, 6 effects in serie in the third parallel circuit etc.

The MED plant in Figure 3-10 consists of 36 effects. Approximately $Q/8$ [MW] is transferred to each effect in the serie circuit. Thus each effect produces 1/8 of product water. A total of 4.5 kg/s product water is produced with a MED plant when water is used as heating medium. The conclusion is that with the same amount of total available heat, the water production capacity decreases by 50% when water is used as heating medium in the first effect of each parallel-serie circuit.

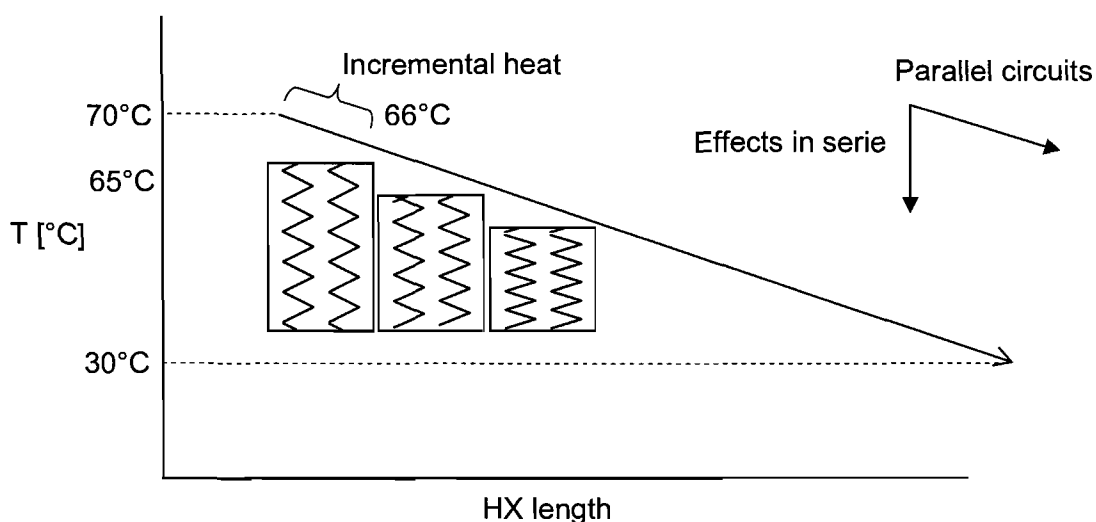


Figure 3-9: Heating water temperature profile

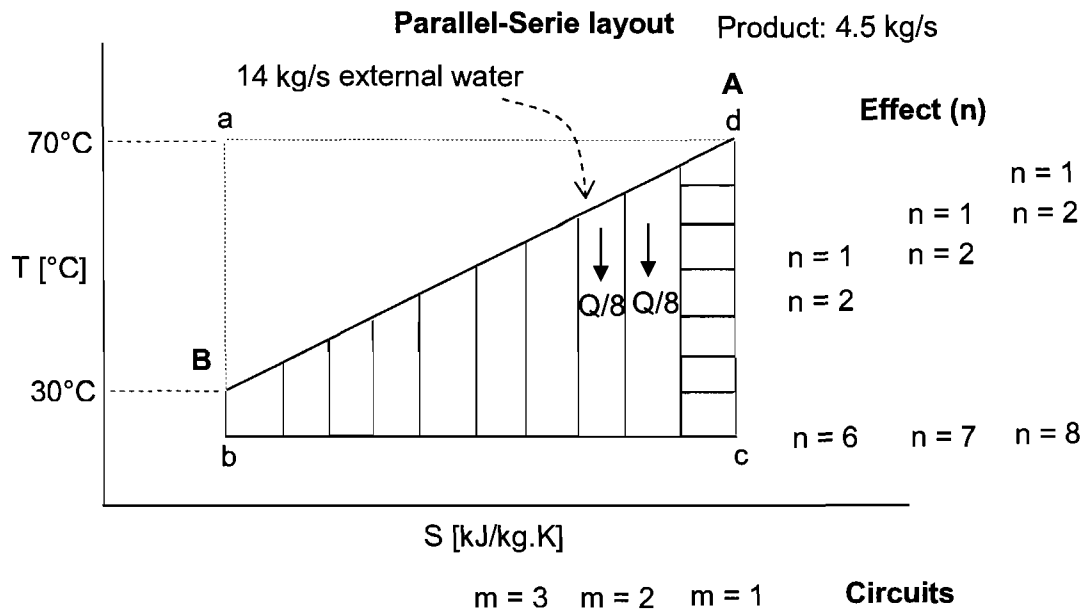


Figure 3-10: MED plant layout utilizing water as heat source (WHS)

3.5.1 Heat source assumptions

The following assumptions with regard to the process heat source are made in order to motivate the layout of the different configurations in the next chapters and to understand the C++ model.

- Heat available from a specific water heat source stream is determined. When water is used as heat source (WHS), a serie-parallel plant layout is selected where the external heat is utilized in incremental parallel circuits as seen in the section of a WHS-MED plant (Figure 3-11). This mode of operation (WHS-mode) simulates a water-heat-source MED plant.
- When steam is utilized as heat source (SHS), all available heat from the water-heat-source is distributed through a single serie plant layout and all the external heat is utilized in a single parallel circuit as seen in Figure 3-8. The assumption is that when a steam heat source is available, a single serie-circuit plant is usually utilized. Thus the total heat available in the heating water is distributed in a single serie circuit and this mode of operation (SHS-mode) simulates a steam-heat-source MED plant.
- Equivalent steam mass flows can be calculated from the total available sensible heat in the WHS-plant

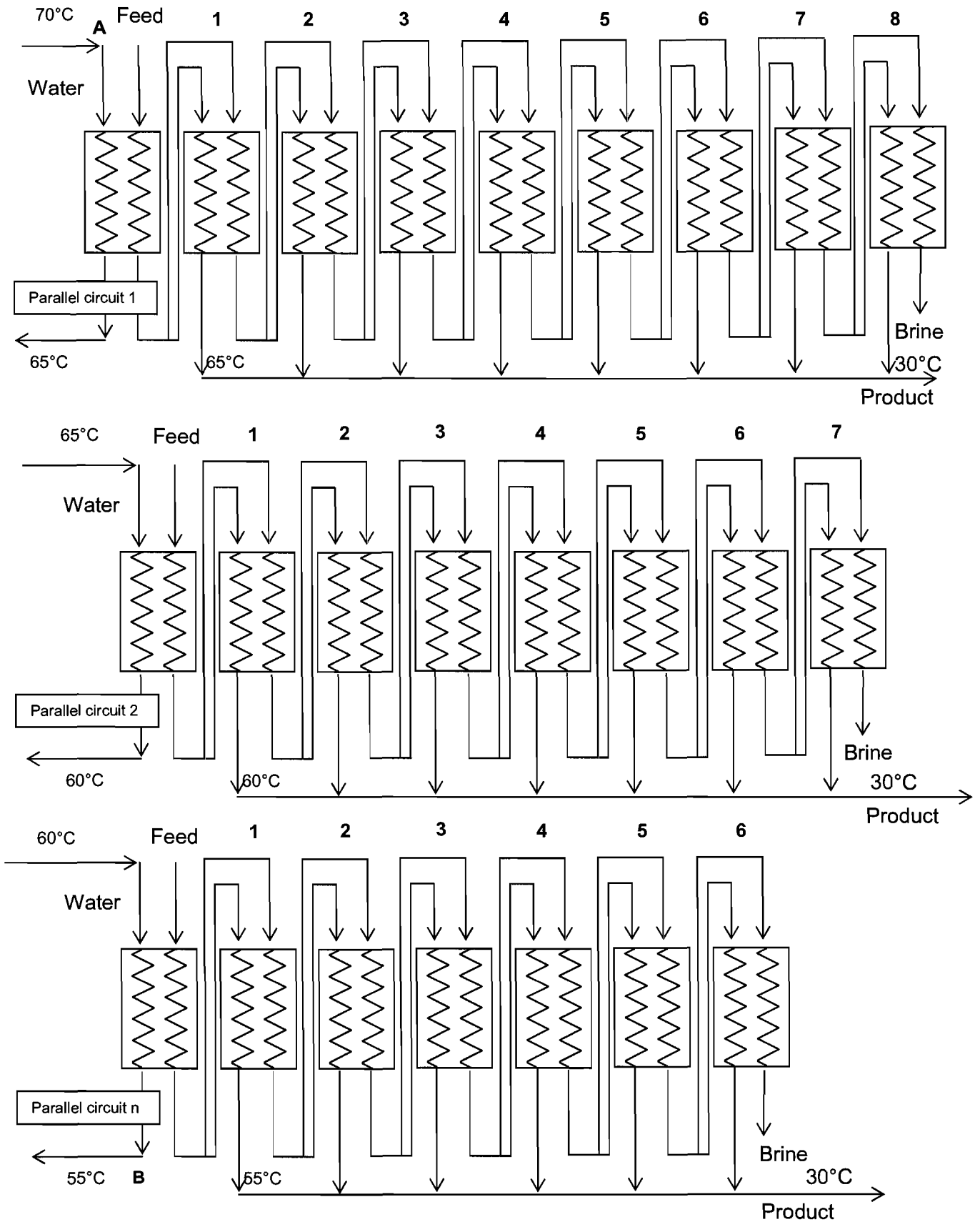


Figure 3-11: MED plant layout utilizing water as heat source

As the number of effects in a plant increases the PR and GOR of the plant increase according to (3.13) and (3.14). Performance in a specific configuration is not well measured by the PR or GOR value since the value will always increase with an increased number of effects. A better measure of the performance of the plant is the relative performance ratio, α , which shows thermodynamically how different heat sources perform in different configurations. Relative performance ratio is defined as:

$$\alpha = \text{PR} / \text{Average circuit effects} \quad (3.24)$$

3.6 Cost considerations

The layout of the plant, which is influenced by the heat source, also impacts the MED plant cost and the cost per kg/s desalinated product. It can be seen that the AU-value plays an important role in the GOR of the MED system, but also the plant cost. According to Equation (3.25) the Q-value is proportional to the AU-value when ΔT is constant.

$$Q = AU\Delta T \quad (3.25)$$

Assume that the AU-value per effect (heat exchanger) is x . The MED plant which utilizes steam as heat source then has a total AU-value of $AU_{\text{steam}} = 8x$ since 8 heat exchangers are used in the MED plant. The MED plant which utilizes water as heat source has a total AU-value of $AU_{\text{water}} = 36(x/8) = 4.5x$ since 36 heat exchangers are used in the MED plant. The cost function of a plant (or heat exchanger) is given by:

$$\text{Cost} = N \times (a + b \text{ AU}) \quad (3.26)$$

where N is the number of heat exchangers in the plant and a and b are constants for a specific heat exchanger. The cost per kg/s desalinated product is given by:

$$\text{Cost}_{\text{product}} = \text{Cost} / \text{total product} \quad (3.27)$$

Thus when 1 kg/s steam is used as heating medium to produce 8kg/s product water in a plant with 8 effects, the cost per kg/s desalinated product becomes:

$$\begin{aligned} \text{Cost}_{\text{product}} &= N \times (a + b \text{ AU}) / \text{total product} \\ &= 8 \times (a + b(x)) / 8 = a + bx \end{aligned} \quad (3.28)$$

When 14 kg/s water is used as heating medium to produce 4.5kg/s product water in a plant with 36 effects, the cost per kg/s desalinated product becomes:

$$\begin{aligned} \text{Cost}_{\text{product}} &= N \times (a + b \text{ AU}) / \text{total product} \\ &= 36 \times (a + b(\frac{x}{8})) / 4.5 = 8a + bx \end{aligned} \quad (3.29)$$

From Equation (3.28) and (3.29) it can be seen that the cost per kg/s desalinated water increases when water is used as heating medium in the first effect of a LT-MED plant and more external heating water (14kg/s) is needed as opposed to using

external steam (1kg/s). An overall heat transfer coefficient (U) of 3 kW/m²K will be assumed in order to determine the evaporator heat transfer area needed for detail cost considerations.

3.7 Conclusion

The method of producing product water in successive effects using an external heat source was discussed. The process which occurs inside each effect was shown in order to gain understanding of the function of each plant component and the different factors which influence the system efficiency. It was shown how heat still available in product and waste streams could be more effectively utilized using pre-heat feed water heat exchangers in order to increase the GOR of the MED plant. Thermodynamic design considerations such as temperature pinching and optimum AU-values were discussed. It was shown that the number of effects is proportional to the GOR. The GOR of the MED system is influenced by the AU-value of the heat exchangers and a good understanding of the factors which influence the AU-value such as temperature pinching. This understanding is necessary in order to predict the system performance.

Different heat sources are utilized in the secondary circuit in order to produce product water from saline feed water. The two main external heat sources used today are liquid water by means of sensible heating and steam by means of latent heating. It was shown that the external heat source impacts the layout, cost and production levels of the MED plant. When steam from conventional dual purpose power plants is used as heating medium, a serie configuration in the secondary circuit of the MED plant is needed opposed to a parallel-serie configuration when water (waste heat) from High Temperature Gas Cooled reactors such as the PBMR is used. More product water can be produced with 1kg/s external steam than with 1kg/s external water. The cost per kg/s desalinated product water using steam is significantly less than the cost per kg/s when water is used as heating medium.

The next step is to identify different secondary circuit process configurations based on the theory of multiple effect evaporation.

Chapter 4

MED Process Configurations

"Water which is too pure has no fish." - Ts'ai Ken T'an

*"There are no such things as applied sciences, only applications of science." -
Louis Pasteur (1822-95), French scientist.*

CHAPTER 4 MED PROCESS CONFIGURATIONS

4.1 Introduction

Various process flow configurations are utilized in the secondary circuit of a MED plant and the flow configuration influences the system efficiency and plant capacity. These configurations mainly differ in terms of the saline feed water, fresh water product and brine water flow directions. These configurations also differ in terms of effective heat utilization of end-of-cycle water. Understanding the mode of operation of each configuration is necessary in order to make good plant design decisions.

4.2 MED process configurations

4.2.1 Forward feed configuration (FFC)

In the so-called *conventional forward feed configuration* (FFC) a single feed water stream flows to the first effect via the final condenser and is heated by the heat source (steam or water) in the evaporator and liquid and vapour forms as products in the first effect as seen in Figure 4-1 and Figure 4-2. The fraction liquid not evaporated is used as feed water in the second effect and the hot vapour is used as the “heat source” in the second effect evaporator. Liquid and vapour is again formed as products in the second effect, whereas the condensed “heat source” vapour is collected as fresh water product from the second effect. The feed water fluid pressure is decreased at each effect inlet in order for the feed water to evaporate at a lower temperature. This mechanism ensures multiple boiling in consecutive effects as seen in the process flow diagram in Figure 4-2. This process continues for a number of effects and the accumulated product freshwater is collected at the end of the process. The excess saline liquid is collected as brine. The system pressure and temperature decreases from the first to last effect. Feed water is used to condense the steam generated in the last effect to form product water.

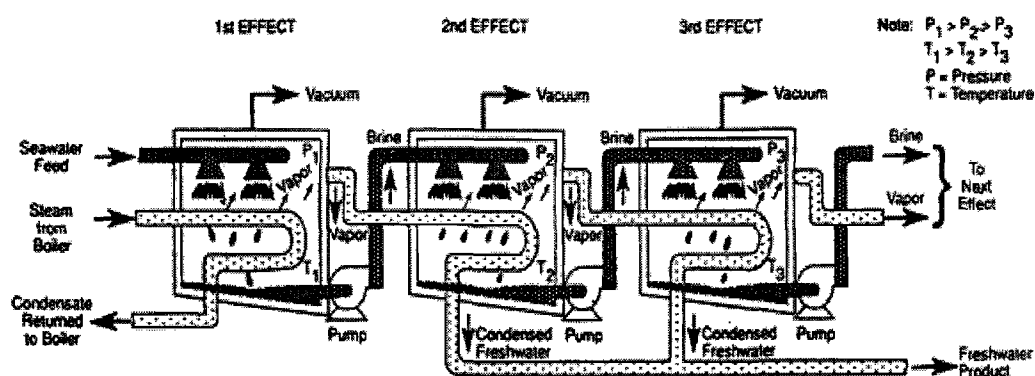


Figure 4-1: Forward Feed Configuration (FFC) schematic illustration

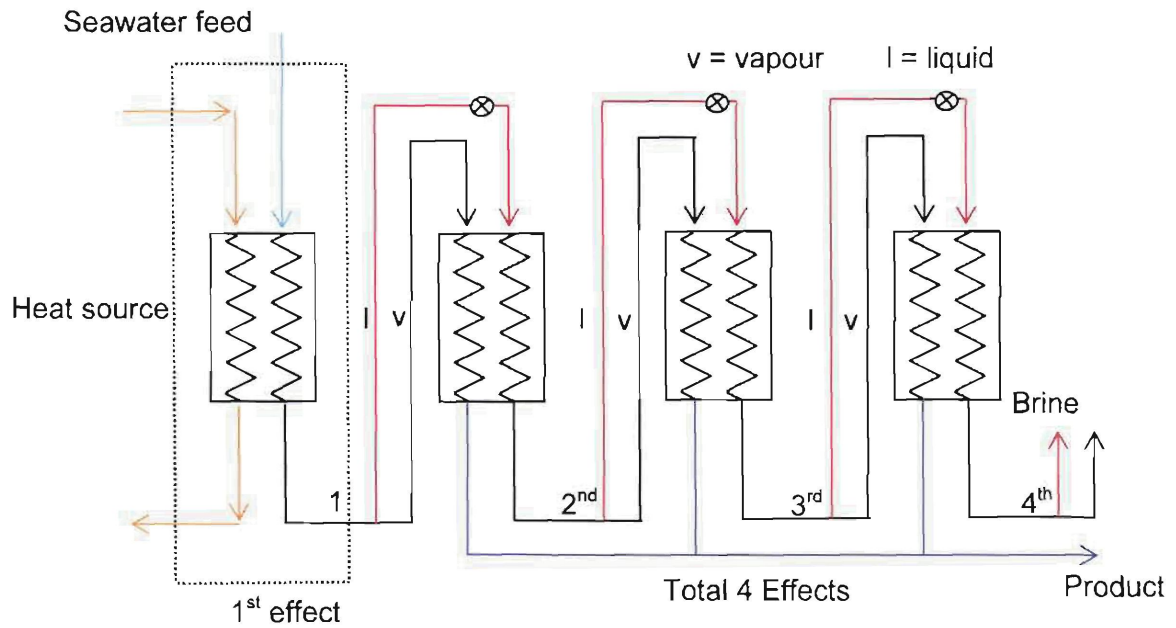


Figure 4-2: Forward Feed Configuration (FFC) process flow diagram

In the FFC, saline (brine) concentration levels increase from the first to the last effect. Mass feed flow decreases in each successive effect and thus the vapour-liquid mixture quality (x) increases from the first to the last effect. This leads to an increased salinity in the last stage evaporators. The total feed stream passes through the first effect and the total product is the sum of all the steam generated in each plant effect. Waste water is collected at the end of the plant cycle. The process T-S diagram can be seen in Figure 4-3. Note that the process flow diagrams are only conceptually illustrating the fluid flow in the MED plant and are by no means attempting to indicate the actual different tube layouts (tube in shell system) for the steam and vapour mix.

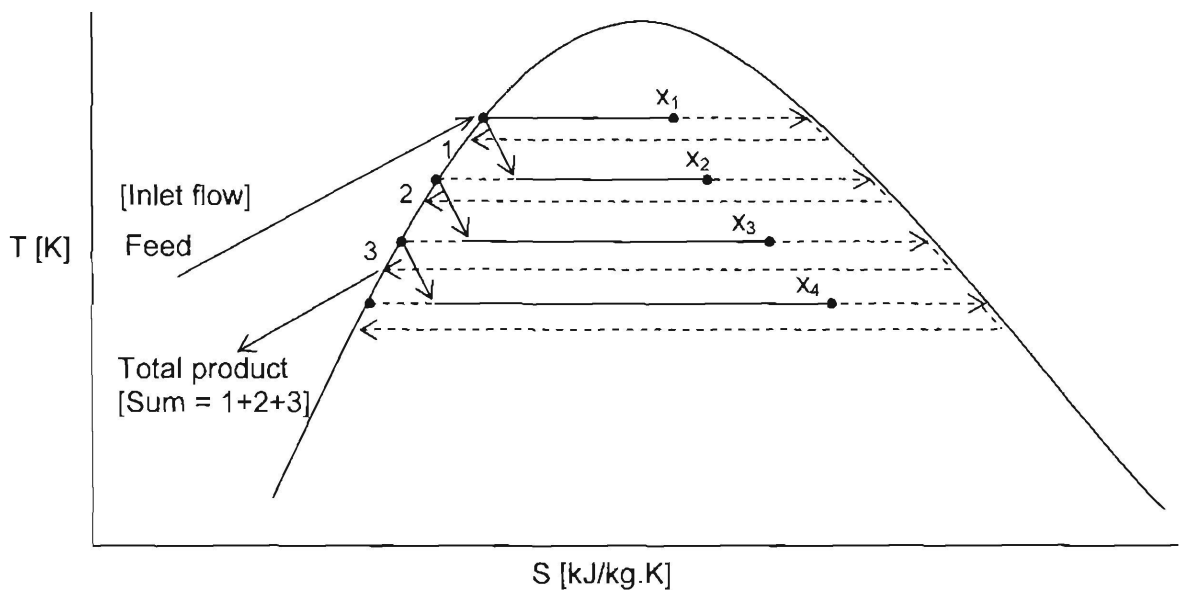


Figure 4-3: T-S Diagram for the FFC

4.2.2 Backward feed configuration (BFC)

The so-called *backward feed configuration* (BFC) is also utilized in MED systems today. In the BFC feed water flows to the last effect, via the final condenser, and flows progressively from the last effect to the first effect as seen in Figure 4-4. Feed water is pumped against the pressure gradient to each effect. Vapour and liquid are formed as products in each effect. Hot vapour is used as the “heat source” in the previous effect and the liquid is used as feed water in the downstream effect. Condensed vapour in each effect is collected as product fresh water. The fraction of seawater feed not evaporated at the end of the system, is collected from the first effect as total brine. Seawater is used in the final condenser to condense the vapour product formed in the last effect. Product and waste streams are collected at separate ends of the plant.

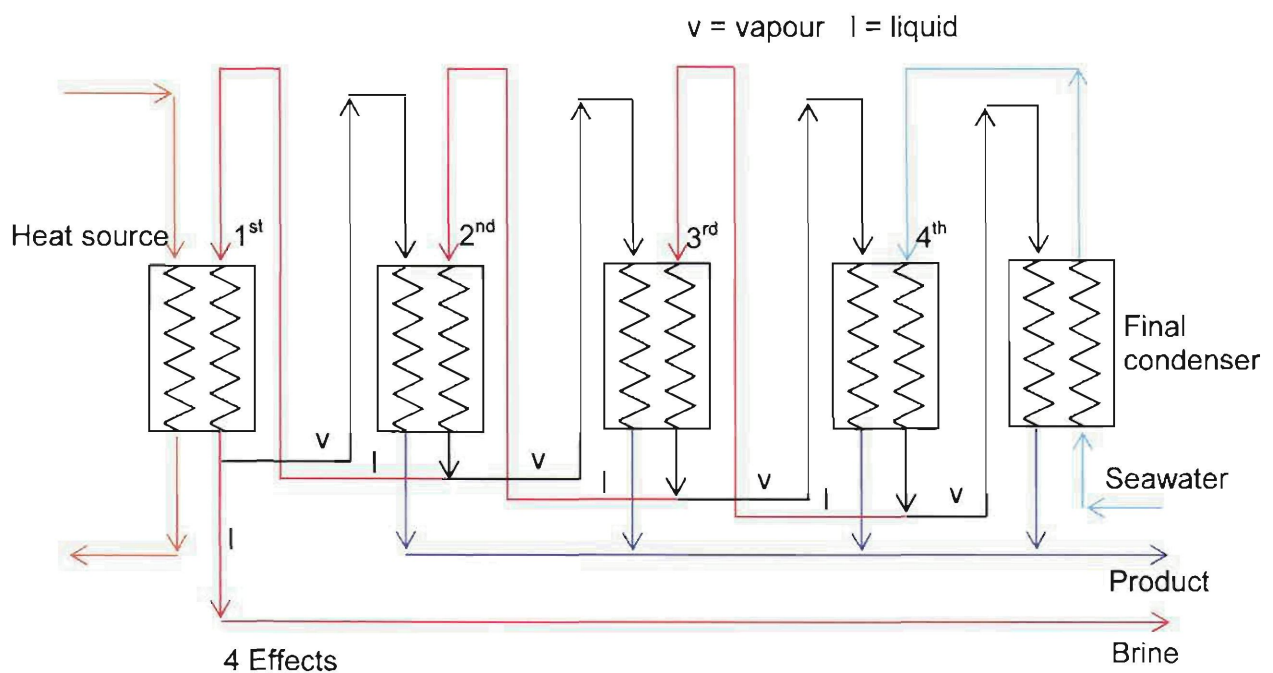


Figure 4-4: Backward Feed Configuration (BFC) process flow diagram

In the BFC, the feed water and product flow in opposite directions as opposed to in the same direction in the FFC. System pressure and temperature decreases from the first to last effect and saline (brine) concentration levels increase from the last to the first effect. The T-S diagram for the BFC is seen in Figure 4-5 and differs from the T-S diagram of the FFC. It is seen that the salinity increases from the last to the first effect as the feed decreases. This phenomena leads to possible fouling in the first stage evaporators since high temperatures exist at the inlet of the MED plant. The opposite is true for the FFC-MED plant.

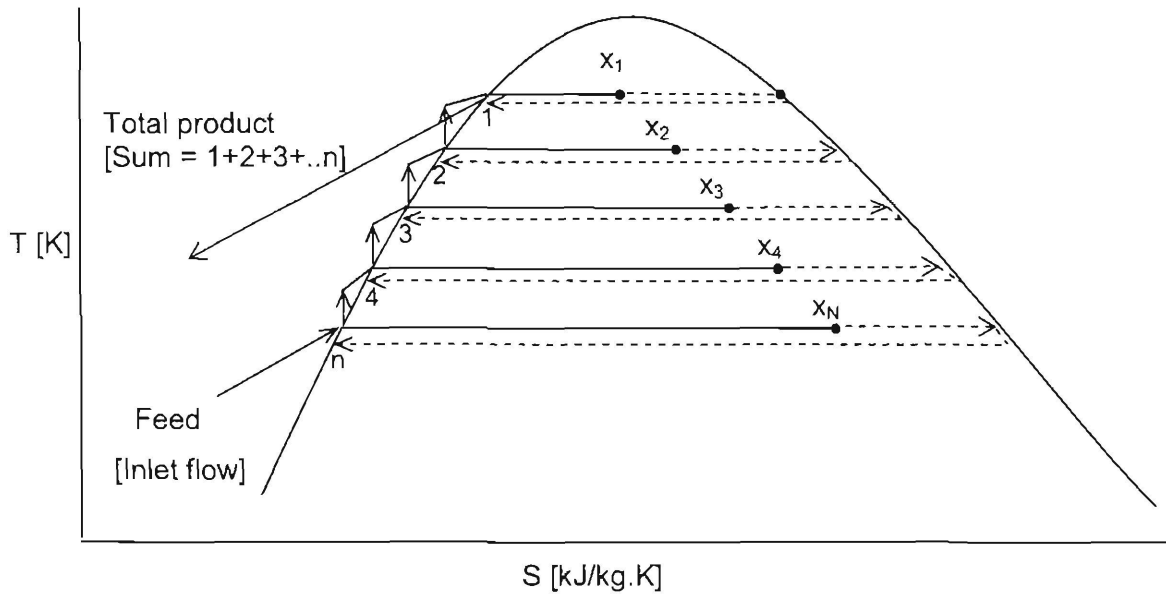


Figure 4-5: T-S Diagram for the BFC

4.2.3 Parallel feed configuration (PFC)

A *parallel feed configuration (PFC)* is also used in the secondary circuits of typical MED systems. In the PFC the main seawater feed stream is divided into multiple feed streams flowing to each effect separately in parallel as seen in Figure 4-6 and Figure 4-7. Vapour and liquid are formed as products in the first effect where the hot vapour is used as the “heat source” in the next effect to evaporate the separate seawater feed streams. The fraction of seawater feed not evaporated in each effect is collected as brine. The condensed vapour in each effect is collected as product fresh water. Seawater is used in the condenser to condense the vapour (steam product) formed from the last MED effect to produce product fresh water.

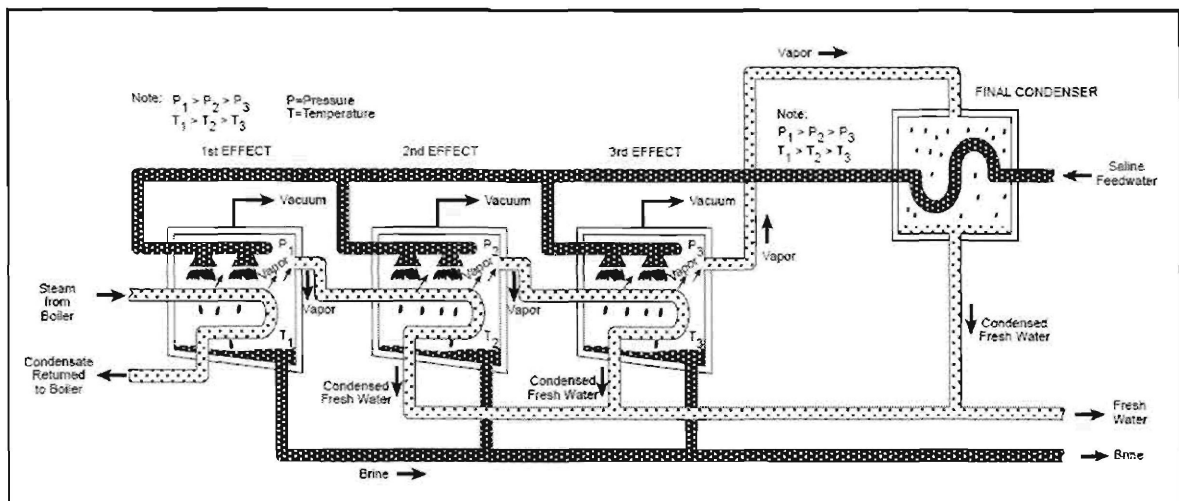


Figure 4-6: Parallel Feed Configuration (PFC) schematic illustration

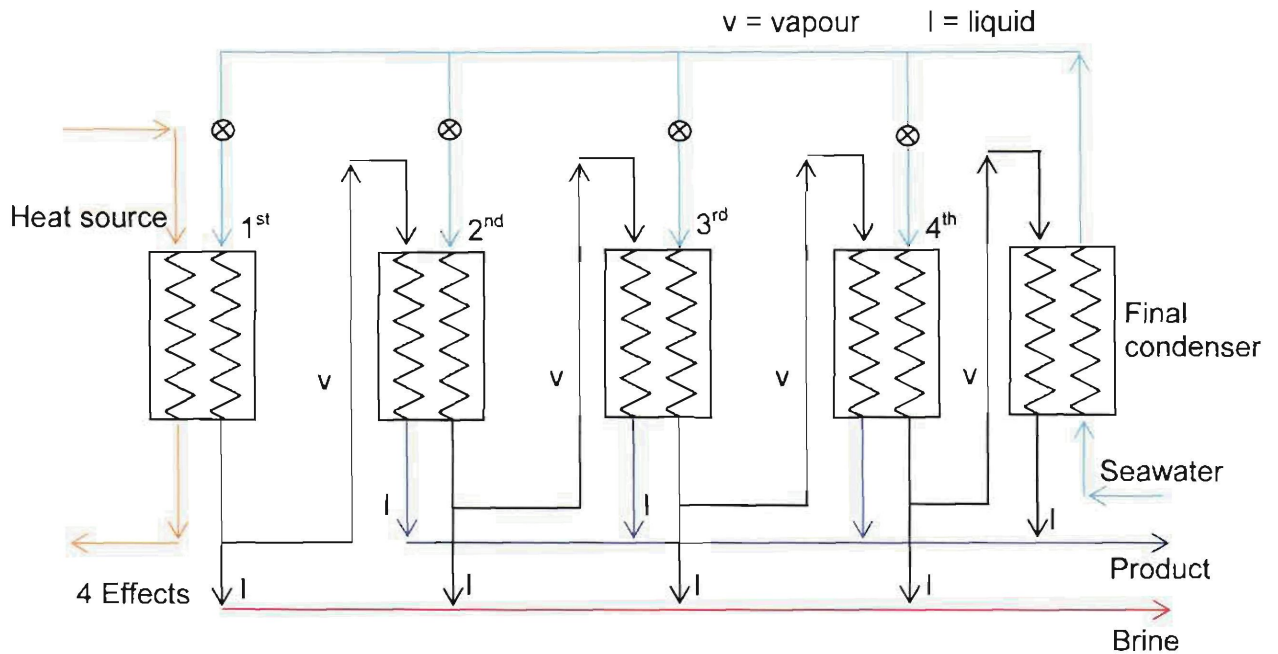


Figure 4-7: Parallel Feed Configuration (PFC) process flow diagram

Variable feed flows, which allow decrease of scaling problems, can be obtained. As the feed decreases from the first to the last effect, the salinity increases with decreasing temperature. This is a good design since the high salinity concentration is at low temperatures, causing less fouling in plant components. The T-S diagram for the PFC is seen in Figure 4-8. However, when designing desalination plants for salt production rather than for water production, brine concentration levels become a desired plant parameter and a trade-off between salt production capacity and plant cost exist.

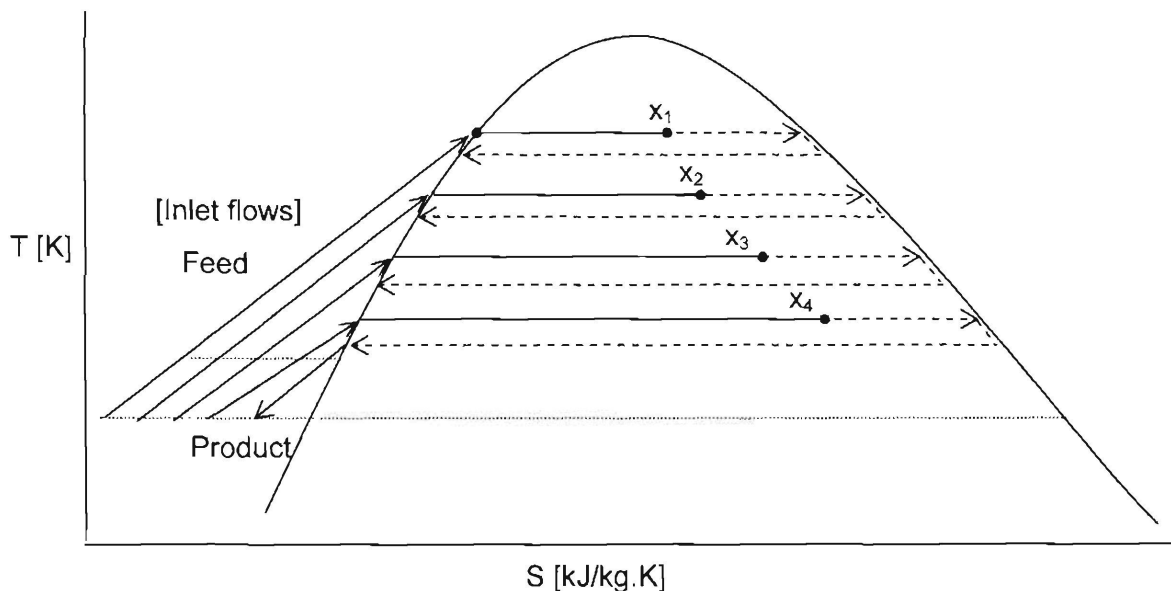


Figure 4-8: T-S Diagram for the PFC

4.3 MED brine utilization

A new concept for dealing with brine from desalination plants, which is economical and profitable rather than the costly disposal to the sea with potential damages to the ambient, has been in operation for the past 9 years in Eilat, Israel. Mekorot Water Company owns and operates a desalination plant in Eilat for the production of 10,000 m³/d of desalinated water. This peculiar plant, commissioned during June 1997, is practically dual purpose, for the production of desalinated water and also for the manufacture of high-quality table salt by the Israel Salt Company [Ravizky, 2006:374]. The concept of dual-purpose plants for the production of desalinated water and salt has additional economical benefits. Brine outfall facilities, and in particular the pipe entering the sea, are saved. The cost of the brine line entering the sea can be high because its length is generally a few hundred meters in order to prevent short circuits between the brine and feed streams. Also it is well known that works below seawater level are expensive.

Feed to the desalination plant is a blend of 80% seawater and 20% brine from adjacent plants [Ravizky, 2006:376]. The brine from the combined plant is blended with seawater, and this stream is fed to a series of evaporation ponds, and thereafter to the salt processing factory of the salt company. A brine discharge line and other discharge facilities are not needed. Their cost is saved. Also potential non-homogenous salinity distribution profile of the sea is prevented, leaving the sea fauna and flora untouched. Salt production in this configuration increased by 30% compared to salt production from seawater alone. The salt produced is of the highest quality within the range of the most severe standards.

When a single purpose desalination plant is designed in order to increase water production, the waste streams (brine) in the MED plant stages play a major role.

4.4 MED feed water preheating

In each process configuration product water is collected when hot vapour condenses. There is still a considerable amount of heat available in the different product streams. In the PFC, brine streams are collected as waste and discarded at the end of each stage or used as an additional feed to the next effect (to generate additional steam through flashing). Heat still available in the brine and product streams are often wasted and unavailable for reuse.

In the FFC and BFC, single feed water streams are used. If the number of effects increases in these plants, the amount of feed water needed to be heated stays constant since the total feed flows through all effects. In the case of the PFC, more

feed streams are needed when the number of effects increases and thus more feed streams need to be heated.

For example, in the PFC, brine from the first effect can be pumped to a pre-heat feed water heat exchanger to utilize EOC heat and thus preheat incoming feed water fed to the second effect. Similarly condensed vapour (product) from the first effect can also be used to perform pre-heating. Different heat exchangers are used when preheating is done. The preheating heat exchangers are water-to-water heat exchangers whereas the steam generating effects are steam-to-water heat exchangers. Remember that this heat utilization increases the GOR or PR since less heat is now used for input to the system. This process continues for a number of effects depending on the capacity of the plant. The choice for preheating becomes a trade-off between the cost of additional heat exchangers and increased product capacity. This needs to be evaluated. A condenser is used at the end of the process to condense the final vapour feed to form fresh water. Figure 4-9 illustrates a possible preheating configuration used in the PFC.

Similar system plant modifications can be applied to the FFC in order to increase the performance of the FFC system.

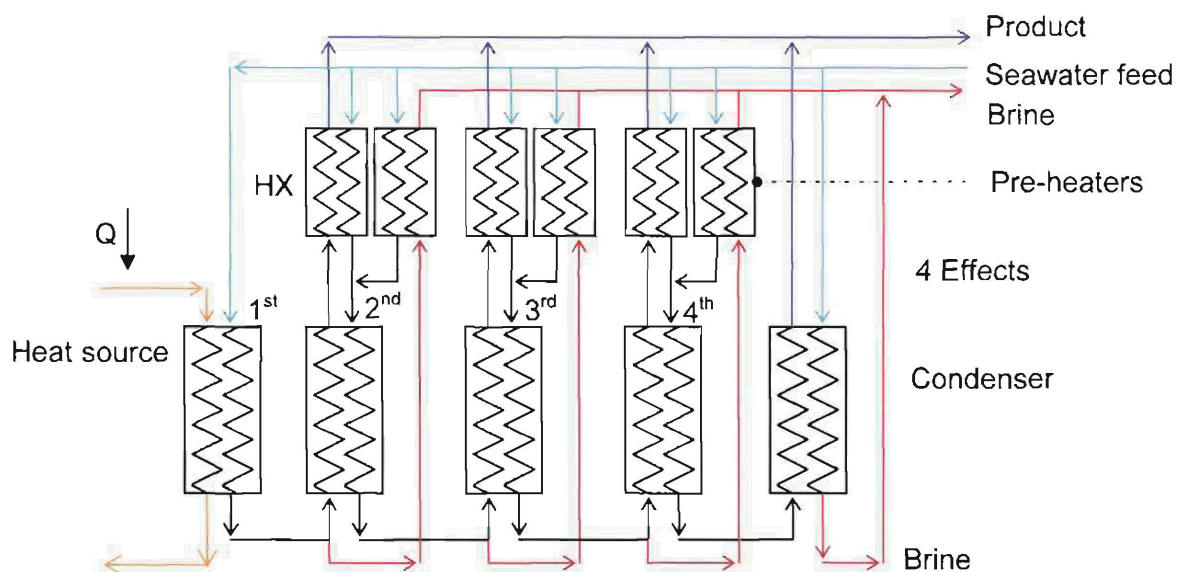


Figure 4-9: Example of preheating in the PFC

4.5 MED configurations characteristics

Each configuration needs to be evaluated as an integrated system in order to determine the different advantages and disadvantages of each configuration.

4.5.1 Configuration advantages

The advantages of the Forward Feed Configuration (FFC) are:

- i. Less fouling in the heat exchanging equipment since lower salinities are achieved at higher temperatures.
- ii. Less pumping power is needed in order to pump feed water through the plant. This leads to an increased PR or GOR since more energy is available for water production.
- iii. Simpler layout and lower cost due to less piping.

The advantages of the Backward Feed Configuration (BFC) are:

- i. More efficient system and better steam economy,
- ii. No need for pre-heaters.

The advantages of the Parallel Feed Configuration (PFC) are:

- i. Controllability of feed streams in order to avoid fouling and scaling. As the feed streams decreases from the first to last stage, the salinity increases at lower temperatures.
- ii. Increased water production with preheating.
- iii. Flexibility of system.
- iv. Can utilize end-of-cycle heat in brine streams more effectively to produce more product water. Additional brine flashing in effects can be achieved.

4.5.2 Configuration disadvantages

The disadvantages of the Forward Feed Configuration (FFC) are:

- i. Limited configuration.
- ii. Ineffective configuration for utilization of process heat. Lower steam economy.
- iii. Pre-heaters needed.

The disadvantages of the Backward Feed Configuration (BFC) are:

- i. High salinity at higher temperatures leads to possible fouling.
- ii. More pumps needed in order to pump against the pressure gradient.

The disadvantage of the Parallel Feed Configuration (PFC) is:

- i. Increased water production requires more energy to preheat all the feed streams.

4.6 Conclusion

Different process configurations which are utilized in practical MED plants today were identified and each mode of operation was discussed. The possibility of recovering heat from waste streams by means of preheating was discussed. Preheating should be evaluated in terms of additional plant costs versus increased production levels. Possible advantages and disadvantages of each configuration were identified and analyses in the following chapters will highlight even more characteristics of the different configurations. The next step is to develop a generic model which can be used to analyze and simulate MED plant configurations.

Chapter 5

MED Plant Performance Prediction

"Everyone understands that water is essential to life. But many are only just now beginning to grasp how essential it is to everything in life – food, energy, transportation, nature, leisure, identity, culture, social norms, and virtually all the products used on a daily basis." - World Business Council for Sustainable Development (WBCSD).

"You could write the story of man's growth in terms of his epic concerns with water." - Bernard Frank

CHAPTER 5 MED PLANT PERFORMANCE PREDICTION

5.1 Introduction

Various mathematical tools are used today to simulate and design MED plants. In order to gain greater understanding of MED desalination, a MED analysis model was developed. This model is described and validated in this section in order to perform MED plant performance investigations and comparisons in the next chapter. All three MED configurations, namely the FFC, BFC and PFC, are thermodynamically analysed and compared with each other. Plant parameters, such as plant capacity (product), performance indices (GOR, α), number of plant effects and AU-values for the heat exchangers, are investigated. Preheating options are also incorporated in the MED model. Assumptions made during the development of the MED model are also shown.

5.2 MED analysis model

It can be seen that the MED model is based on a system design approach rather than a detail design approach. The C++ model input for the different configurations are all the same in order to evaluate each configuration under the same design specifications. Note that the different configurations only differ in terms of number of feed streams and the product flow directions. This model evaluates both steam and water heat sources, utilized in each configuration type, by altering the plant layout and heat distribution in the C++ code. The MED C++ model is based on the schematic layouts of the different MED configurations as shown in *Appendix C*. The different model parameters and fluid property positions are indicated on the diagrams in order to give better clarity to the C++ model. Different definitions, used in this section, are shown in Table 5-1.

Table 5-1: MED model definitions

Definitions	Description
AU ₁ -value	AU-value of the water-to-steam effect steam generators (HXs) in the main circuit.
AU ₂ -value	AU-value of the water-to-water and steam-to-steam pre-heaters (HXs).
i-index	Refers to the effects in serie
j-index	Refers to the parallel circuits
Parallel circuit	Consecutive coupled effects in serie forms a parallel circuit.

5.2.1 C++ Model overview

The method of approach, followed during the development of the MED model, is discussed in this section. Model input parameters, valid for all configurations, are shown in Table 5-2. These input parameters are the only design inputs from the user.

Table 5-2: Model input parameters

Input parameter	Description
T_{max}	Maximum available heat source temperature
T_{feed}	The inlet feed water temperature
ΔT_1	Temperature difference across each serie effect
ΔT_2	Temperature difference across each parallel circuit
ΔT_{pinch}	The temperature difference allowed for pinching in the heat exchangers.
T_{min1}	Exit steam temperature in last effect
T_{min2}	The temperature at exit of last parallel circuit
MW	Heating water flow rate
PR	Product ratio. Ratio of total product flow over total inlet flow for circuit as a whole.

From these input parameters the number of parallel circuits utilized in the MED plant is calculated:

$$N_2 = \frac{T_{max} - T_{min2}}{\Delta T_2} \quad (5.1)$$

Likewise, the number of serie effects can also be calculated according to:

$$N_1 = \left[\frac{T_{max} - T_{min1}}{\Delta T_1} + 1 \right] \quad (5.2)$$

The additional effect is the steam generator (1st effect). The number of effects is rounded to the nearest integer and a new ΔT_1 and ΔT_2 are calculated to fit with this new practical calculated number of effects according to:

$$\Delta T = \frac{T_{max} - T_{min}}{N} \quad (5.3)$$

Boundaries of each layout and the total number of effects in the plant are now known. The calculated number of effects and updated ΔT_1 and ΔT_2 determine the layout of the SHS-mode and WHS-mode plants. Number of effects in WHS-mode and SHS-mode is now known and can be compared with each other. The steam temperature of the 1st effect is calculated as:

$$T_{steam} = T_{max} - \Delta T_2 - \Delta T_{pinch} \quad (5.4)$$

Next, calculate the amount of heat required (q_1), to evaporate 1 kg of feed water (mm_1) in the first effect, and the amount of external heat available to drive the circuit. The latter is calculated according to:

$$q_h = m_w \times cp_w \times \Delta T_2 \quad (5.5)$$

Amount of product water produced is then determined. Remember that the product ratio¹ is an input parameter and defined as:

$$PR = \frac{\text{Total product flow}}{\text{Total feed}} = \frac{\sum_{i=1}^{N_1} ms_i}{mm_1} \quad (5.6)$$

For the SHS option the amount of product water is determined by defining the ratio r_s which could then be used to determine the product:

$$r_s = \frac{m_w \times cp_w \times (T_{\max} - T_{\min 2})}{q_1} \quad (5.7)$$

$$m_{\text{product}} = mm_1 \times r_s \times PR \quad (5.8)$$

For the WHS option the amount of product water is determined by defining the ratio r_w which could then be used to determine the product:

$$r_w = \frac{q_h}{q_1} \quad (5.9)$$

$$m_{\text{product}} = mm_1 \times r_w \times PR \quad (5.10)$$

It can be seen that q_1 and the amount of steam generated in each effect are the unknown variables that need to be determined in order to solve the circuits. Steam and feed concentrations vary in each configuration and lead to an inverse design problem needed to be solved since the PR specified is dependant upon the unknown steam produced in each effect. A Newton-Raphson method is used to solve this inverse design problem given the PR for the circuit as a whole. The mass steam is calculated and the PR is evaluated until the value converges to the specified PR value. Assume $PR_1 = PR$. Stream mass balances of each configuration stage are shown in Figure 5-1, Figure 5-2 and Figure 5-3.

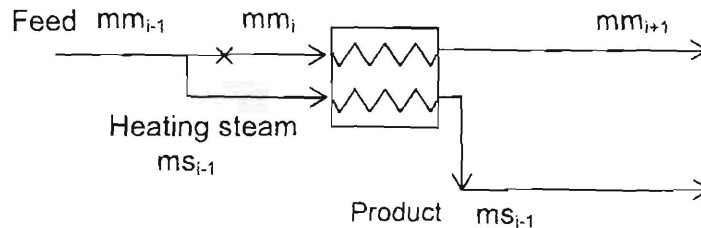


Figure 5-1: Mass balance of a FFC effect

¹ Note that in this section the variable PR refers to the product ratio and not the performance ratio as defined in Chapter 3.

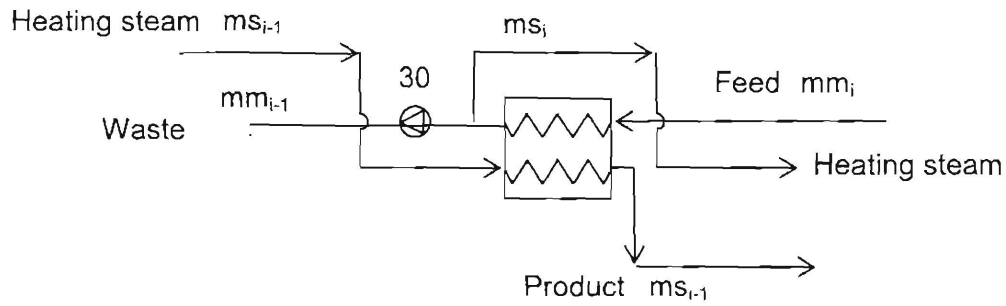


Figure 5-2: Mass balance of a BFC effect

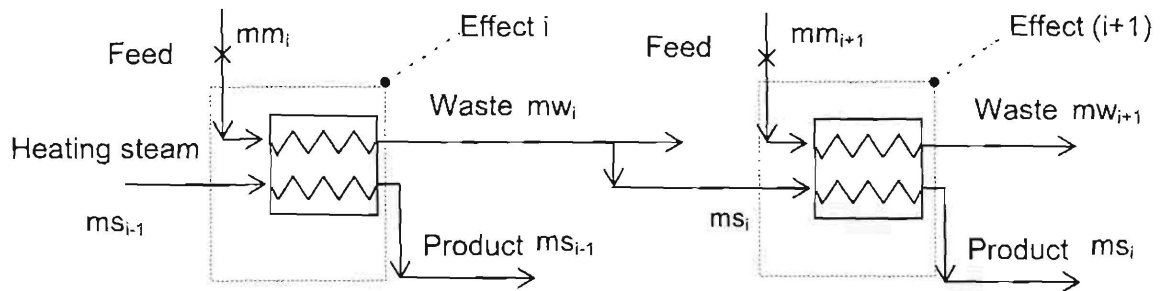


Figure 5-3: Mass balance of a PFC effect

The following steps are used to calculate the *unknown variables*:

- i. For a first iteration or guess assume that the steam produced in each effect is equal:

$$ms_1 = ms_2 = ms_3 = \dots = ms_N \quad (5.11)$$

Then the total product could be determined from:

$$\sum_{i=1}^{N_1} ms_i = N_1 \times ms_1 \quad (5.12)$$

- ii. Combining (5.6) and (5.12) then the amount of steam generated in the first effect is determined according to (5.13):

$$ms_1 = (mm_1 \times PR_1) / N_1 \quad (5.13)$$

- iii. Assume mass balance at the outlet of the first effect and calculate the quality and fluid temperature at the exit of the first effect.

$$x_1 = \frac{ms_1}{mm_1} \quad (5.14)$$

$$t_1 = T_{\text{stream}} \quad (5.15)$$

- iv. The fluid and vapour properties are calculated at the different positions in the system (see Figure C-1 for all property locations).

$$p_1 = \text{function}(t_1, x = 0) \quad (5.16)$$

$$h_f = \text{function}(t_1, x = 0) \quad (5.17)$$

$$h_{in} = \text{function}(T_{feed}, p_1) \quad (5.18)$$

$$h_{ff} = \text{function}(t_1 - 10, p_1) \quad (5.19)$$

The cp-value for the first effect is then calculated as:

$$cp_1 = (h_f - h_{ff})/10 \quad (5.20)$$

The inlet temperature of the feed water to the first effect needs to be determined in order to calculate the heat required in first effect. Consider the last effect now as seen in Figure C-1. The fluid and vapour enthalpy at the outlet of the final condenser:

$$h_f = \text{function}(T_{min1}, x = 0) \quad (5.21)$$

$$h_g = \text{function}(T_{min1}, x = 1) \quad (5.22)$$

$$\begin{aligned} &\text{IF } (ms[N_1] \times [h_g - h_f]) > (mm_1 \times cp_1 \times (\Delta T_{min1} - \Delta T_{feed})) \\ &\text{THEN } h_{in} = \text{function}(p_1, T_{min1} - \Delta T_{pinch}) \\ &\text{ELSE } h_{in} = ms[N_1] \times ([h_g - h_f] / mm_1) + h_{in} \end{aligned} \quad (5.23)$$

Now calculate q_1 according to:

$$h_{g_1} = \text{function}(t_1, x = 1) \quad (5.24)$$

$$h_1 = h_f + x_1(h_{g_1} - h_f) \quad (5.25)$$

$$q_1 = mm_1 \times (h_1 - h_{in}) \quad (5.26)$$

This same methodology is applied for the rest of the effects in each configuration. Total product flow is the sum of all the steam generated in the effects. The system is solved without preheating ($k=0$) and with preheating ($k=1$). Heat recovered from the product streams is calculated according to:

$$q_r = ms_i \times c_p \times (t_i - T_{in} - \Delta T_i) \quad (5.27)$$

In preheating mode ($k=1$) the q_r value is subtracted from q_1 since less heat is now required to evaporate 1 kg of feed water. The q_1 value decreases and the ratios r_s and r_w increases according to (5.7) and (5.9). Water production levels thus also increase now according to (5.8) and (5.10). This indicates that preheating of feed water increases water production levels. AU-values of the different heat exchanger types are also incorporated. The AU values for the water-to-steam heat exchangers (main stages) are calculated according to:

a. For the pre-heaters of the feed water:

$$AU_1 = (mm_1 \times \Delta h) / \Delta T_1 \quad (5.28)$$

b. For all other effect heat exchangers:

$$AU_1 = q_1 / \text{LMTD} \quad (5.29)$$

$$\text{LMTD} = \frac{[(t_{h1} - T_{\text{steam}}) - (t_{h2} - T_{\text{steam}})]}{\ln((t_{h1} - T_{\text{steam}})/(t_{h2} - T_{\text{steam}}))} \quad (5.30)$$

$$t_{h2} = T_{\text{steam}} + \Delta T_{\text{pinch}} \quad (5.31)$$

$$t_{h1} = t_{h2} + \Delta T_2 \quad (5.32)$$

The AU values for the water-to-water and steam-to-steam heat exchangers (pre-heaters) are calculated according to:

$$AU_2 = q_r / \Delta T_1 \quad (5.33)$$

The relative performance ratio, α , can now also be calculated:

c. For the SHS-option:

$$\alpha = \left(\frac{m_{\text{product}}}{q_1 \times \Gamma_s} \right) / N_1 \quad (5.34)$$

d. For the WHS-option:

$$\alpha = \left(\frac{m_{\text{product}}}{Q_{\text{sum}}} \right) / \left(\frac{N_{\text{sum}}}{N_2} \right) \quad (5.35)$$

The Gained Output Ratio (GOR) is calculated for the SHS-option according to:

$$h_{11} = \text{function}(T_{\text{max}}, x = 0) \quad (5.36)$$

$$h_{22} = \text{function}(T_{\text{max}}, x = 1) \quad (5.37)$$

$$m_{\text{steam}} = (mw \times cp_w \times (T_{\text{max}} - T_{\text{min}2})) / (h_{22} - h_{11}) \quad (5.38)$$

$$\text{GOR} = m_{\text{product}} / m_{\text{steam}} \quad (5.39)$$

5.3 MED model validation study

The MED model needs to be validated before system simulations can be done. Desalination plant design validations are important since different mathematical models have been developed each with different process (model) assumptions and configuration layouts. This is due to many different MED plant designs being utilized in different countries and regions of the world where energy availability and water needs differ. The ideal validation would be with actual plant data and relevant literature, but limited plant data is available and the process flow configuration utilized in the plant is normally unknown to the researcher. Another obstacle is that currently only steam heat sources are evaluated with desalination software. These programs also do not utilize the exact same system configuration as identified in this study since user needs differ worldwide. For example, preheating of feed streams with waste or brine is usually not a design option in these programs, but the brine rather

flows to the next effect for additional evaporation by means of flashing. This method also increases the product capacity.

Validation simulations were initially performed with the CAMEL® software, but this particular software is more suitable for detail design calculations where exact plant component dimensions are needed. Using CAMEL® it is essential to have initial guess values, such as heat exchanger characteristics, as accurate as possible to ensure that the solution can be found. Detail calculations of heat transfer coefficients and component dimensions were not determined with the MED model. The validation study was rather performed using the program MEE-TVC, which seemed more suitable for a system design approach. An overview of the MEE-TVC software can be seen in *Appendix A*.

Validation case study, *Test Case 1*, is now being simulated with the C++ model and with the MEE-TVC software. Results are compared with each other. In *Test Case 1* a parallel feed configuration (PFC), without preheating, is chosen as the validation configuration layout. *Test Case 1* operates in SHS-mode. In the C++ model no preheating of feed water is done and in the MEE-TVC program the brine is allowed to flash in the next effects. It can be seen, from the MEE-TVC results in *Appendix A*, that flashing contributes little to the steam production. The C++ model system parameters and plant layout identified can be seen in Table 5-3 and Figure 5-4.

Verification studies were performed using EES (Engineering Equation Solver) in order to verify the calculation of the different fluid properties, stream flows (mass balances) and product streams in C++. The verifications were found satisfactory and correct.

Table 5-3: Test case 1 – C++ model evaluation system parameters

System Parameter (Input)	Test case SHS Plant	Plant layout & Capacity (Output)	Test case SHS Plant
T_{max} [°C]	70	N_1	8 effects
T_{feed} [°C]	20	N_2	n/a
ΔT_1 [°C]	2.5	N_{sum}	8 effects
ΔT_2 [°C]	5.0	Alfa [kg/MW/ N_{avg}]	0.34
ΔT_{pinch} [°C]	1	Product [m^3/d]	10921.5
T_{min1} [°C]	43	Product [kg/s]	126.4
T_{in} [°C]	42	ΔT_1 (actual) [°C]	≈3.0
T_{min2} [°C]	50	AU1[kW/K]	112,905.4
mw [kg/s]	555		
ms [kg/s]	19.9	GOR	6.35
Product Ratio (PR)	0.50	LMTD	2.9

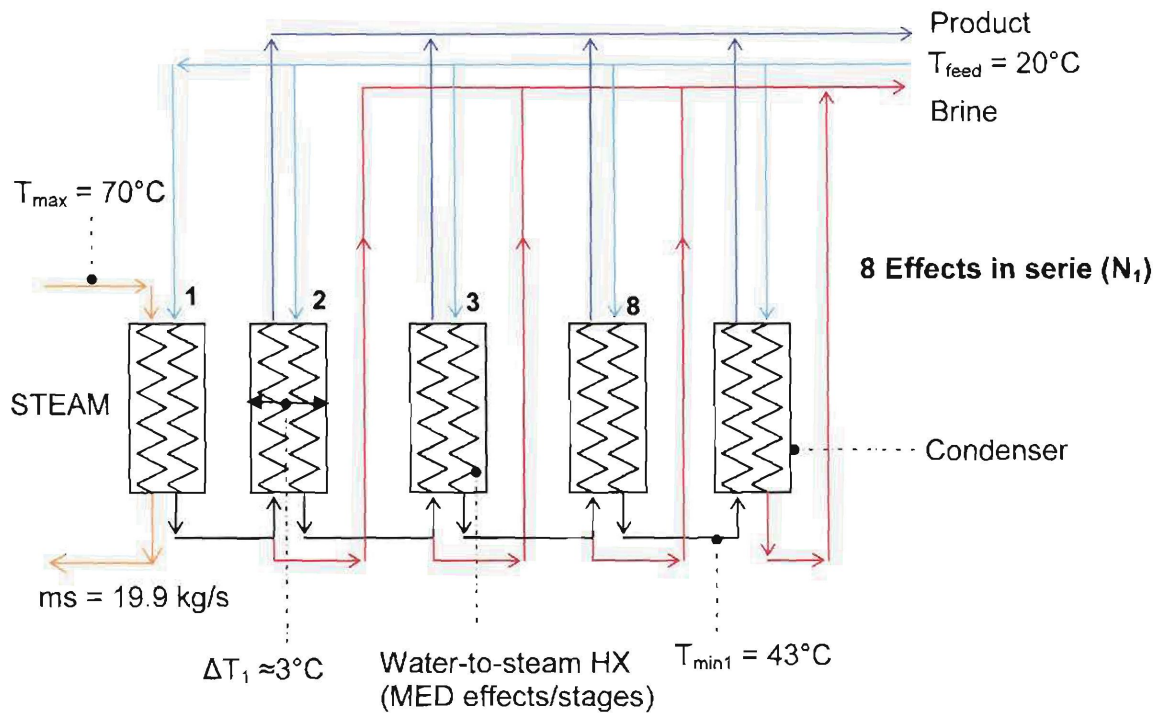


Figure 5-4: Test case 1 – C++ model SHS plant (without preheating) layout

Model system parameters and the plant layout configuration identified for the simulation with MEE-TVC can be seen in Table 5-4 and Figure 5-5. Component characteristics, such as evaporator and condenser dimensions are given as default values. Complete validation results with the MEE-TVC program can be seen in Section A.1.

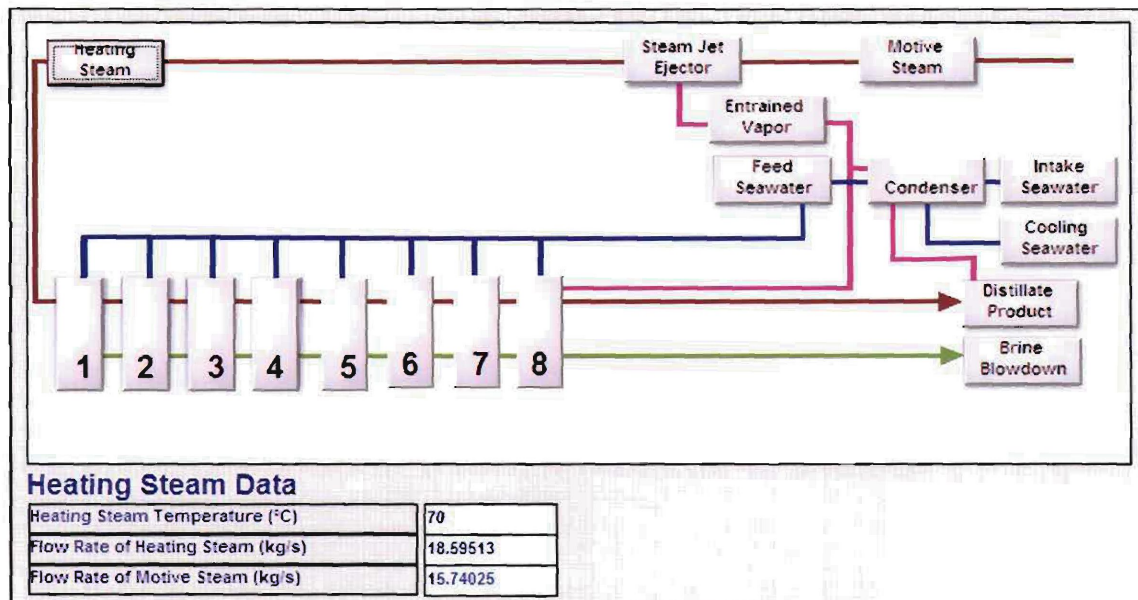


Figure 5-5: Test case 1 – MEE-TVC SHS plant (without preheating) layout

Table 5-4: Test case 1 – MEE-TVC system parameters

System User Parameter (Input)	Test case SHS Plant	System Default Parameter (Input)	Test case SHS Plant
Number of effects	8	Outer diameter of evaporator tubes	0.025 [m]
Plant capacity	10 921.5 [m ³ /d]	Wall thickness of evaporator tubes	0.005 [m]
Heating steam temperature	70 [°C]	Wall thickness of condenser tubes	0.005 [m]
Rejected brine temperature	43 [°C]	Outer diameter of condenser tubes	0.025 [m]
Feed temperature	42 [°C]	Thermal conductivity of evaporator tubes	0.042 [kW/m°C]
Intake seawater temperature	20 [°C]	Thermal conductivity of evaporator tubes	0.042 [kW/m°C]
Feed salinity	35000 [ppm]	Fouling resistance in evaporator	0.1 [°C/kW]
Salinity of brine leaving each effect	70000 [ppm]	Fouling resistance in condenser	0.1 [°C/kW]
Compression ratio	3	Length of evaporator tubes	7 [m]
Pressure of motive steam	31 [kPa]	Length of condenser tubes	7 [m]
Vapour velocity in demister	5 [m/s]	Demister thickness	0.5 [m]
		Demister density	300 [kg/m ³]

Table 5-5: Test case 1 – Validation comparison

Parameter	C++ MODEL	MEE-TVC	% Difference
Plant effects	8	8	-
Plant capacity [m ³ /d]	10 921.5	10 921.5	-
GOR	6.35 (MEE ²)	6.797 (MEE) 8.03 (MEE-TVC ³)	6.58 %
Heating steam flow rate [kg/s]	19.9	18.6	6.53 %
ΔT_1 [°C]	3	3.2-3.5	9%
Recovery ratio	0.5	0.51	2%

From the validation Case Study 1 comparison (Table 5-5) it was found that the same amount of external heat is distributed through 8 serie MED effects, producing the same amount of water product. Plant performance of both simulations also compares well (6.58% difference), but the MEE-TVC case leads to a higher GOR when thermal

² Multi-Effect Evaporation

³ Multi-Effect Evaporation with Thermal Vapour Compression

vapour compression is used. Thermal vapour compression usually increases the plant performance and production since higher steam pressures and temperatures are achieved, allowing a higher temperature range for the MED process.

Brine temperature and pressure distributions in the MED plant also compare well, as seen in Figure 5-6 and Figure 5-7, and indicate similar flow profiles through the MED plant. The stage temperature differences shown in Figure 5-8 differ slightly because of the higher pressures associated with thermal vapour compression.

It is assumed that the developed MED model performs and reacts similarly to other system design tools. This is evident in the following process graphs.

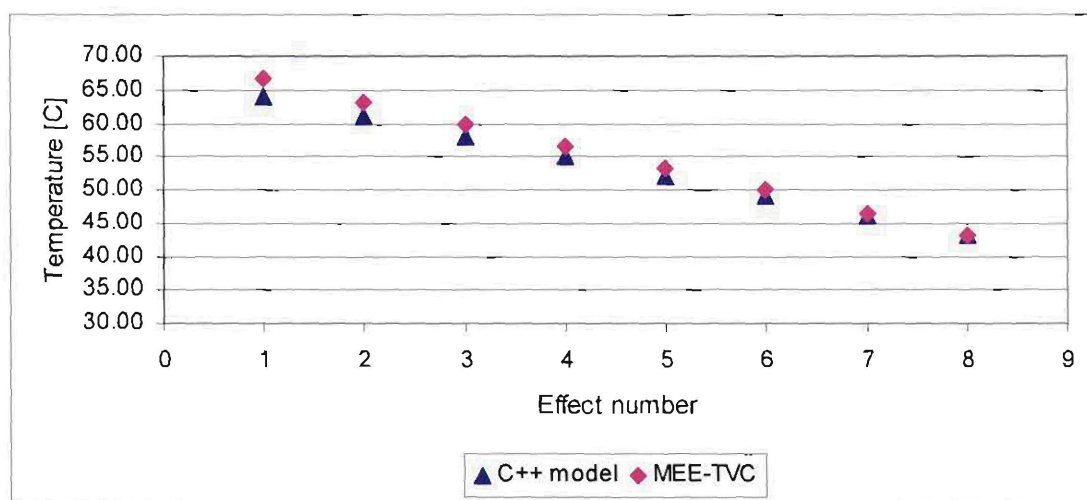


Figure 5-6: Test case 1 - Brine saturation temperature comparison

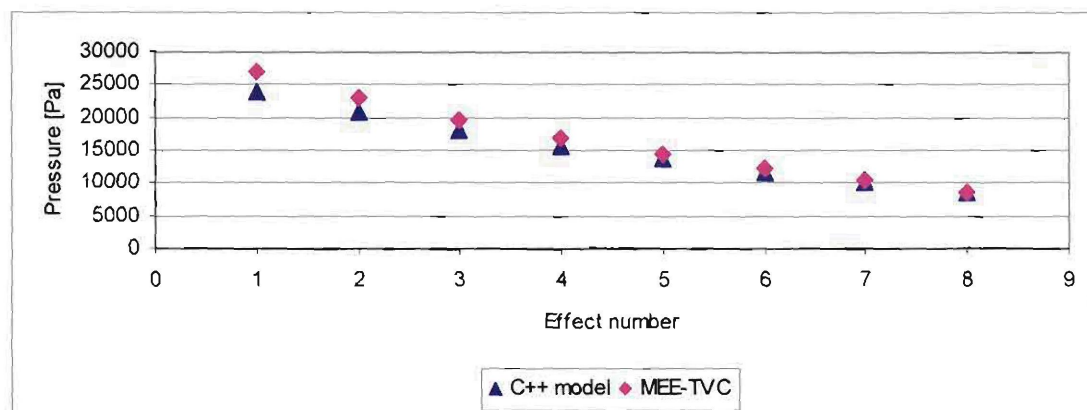


Figure 5-7: Test case 1 - Brine saturation pressure comparison

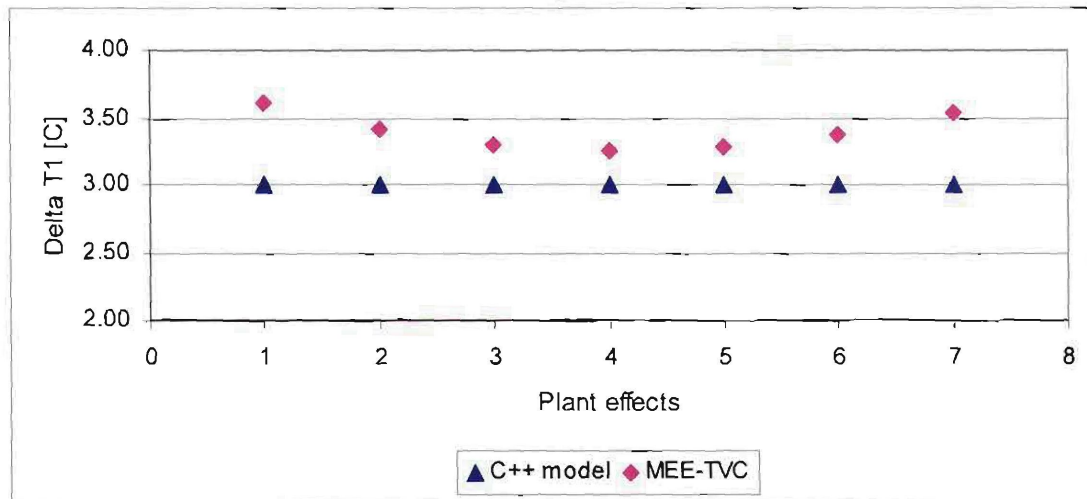


Figure 5-8: Test case 1 – Serie effect temperature differences comparison

The uniqueness of this study is the fact that different MED process configurations, under the same plant design conditions, are evaluated thermodynamically in order to identify the optimum MED process flow configuration. Performing system simulations will indicate further advantages and disadvantages of each configuration.

5.4 Conclusion

The MED analysis model was described. Methodology followed in order to evaluate the plant performance was thus indicated. It was stated that desalination literature and software, which describe the exact plant conditions as in the C++ model, are often limited. Validation simulations were performed with the C++ model and MEE-TVC software. With the same amount of external heat supply both systems perform similarly in terms of GOR and product levels. The same brine steam and pressure distribution is found in both systems indicating similar steam streams produced in each effect. It is concluded that the developed MED model is a valid simulation tool. The next step would be to investigate plant performance using the MED analysis model.

Chapter 6

Investigation Studies

"Anyone who can solve the problems of water will be worthy of two Nobel prizes, one for peace and one for science" - John F. Kennedy

*"Till taught by pain, men really know not what good water is worth."
From "Don Juan" by Byron*

CHAPTER 6 INVESTIGATION STUDIES

6.1 Introduction

In order to optimize MED plant designs and gain more understanding into MED desalination technology it is important to perform system simulations. By varying different plant parameters and evaluating the sensitivity of the plant performance one can obtain valuable insight into the important system parameters. This knowledge will allow for optimized plant designs and thus ultimately lower water product costs. Analyses of the different process flow configurations are performed and different factors which influence system efficiency and plant production capacities are shown. The effect of heat source utilization in MED plants is also assessed.

Various case studies are evaluated in order to fully understand the effect of different system parameters on the plant performance. In each case a different system parameter is varied. The MED plant layout is then determined by calculating the number of serie effects, parallel circuits and total number of plant effects according to the varying and fixed parameters. This allows for sensitivity analyses over a range of plant effects.

6.2 Nature of heat source evaluation

6.2.1 System input parameters

In Case Study 1 the aim is to evaluate the effect of heat source utilization on the cost and water production of MED plant configurations. The system input parameters chosen for Case Study 1 are illustrated in Table 6-1. The assumptions of the ΔT_1 and ΔT_2 are made based on acceptable values used in modelling MED type plants. The mass flow of the water is also chosen based on possible flow rates in the PBMR plant.

Table 6-1: System input parameter assumptions for Case Study 1

Parameter	Value
T_{max}	70 [°C]
T_{feed}	20 [°C]
ΔT_1	5 [°C]
ΔT_2	7 [°C]
ΔT_{pinch}	1 [°C]
T_{min1}	30 [°C]
T_{min2}	40 [°C]
mw	555 [kg/s]
Product Ratio (PR)	0.8

6.2.2 System configuration

Plant cost is related to the number of plant effects and pumping equipment. Water production is related to the total amount of steam produced in the plant. The system input parameters are evaluated and the number of serie and parallel effects is calculated in order to determine the practical plant layout for the WHS and SHS mode of operations. Note that the same number of serie effects and parallel circuits are used for each configuration. Connectivity of feed water streams, brine and product flows, in the system, are the only differences. The MED plant, in SHS-mode, consists of 7 effects in one circuit as seen in Figure 6-1.

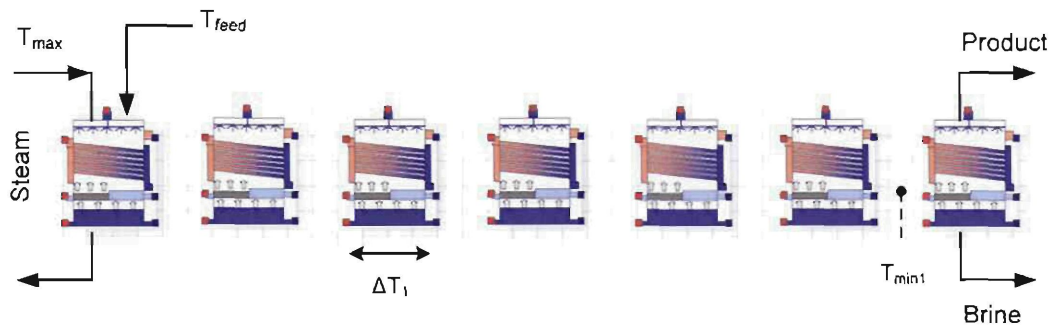


Figure 6-1: Case Study 1: SHS plant layout

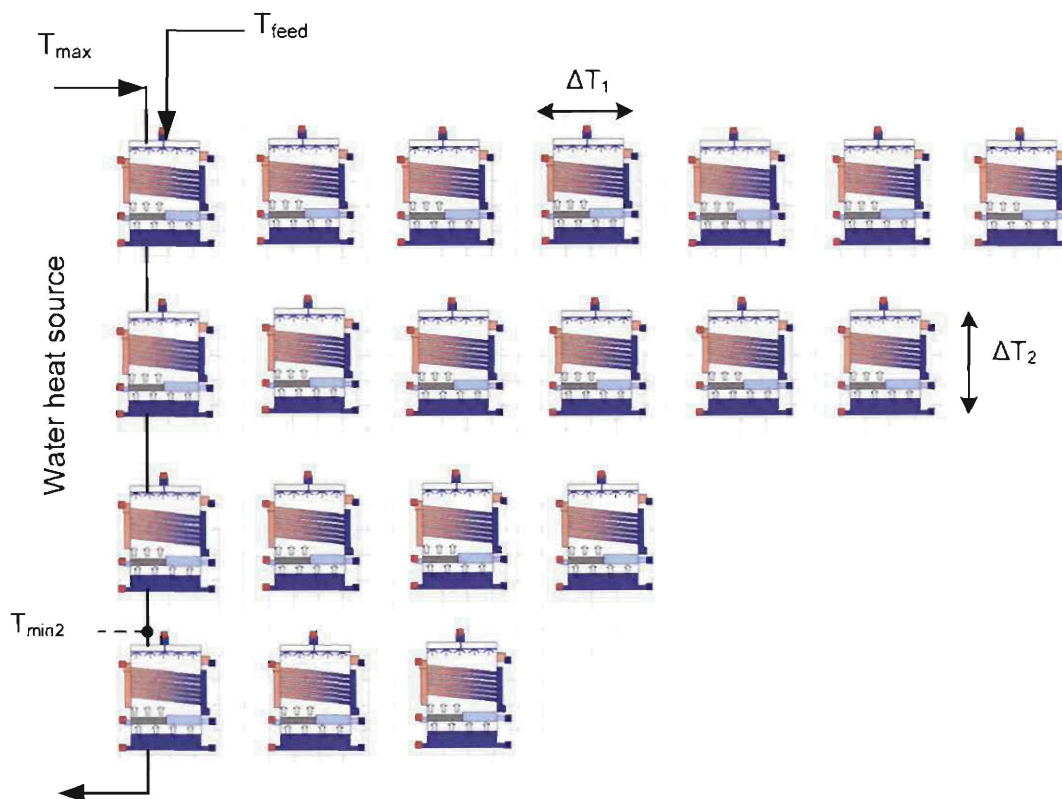


Figure 6-2: Case Study 1: WHS plant layout

The MED plant, in WHS-mode, consists of 7 effects in the first parallel circuit. A total of 4 parallel circuits are utilized. As seen in Figure 6-2 the total number of plant effects is 20. It can be concluded that the WHS-plant has higher cost implications than the SHS-plant. This is due to the nature of the heat source. Pre-heaters are not shown here and only the water-to-steam main effect steam generators are indicated.

6.2.3 Preliminary system results

The preliminary results indicate the number of MED plant effects utilized in order to produce a certain amount of product water. Each configuration is evaluated in a steam heat source (SHS) mode and water heat source (WHS) mode and also shows the effect of preheating on the plant product capacity. The temperature and pressure distributions in a FFC (SHS) plant are shown in Figure 6-3 and Figure 6-4. Similar distributions were calculated for other configurations, but are not shown here. Different plant configuration product capacities for Case Study 1 are indicated in Table 6-2, Table 6-3 and Table 6-4.

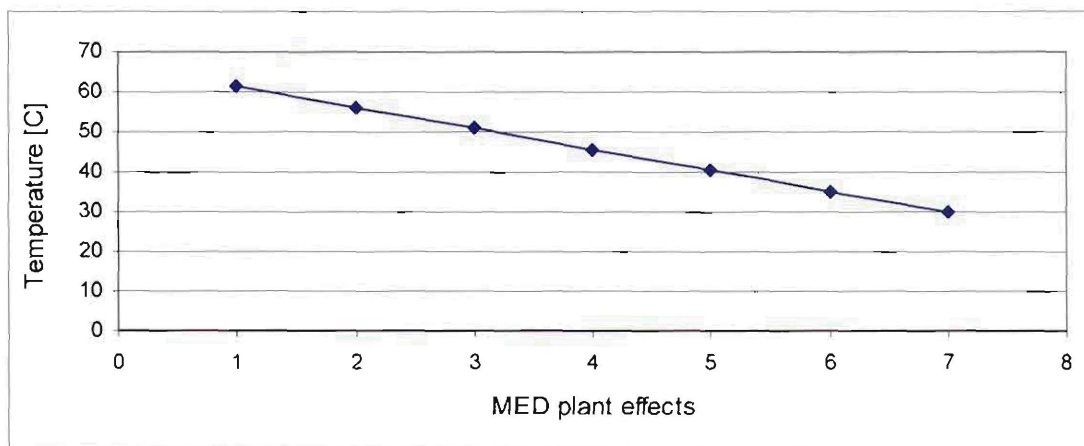


Figure 6-3: Brine temperature distribution in FFC (SHS) MED plant

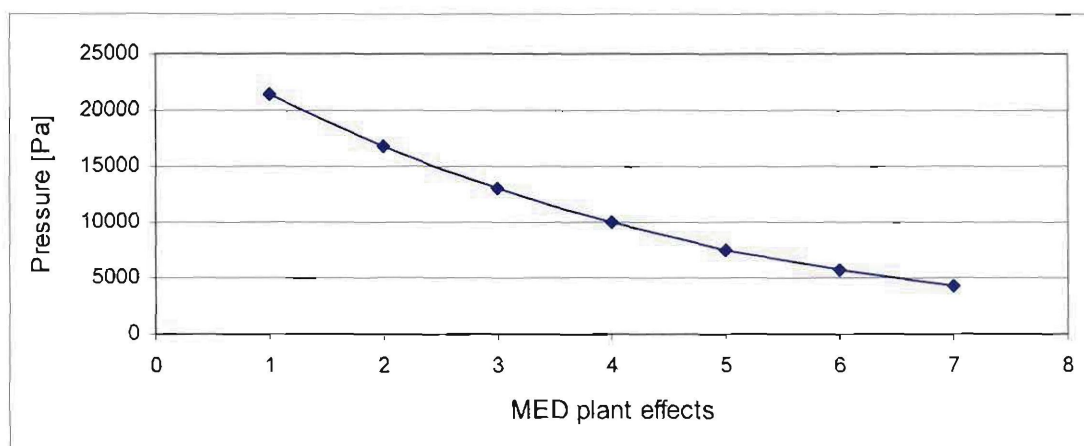


Figure 6-4: Brine pressure distribution in FFC (SHS) MED plant

Table 6-2: Production capacity levels (Case Study 1, FFC)

FFC (Steam Heat Source)	Without Preheating	With Preheating
N ₁	7	7
N _{sum}	7	7
Product	13,286 [m ³ /day]	14,824 [m ³ /day]
FFC (Water Heat Source)	Without Preheating	With Preheating
N ₁	7	7
N ₂	4	4
N _{sum}	20	20
Product	10,453 [m ³ /day]	11,166 [m ³ /day]

Table 6-3: Production capacity levels (Case Study 1, BFC)

BFC (Steam Heat Source)	Without Preheating	With Preheating
N ₁	7	n/a
N _{sum}	7	n/a
Product	15,400 [m ³ /day]	n/a
BFC (Water Heat Source)	Without Preheating	With Preheating
N ₁	7	n/a
N ₂	4	n/a
N _{sum}	20	n/a
Product	11,486 [m ³ /day]	n/a

Table 6-4: Production capacity levels (Case Study 1, PFC)

PFC (Steam Heat Source)	Without Preheating	With Preheating
N ₁	7	7
N _{sum}	7	7
Product	14,769 [m ³ /day]	16,432 [m ³ /day]
PFC (Water Heat Source)	Without Preheating	With Preheating
N ₁	7	7
N ₂	4	4
N _{sum}	20	20
Product	11,172 [m ³ /day]	11,900 [m ³ /day]

6.2.4 Preliminary system observations

From Case Study 1 the following observations can be made:

- i. Preheating in both the FFC and PFC leads to an approximate increase of 8-10% in configuration product production levels. The BFC requires no preheating. As more effects are utilized in a PFC, an increase of 30% in product production levels is possible with preheating.
- ii. In all three configurations the use of a steam heat source leads to 25-35% higher product production levels than when a water heat source is utilized.

also be utilized which leads to higher production levels. However, more plant effects are utilized in WHS-mode. For example a ΔT_1 of 3°C across the plant stages of a PF1-configuration (WHS) leads to 12 plant effects in the first of 4 parallel circuits with a total of 32 plant effects. A plant capacity of $19\,000\text{ m}^3/\text{day}$ is obtained. It is clearly seen that, as the fixed design temperature difference across the serie stages decreases, the water production increases for both the SHS and WHS plants. However, the number of plant stages, which relate to cost, increases as well.

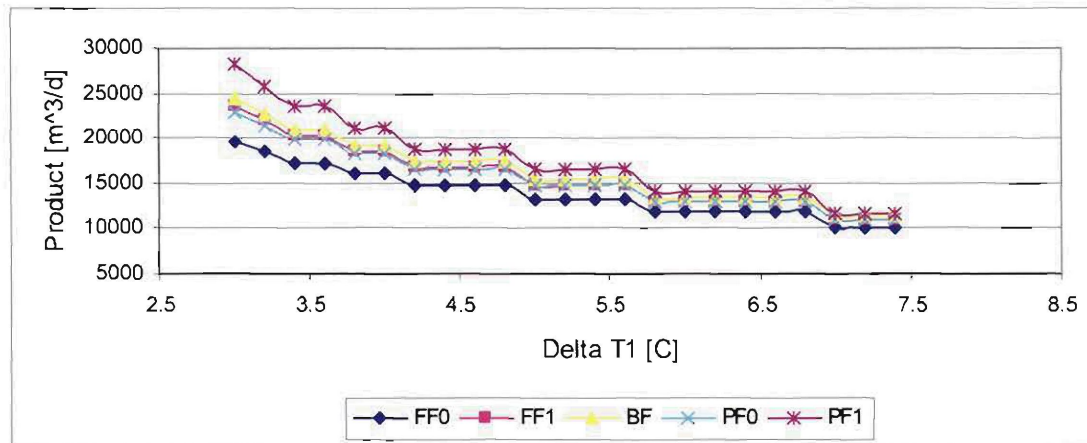


Figure 6-5: Case study 2: Comparison of product capacities in SHS mode

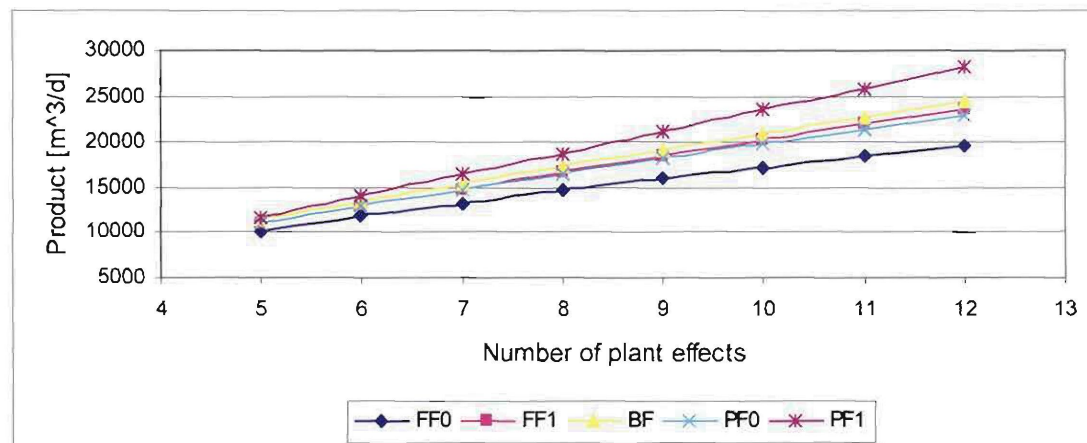


Figure 6-6: Case study 2: Comparison of product capacities in SHS mode

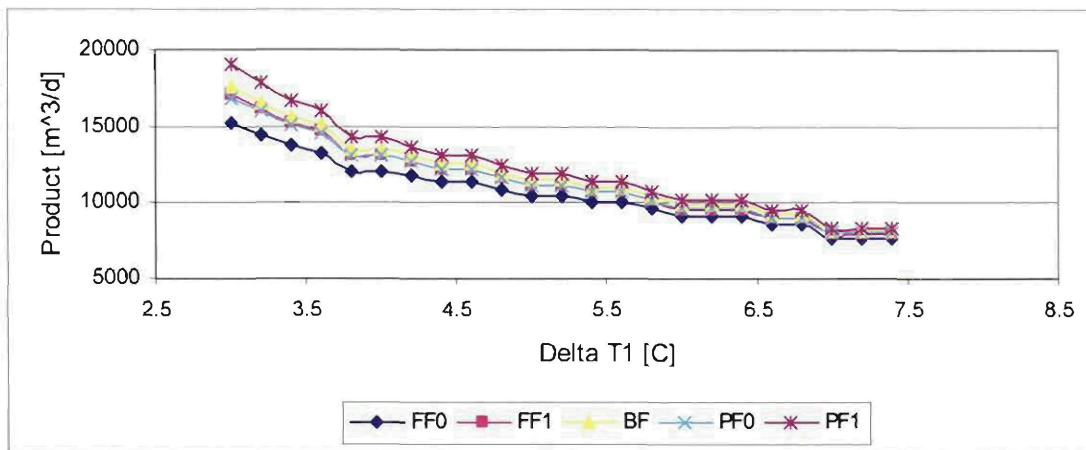


Figure 6-7: Case study 2: Comparison of product capacities in WHS mode

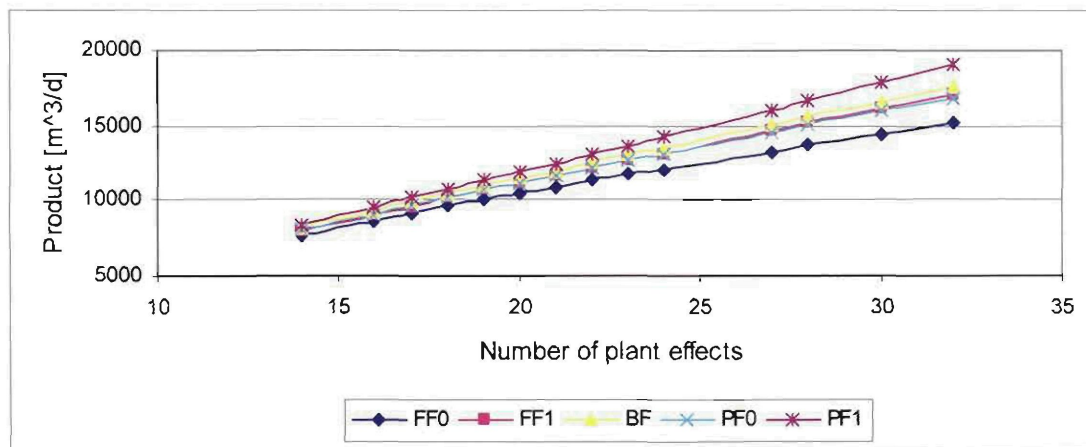


Figure 6-8: Case study 2: Comparison of product capacities in WHS mode

When ΔT_1 decreases, more effects can be utilized and the GOR value increases. In the ideal configuration (PF1) the GOR approaches the number of plant effects.

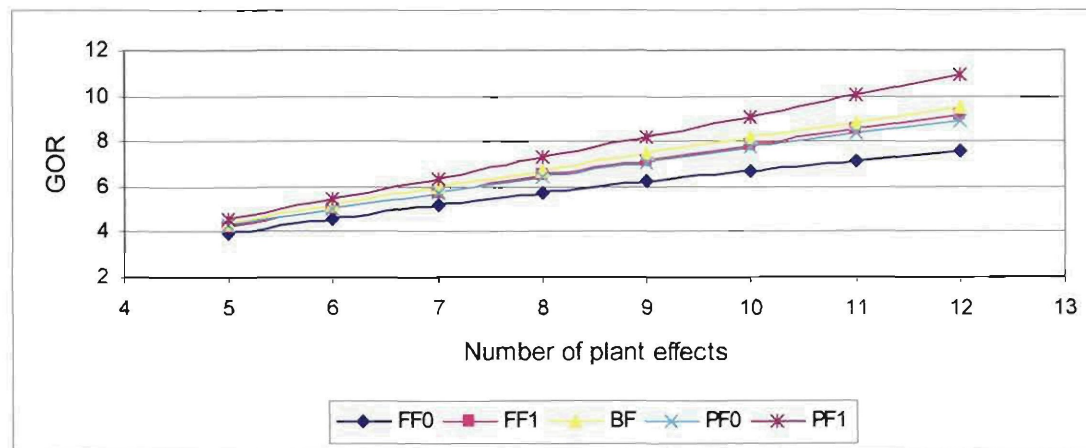


Figure 6-9: Case study 2: Gained Output Ratios for SHS plant

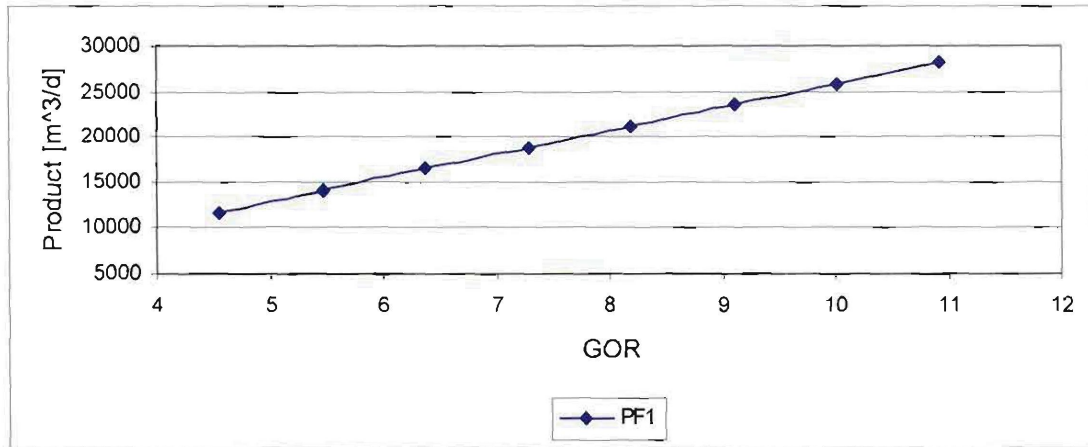


Figure 6-10: Case study 2: Gained output ratio vs plant capacity (SHS)

A comparison of relative performance ratios in SHS-mode and WHS-mode is also evaluated. It is seen from Figure 6-11 and Figure 6-12 that as the number of plant effects increases, the relative performance ratios (α) decrease (although the performance ratio increases) since more water needs to be preheated now. As the fixed design temperature difference across the serie stages increases, the relative performance ratio also increases. In all configurations, except the PF1 configuration, the WHS-mode of operation performs relatively better than the SHS-mode since more average effects are utilized at lower temperatures (where less energy is consumed). In the SHS-mode all the stages operate at higher temperatures requiring more heat. In the PF1 configuration all the heat for preheating is recovered.

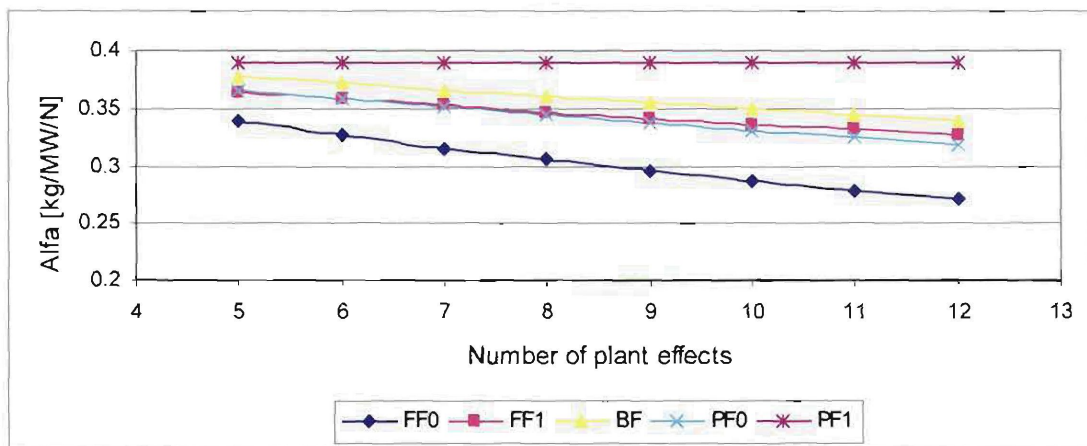


Figure 6-11: Case study 2: Relative performance ratios in SHS mode

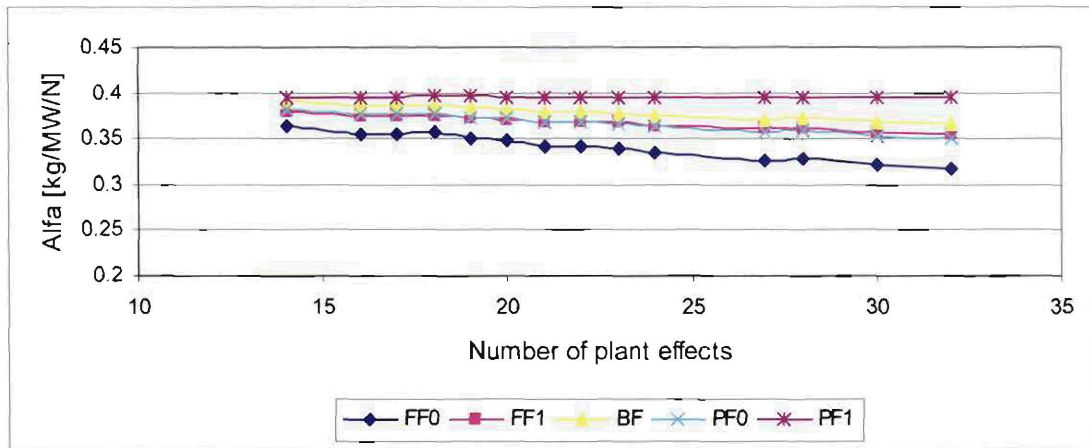


Figure 6-12: Case study 2: Relative performance ratios in WHS mode

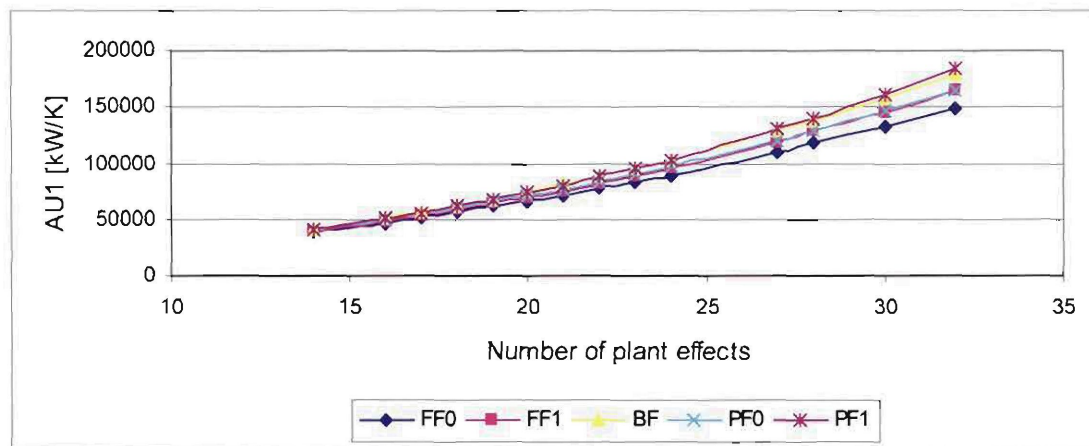


Figure 6-13: Case study 2: AU-values for water-to-steam effects/HX (WHS)

The AU-value of a heat exchanger is usually a good indication of the cost of the heat exchanger. Evaluating the total AU-value of the MED plant (WHS) will indicate the cost implication of the specific configuration. It is seen from Figure 6-13 that as ΔT_1 decreases, the number of effects (stages) required increases which leads to a large increase in the AU-values. It seems that the BFC and PFC have higher plant cost implications than the FFC. In configurations with preheating (FF1&PF1) the number of plant effects determines the amount of preheating needed. It is seen in Figure 6-14 that as ΔT_1 decreases, the number of effects (stages) increases which leads to an exponential increase in the AU-values for the pre-heaters. When preheating is done the PFC has the higher cost since the BFC requires no pre-heating.

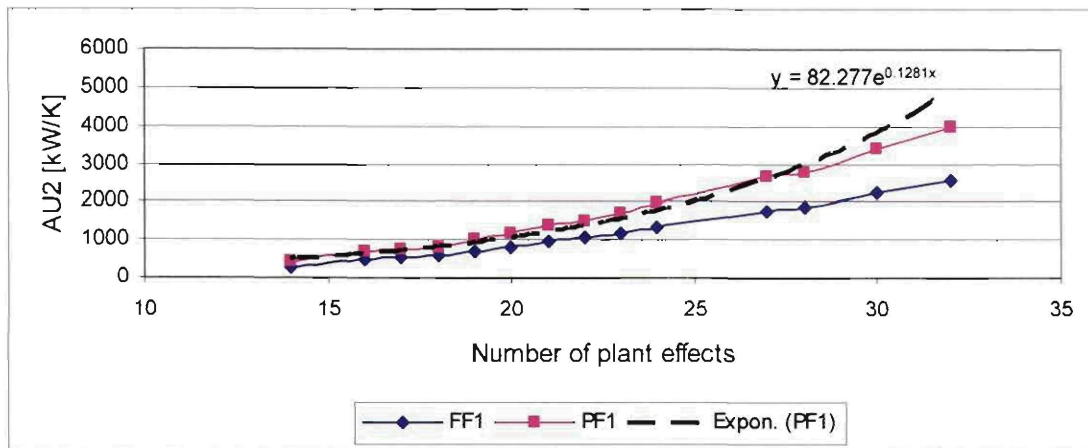


Figure 6-14: Case study 2: Comparison of AU-values for pre-heaters (WHS)

6.4 Varying parallel-circuit temperature difference

In Case Study 3 the aim is to investigate the sensitivity of plant performance when the temperature difference across each parallel circuit is varied. The temperature difference is varied between 4 and 10°C. It is seen from Figure 6-16 that as the temperature difference across the parallel circuits decreases, more plant effects can be utilized which leads to slightly increased production levels. A ΔT_2 of 4°C across each parallel circuit of a FF0-configuration (SHS) leads to 13 plant effects in serie with a plant capacity of 19 900 m³/day. A ΔT_2 of 4°C across each parallel circuit of a FF0-configuration (WHS) leads to 13 plant effects in the first of 8 parallel circuits with a total of 68 plant effects. A plant capacity of 15 750 m³/day is obtained. As the fixed design temperature difference across the parallel circuits decreases, the water production increases for both the SHS and WHS plants. However the number of plant stages required increases as well and therefore the costs as well. It seems that the water product production levels are not influenced too much by a varied ΔT_2 .

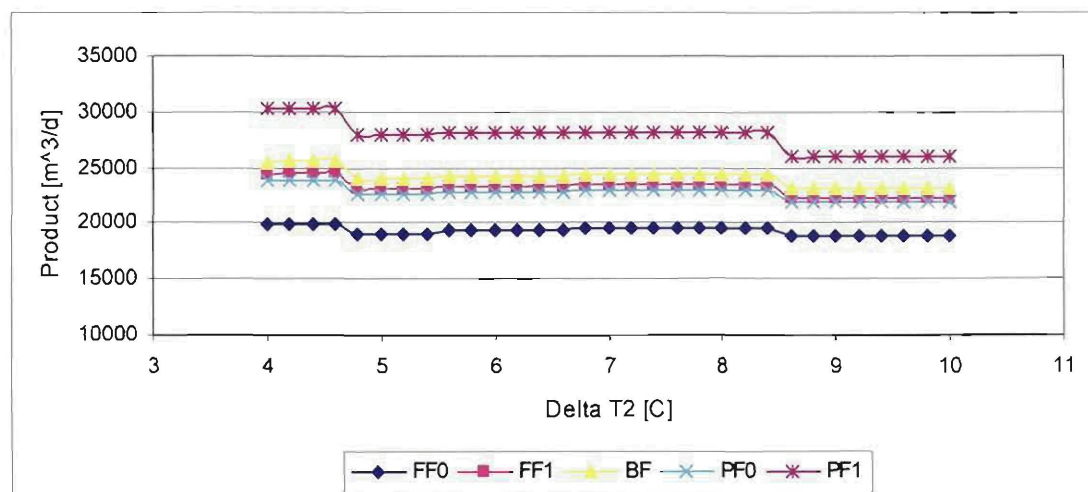


Figure 6-15: Case study 3: Product capacities in SHS mode

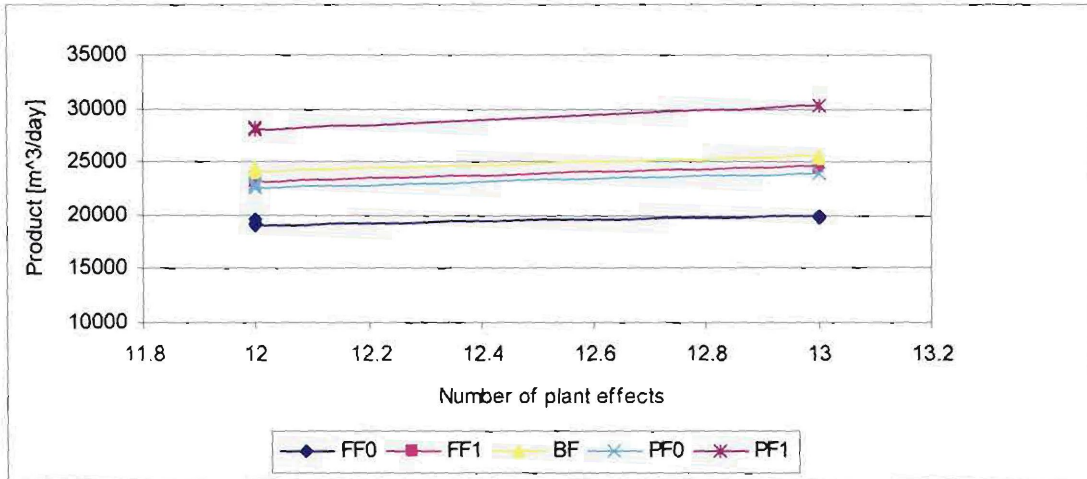


Figure 6-16: Case study 3: Product capacities in SHS mode

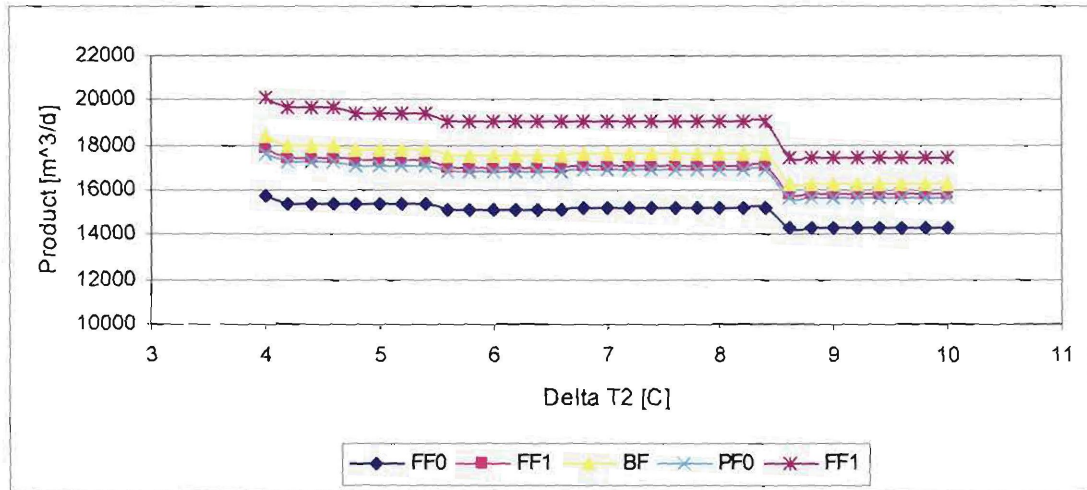


Figure 6-17: Case study 3: Comparison of product capacities in WHS mode

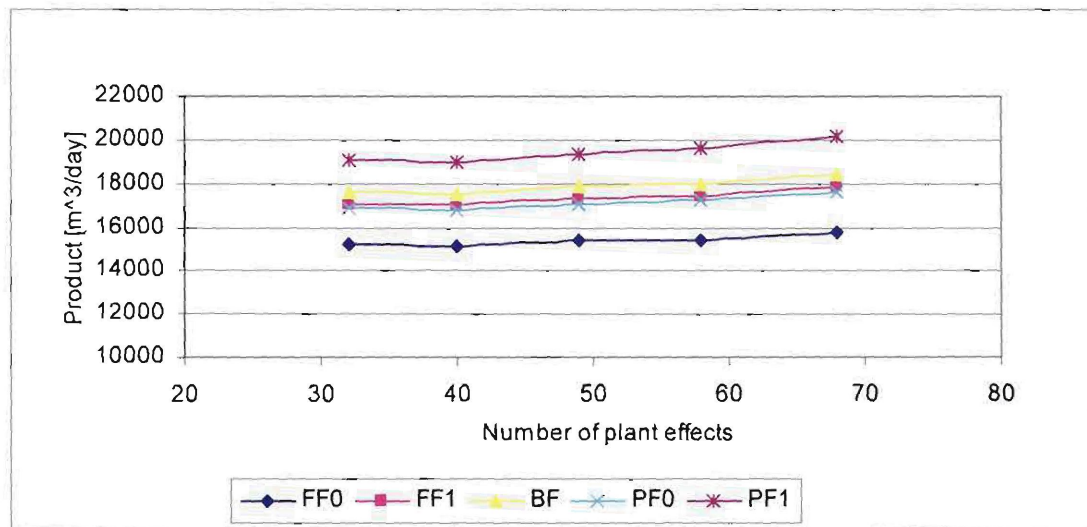


Figure 6-18: Case study 3: Comparison of product capacities in WHS mode

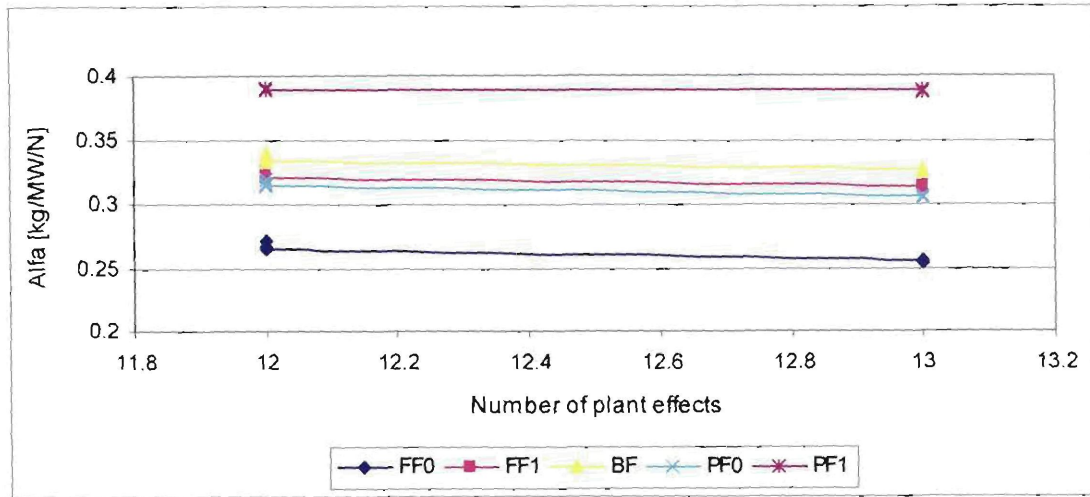


Figure 6-19: Case study 3: Relative performance ratios in SHS mode

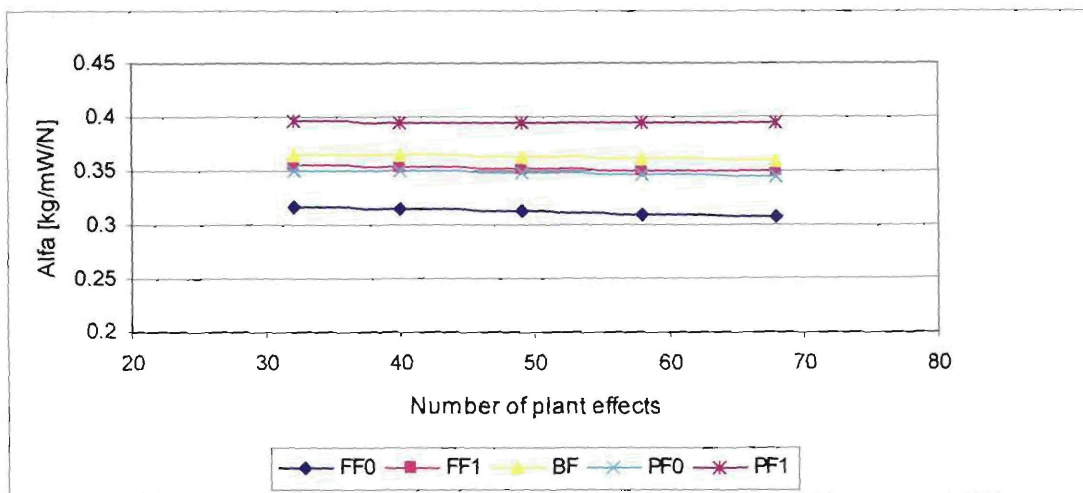


Figure 6-20: Case study 3: Relative performance ratios in WHS mode

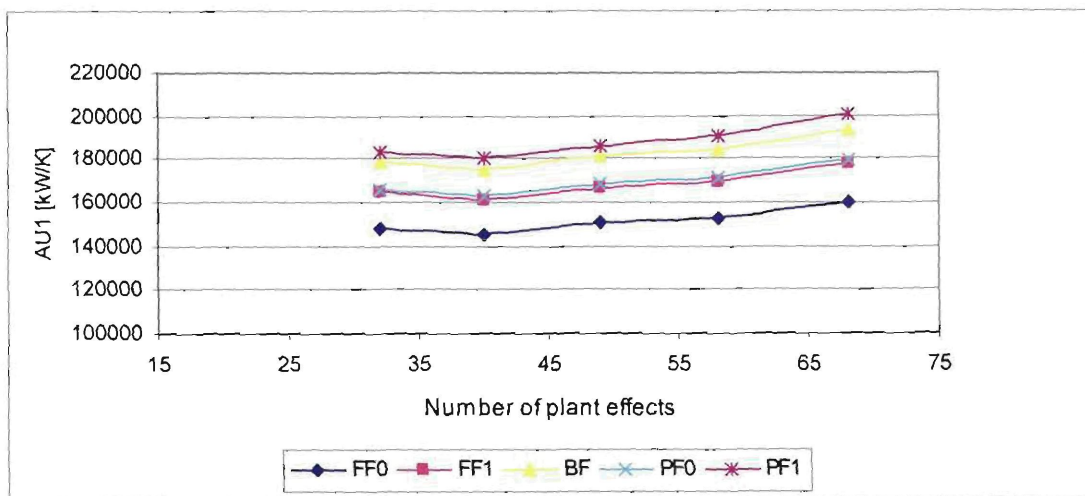


Figure 6-21: Case study 3: AU-values for water-to-steam effects/HX (WHS)

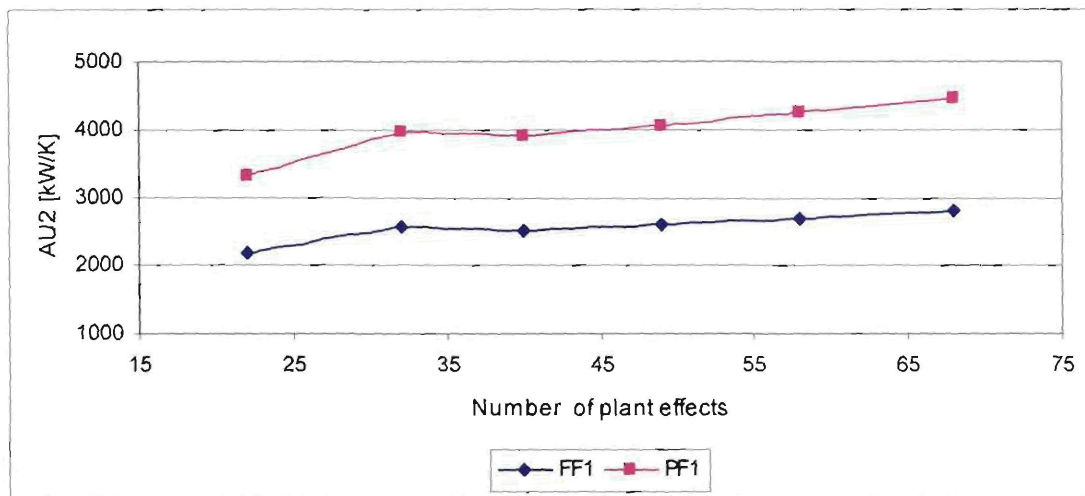


Figure 6-22: Case study 3: Comparison of AU-values for pre-heaters (WHS)

6.5 Varying inlet feed water temperature

In Case Study 4 the inlet feed water temperature of the MED plant is varied between 9 and 20°C in order to investigate the impact of different seawater temperatures on plant performance. As the inlet feed water temperature increases, the same amount of plant effects are utilized which show that the inlet feed water temperature has little impact on the number of stages in the MED plant, plant product water capacity and relative performance ratio.

For example a T_{feed} of 9-20°C in a FF0-configuration (SHS) leads to 7 plant effects (stages) in serie with a plant capacity of 13 300 m³/day. In the WHS mode 7 plant effects are utilized in the first of 4 parallel circuits with a total of 20 effects in the plant. A plant capacity of 10 450 m³/day is obtained. However, the inlet feed water temperature impacts the size of the heat exchangers used in the plant. From Figure 6-23 it can be seen that smaller steam-to-water heat exchangers can be utilized in the MED plant, as the inlet feed water increases, since less heat load for evaporation is needed. Thus as the inlet feed water temperature increases, the cost of the plant decreases.

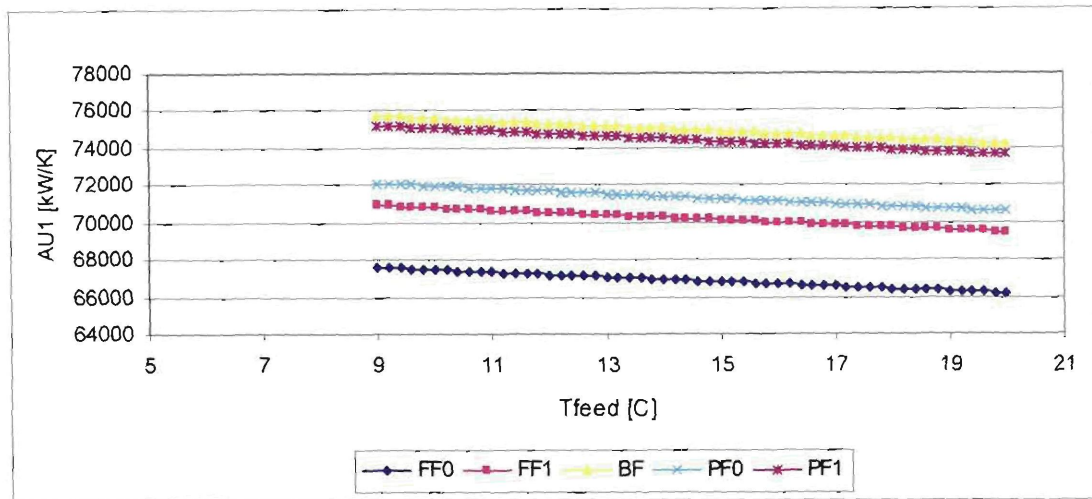


Figure 6-23: Case study 4: AU-values for water-to-steam effects in WHS-mode

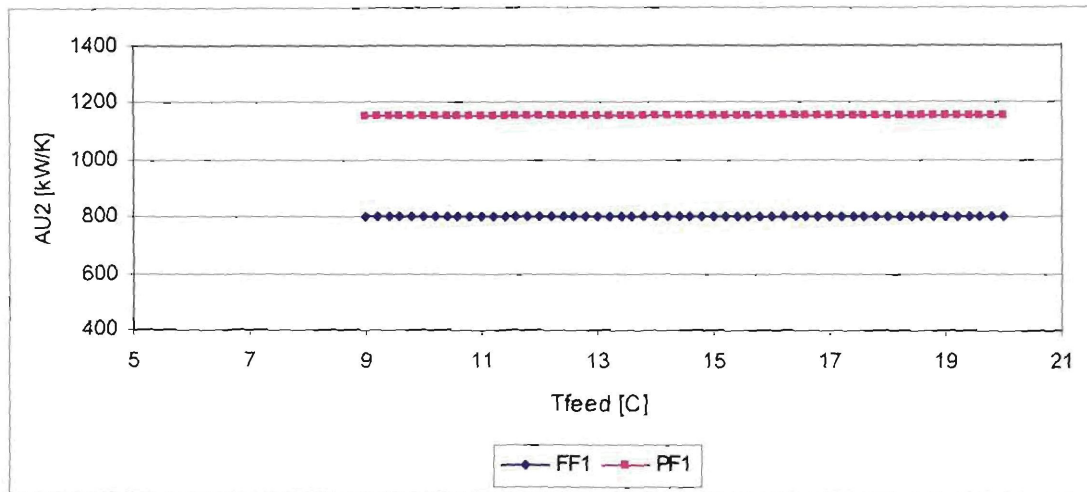


Figure 6-24: Case study 4: Comparison of AU-values for pre-heaters (WHS)

6.6 Varying exit steam temperature in last serie effect

In Case Study 5 the exit steam temperature (T_{min1}) in the last serie effect of each circuit is varied between 25-30°C, in order to identify plant performance trends.

An increase in T_{min1} results in a decrease of number of plant effects and thus the water product levels decrease in both the SHS and WHS mode. The relative performance ratio is influenced to a lesser extent by a change in T_{min1} . As T_{min1} decreases and the number of plant effects (stages) increases, the AU-value of the plant effects also increases which leads to higher capital costs.

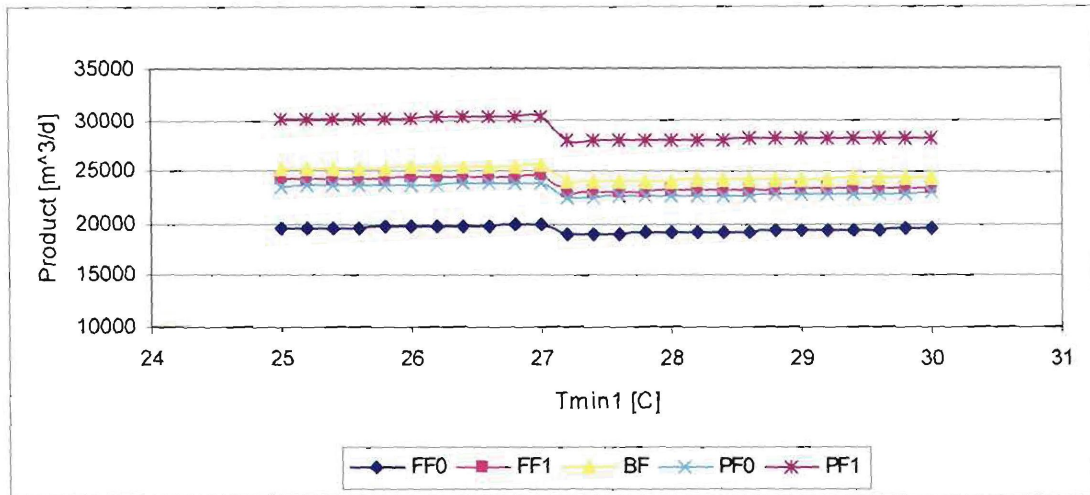


Figure 6-25: Case study 5: Comparison of product capacities in SHS mode

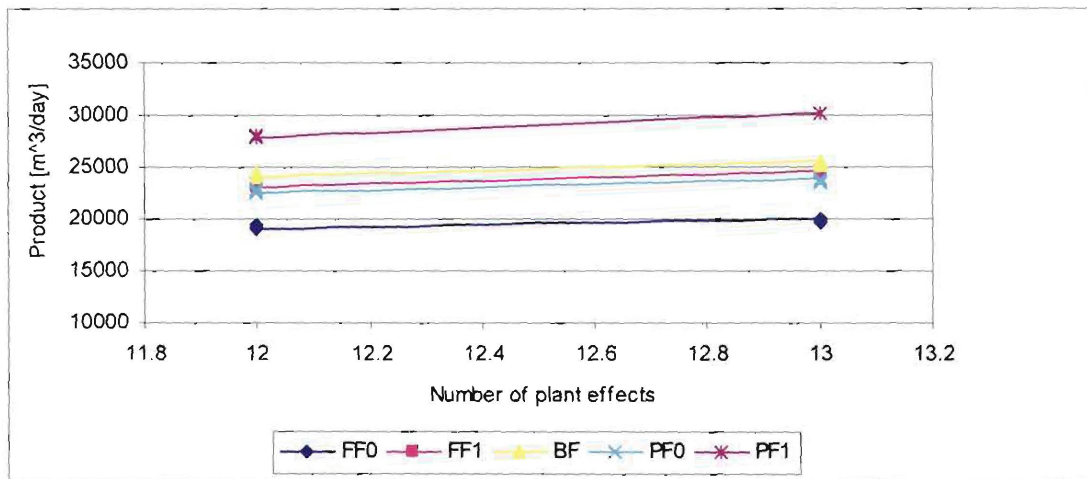


Figure 6-26: Case study 5: Comparison of product capacities in SHS mode

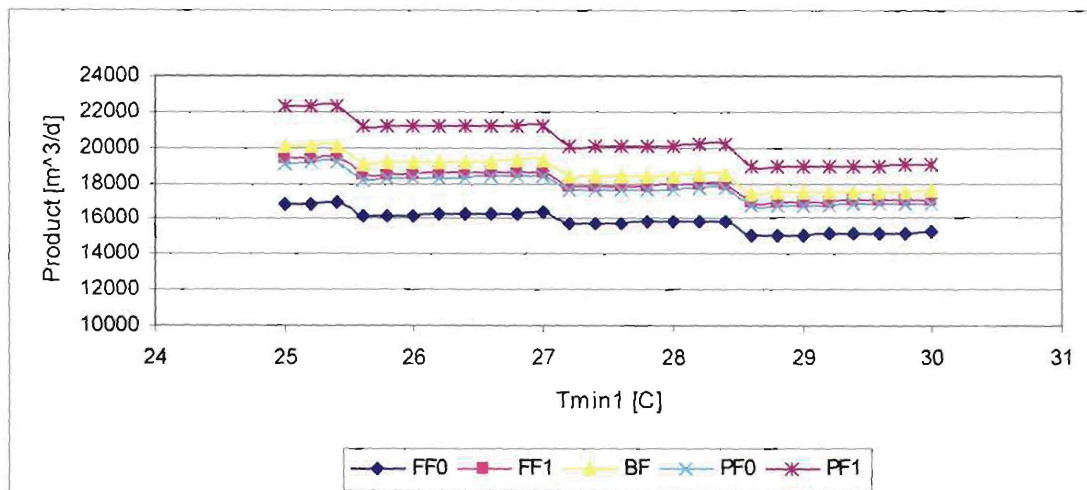


Figure 6-27: Case study 5: Comparison of product capacities in WHS mode

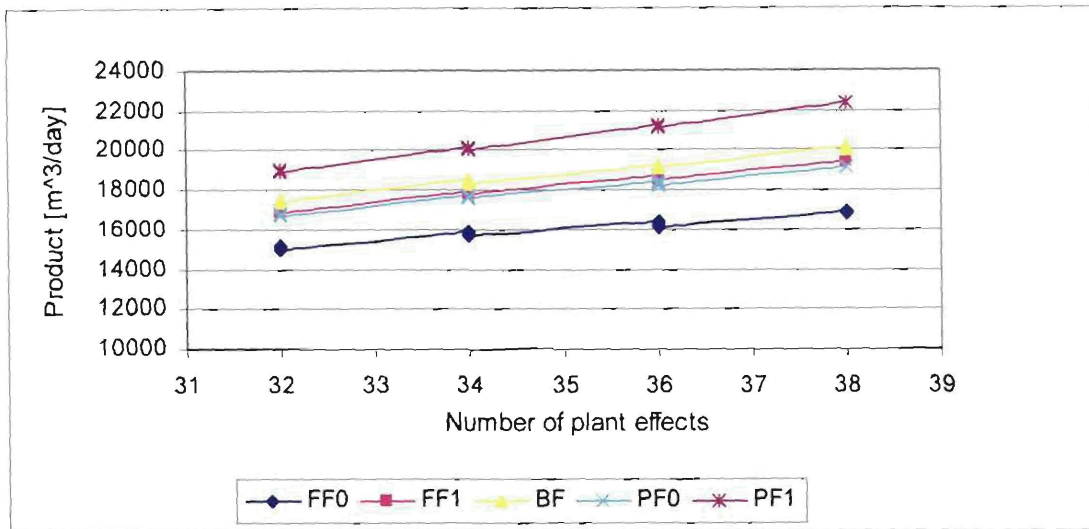


Figure 6-28: Case study 5: Comparison of product capacities in WHS mode

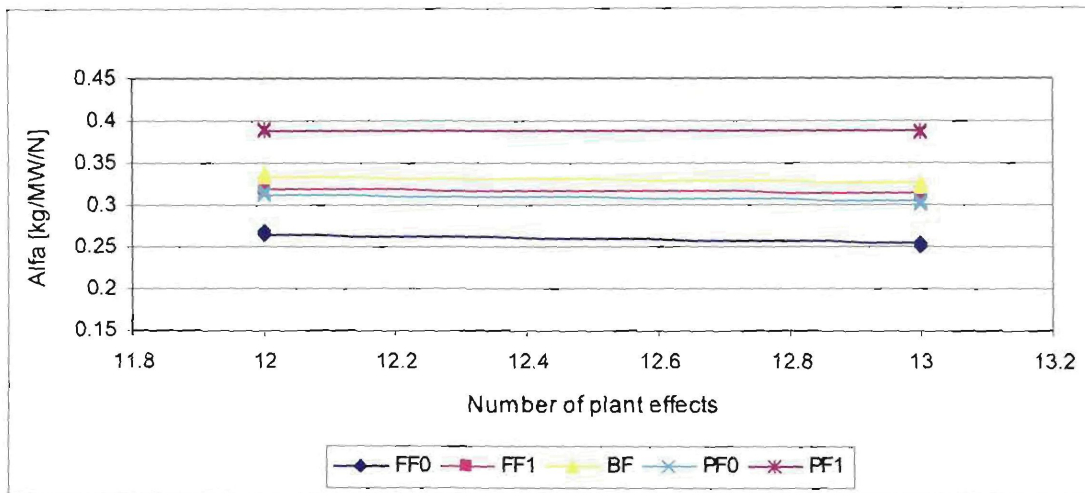


Figure 6-29: Case study 5: Relative performance ratios in SHS mode

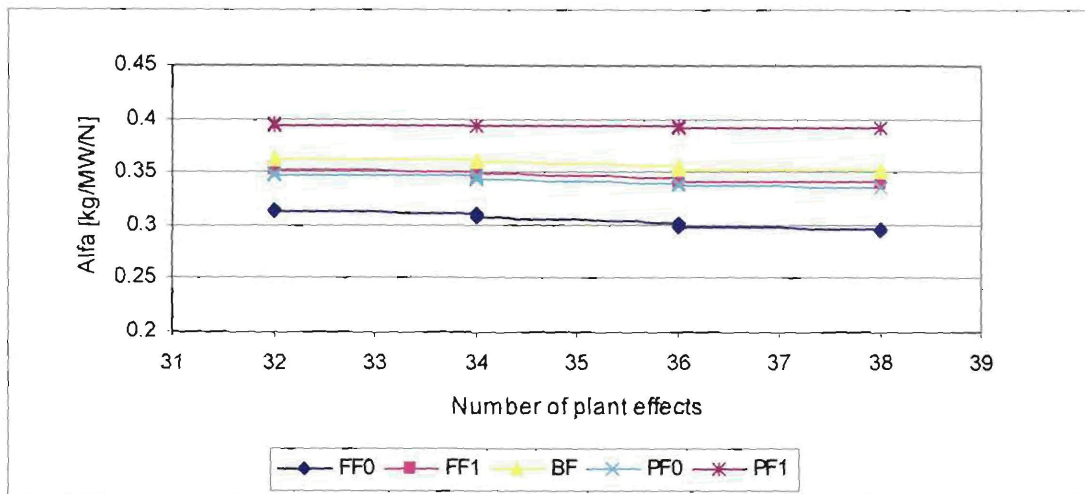


Figure 6-30: Case study 5: Relative performance ratios in WHS mode

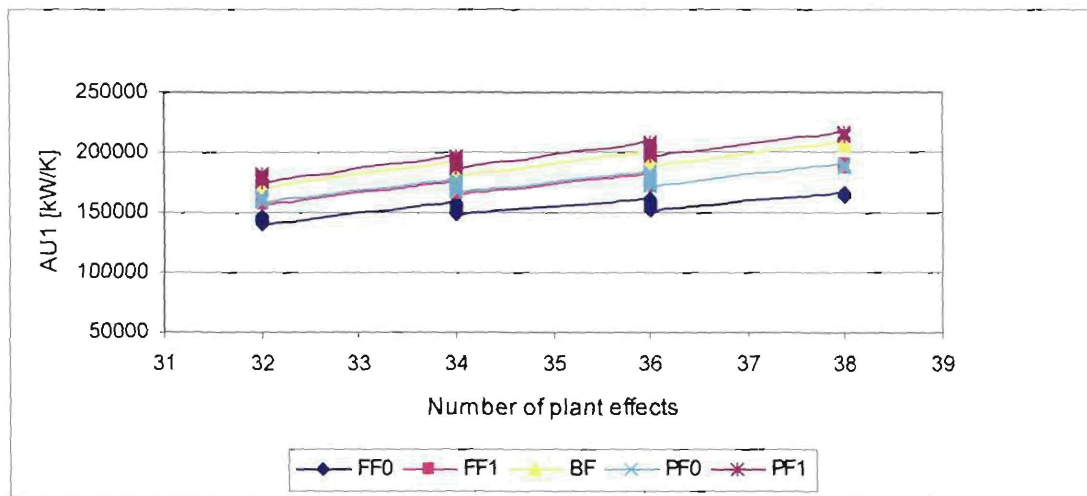


Figure 6-31: Case study 5: AU-values for water-to-steam effects in WHS mode

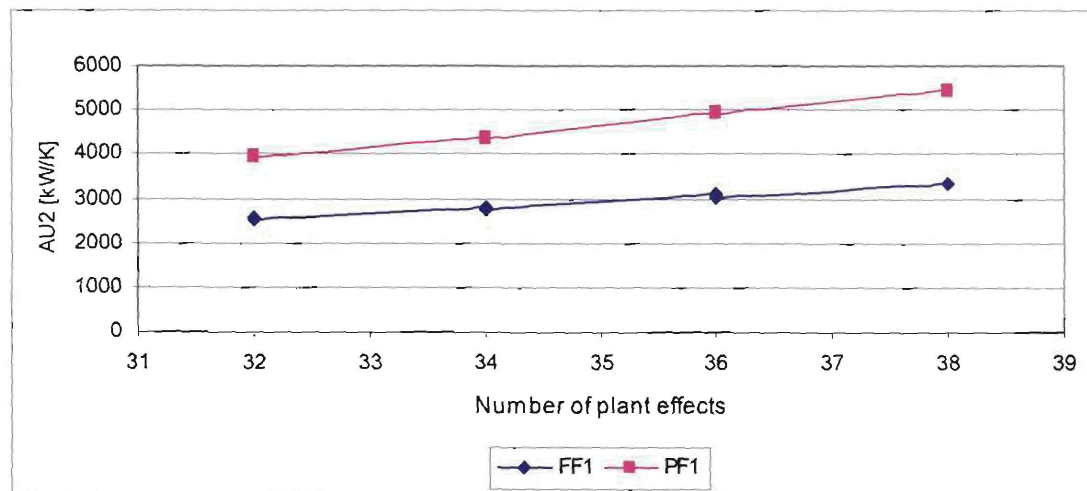


Figure 6-32: Case study 5: AU-values for pre-heaters (WHS)

6.7 Varying product ratio

In Case Study 6 the product ratio is varied between 0.65 and 0.8. See Equation (5.6) for the definition of the product ratio. As the product ratio increases, the product water capacity increases slightly (for both SHS and WHS modes) since more "fresh water" is recovered from the feed water. Relative performance ratios and AU-values also increase slightly with increased product ratios. The choice for a fixed product ratio is, however, a practical decision which is influenced by:

- i. The amount of brine needed at the plant outlet to transport concentrate still contained in waste water.
- ii. The amount of post treatment required and quality of the product water.
- iii. The main product of the desalination plant (water or salt production).

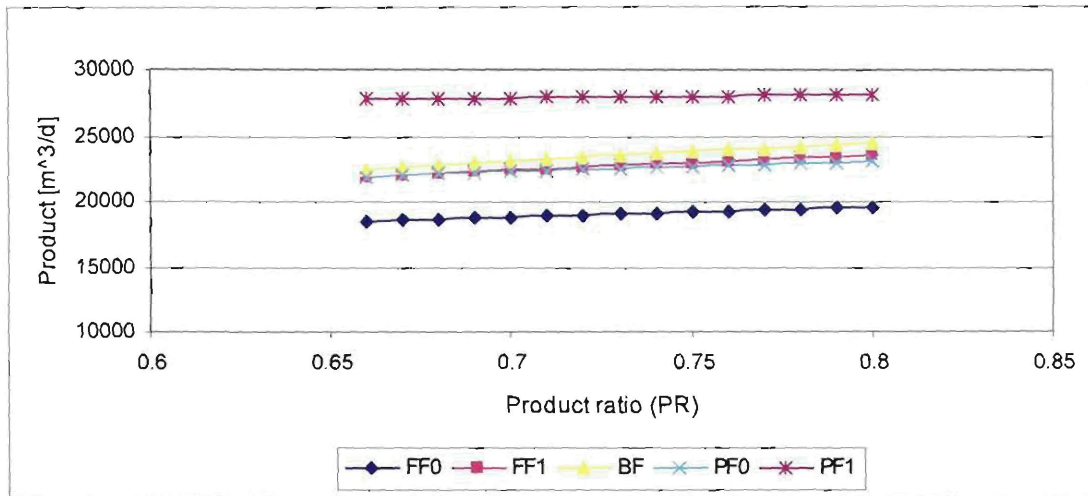


Figure 6-33: Case study 6: Plant product capacities in SHS mode

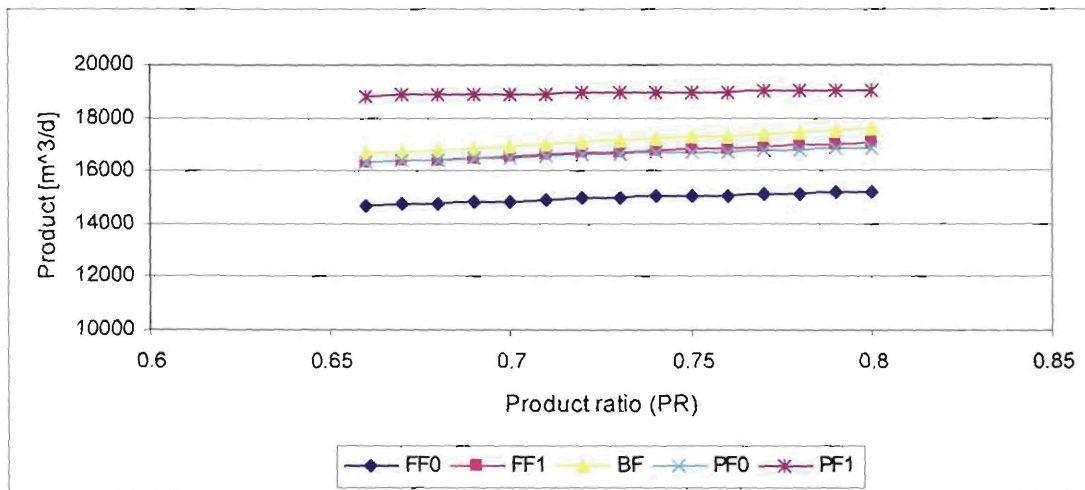


Figure 6-34: Case study 6: Plant product capacities in WHS mode

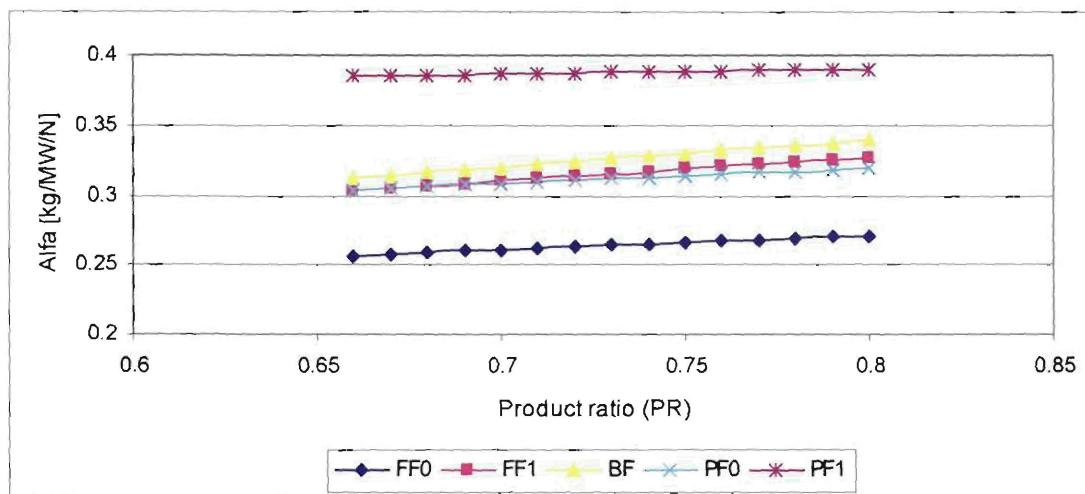


Figure 6-35: Case study 6: Relative performance ratios in SHS mode

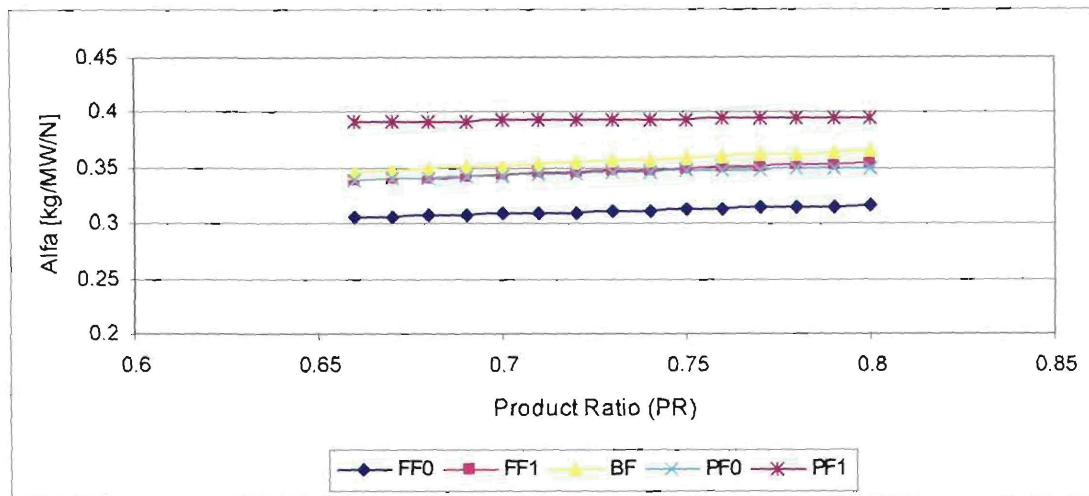


Figure 6-36: Case study 6: Relative performance ratios in WHS mode

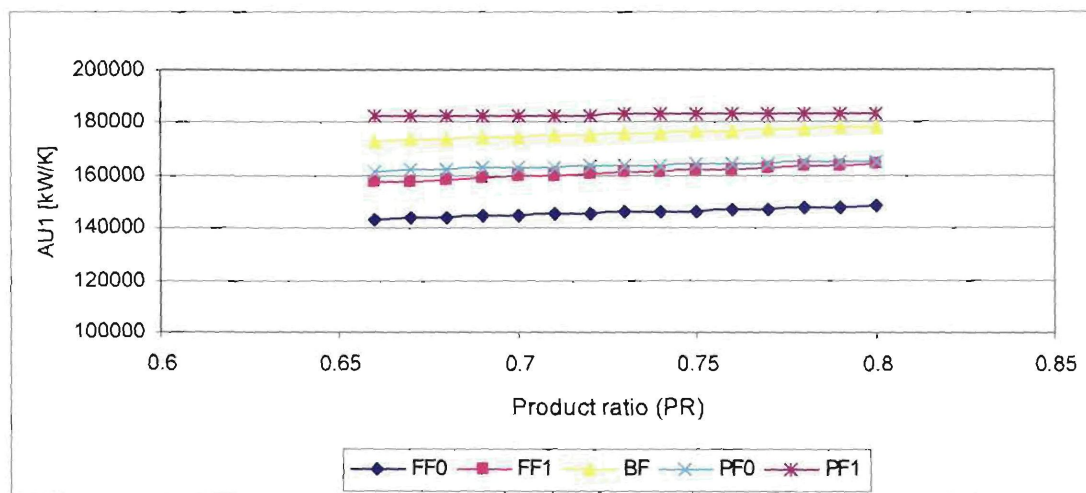


Figure 6-37: Case study 6: AU-values for water-to-steam effects (WHS)

6.8 Optimized MED plant configuration

Based on all previous plant simulation cases, the following conclusions can be made:

- i. The parallel feed configuration (PFC) with preheating performs the best in terms of water production, but has a higher AU-value which makes the PFC a more expensive configuration.
- ii. The forward feed configuration (FFC) without preheating produces the least water, but also has the lowest AU-value which makes the FFC less expensive.
- iii. A low serie-effect temperature difference (ΔT_1) and low parallel-circuit temperature difference (ΔT_2) leads to more MED plant effects (stages) which allows for increased water production levels. The MED plant performance is more dependent upon ΔT_1 than upon ΔT_2 .

- iv. The number of MED plant effects or stages is independent on the inlet feed water temperature (T_{feed}). However, the AU-value (plant cost) is influenced by T_{feed} .
- v. The exit steam temperature (T_{min1}) and product ratio influence the product capacity and plant costs.

An optimized parallel feed MED plant with preheating can now be designed to utilize steam-and-water heat sources.

When waste water from HTGR plants is available at 70°C for heating and feed water at 20°C is fed to the MED plant, approximately 21 260 m³/day of fresh water can be produced in a plant with 54 effects in parallel and serie. The heating medium (water) flow is 555 kg/s. The available driving heat, for the MED process, is thus:

$$Q_{WHS} = m \times C_p \times (T_{max} - T_{min2})$$

$$= 555 \times 4180 \times (70 - 35) = 81.2 \text{ MW} \quad (6.1)$$

When steam from conventional power plants is available at 70°C for heating and feed water at 20°C is fed to the MED plant, approximately 32 500 m³/day of fresh water can be produced in a plant with 12 effects in serie. The same amount of driving heat is utilized in the MED plant, but distributed in a single circuit (as in Section 3.5.1).

The heating medium (steam) flow is calculated as (see also (5.38)):

$$Q_{SHS} = Q_{WHS} = m_{steam} \times (h_2 - h_1) = 81.2 \text{ MW} \quad (6.2)$$

$$m_{steam} = 34.97 \text{ kg/s}$$

where h_1 and h_2 are the liquid and vapour saturated enthalpy, at 70°C, respectively.

The optimized PFC-MED plant specifications can be seen in Table 6-6 and the plant layouts for a SHS and WHS mode can be seen in Figure 6-38 and Figure 6-42.

Table 6-6: Optimized PFC-MED plant specifications

System Parameter (Input)	Optimized SHS Plant	Optimized WHS Plant	Plant layout & Capacity (Output)	Optimized SHS Plant	Optimized WHS Plant
T_{max} [°C]	70	70	N_1	12	12
T_{feed} [°C]	20	20	N_2	n/a	7
ΔT_1 [°C]	2.9	2.9	N_{sum}	12	54
ΔT_2 [°C]	5.0	5.0	Alfa	0.385	0.393
ΔT_{pinch} [°C]	1	1	[kg/MW/N _{agg}]		
T_{min1} [°C]	27	27	Product [m ³ /d]	32,492	21,258
T_{min2} [°C]	35	35	GOR	10.75	n/a
mw [kg/s]	n/a	555	AU1[kW/K]	277,782.6	188,804
ms [kg/s]	34.97	n/a	AU2[kW/K]	9,540.81	4,270
Product Ratio (PR)	0.8	0.8	Heat load [MW]	81.2	81.2
			Driving heat per circuit [MW]	81.2	11.6

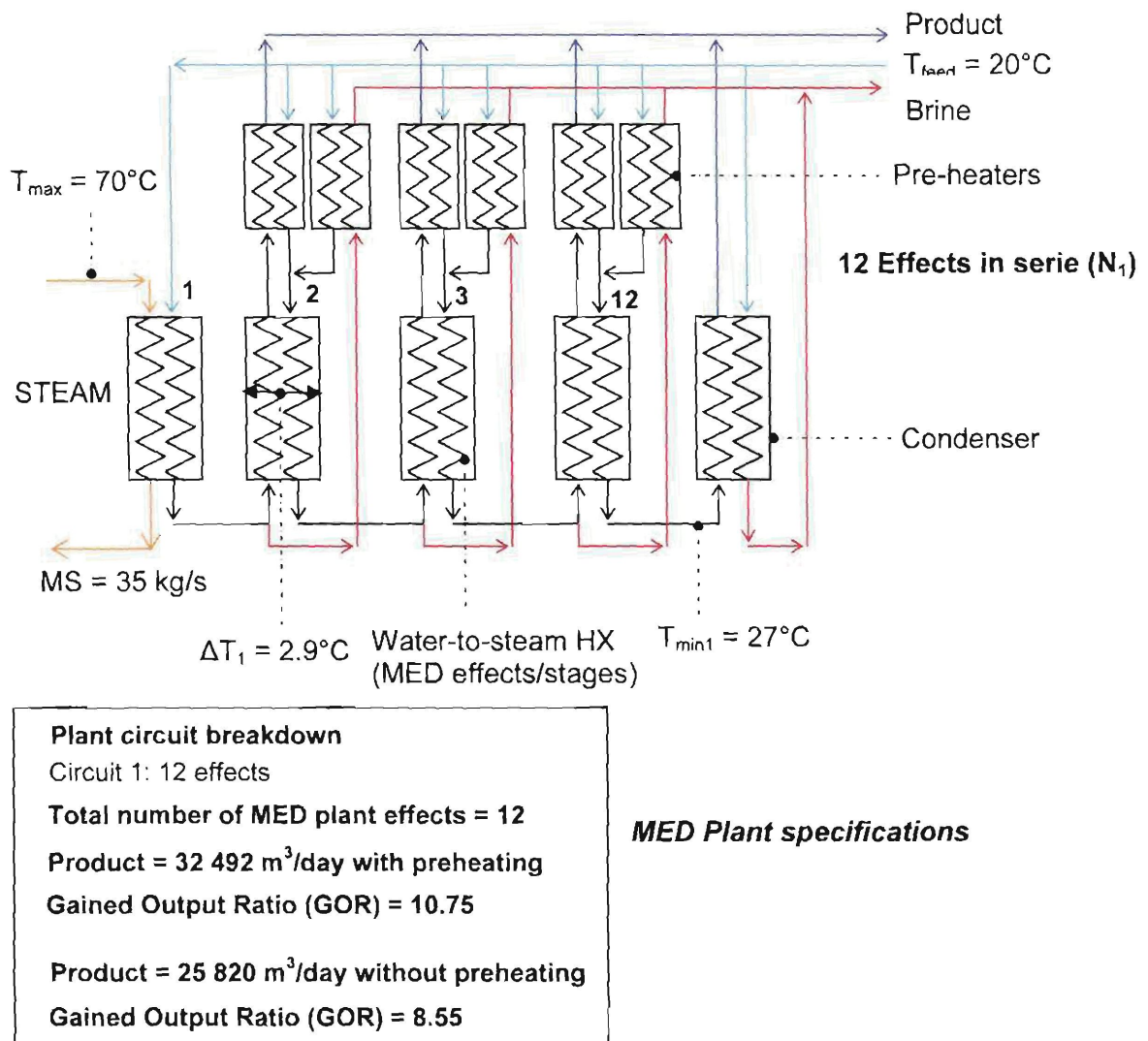


Figure 6-38: Optimized SHS plant

The MED plant and product water costs, for both the SHS and WHS plant, were determined. Economic assumptions made and methodologies used, during the cost evaluation, can be seen in *Appendix B*. Plant costs for the SHS and WHS type plants can be seen in Table 6-7. It is seen that the total capital cost of the WHS plant is approximately 32.8% lower than the SHS plant, due to 34.5% lower product capacity of the WHS plant. Although the WHS plant is less expensive, for the same energy input cost, the cost of water per m³ is 5% higher. This doesn't seem significant, but the total cost consists of capital and operating costs. Cost of water was based on equal O&M costs for the SHS and WHS plant. In reality, O&M costs for the WHS plant will be significantly higher due to more plant components (54 effects) delivering less product. This will increase the WHS cost of water even more. Different SHS and WHS MED plant costs, based on area per stage and number of stages, are compared with each other in Figure 6-39 and Figure 6-40.

Table 6-7: Optimized PFC-MED plant costs

	SHS Plant	WHS plant
Product capacity [m ³ /d]	32,492	21,258
Plant effects [#]	12	54
Total capital cost [US \$ million]	50.13	33.70
Plant life [yrs]	25	25
Load factor [%]	80	80
Interest rate [%]	8	8
Capital cost [US \$/m ³]	0.49	0.56
Cost of water [US \$/m ³]	1.65	1.70

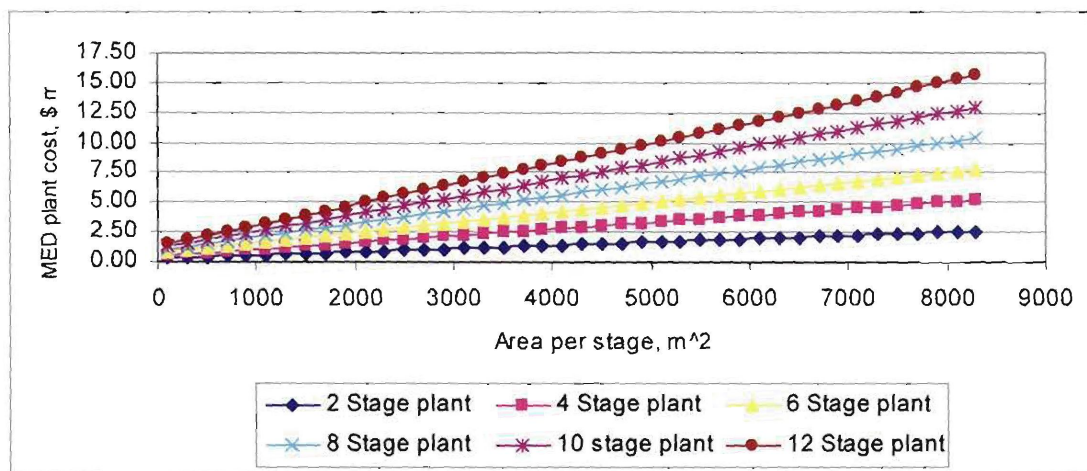


Figure 6-39: MED plant costs for different size SHS plants

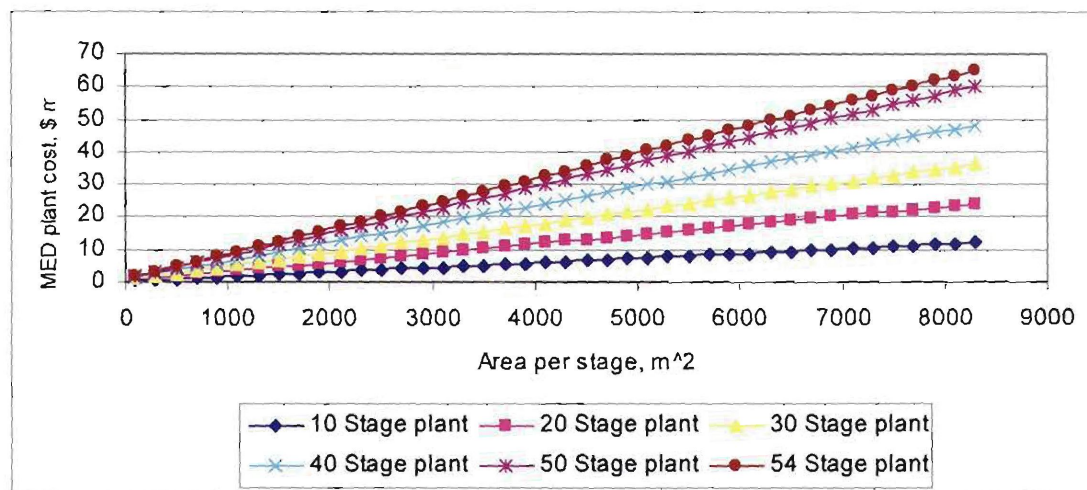


Figure 6-40: MED plant costs for different size WHS plants

As mentioned, the optimized SHS plant is shown in Figure 6-38 and the performance prediction (plant data) of the relevant plant is shown in Figure 6-41. This figure gives an indication of the temperature, pressure and enthalpy distribution in the 12 stage

MED plant. Plant data for the WHS plant is not given due to complex geometry of plant. The WHS-plant, however, behaves similarly.

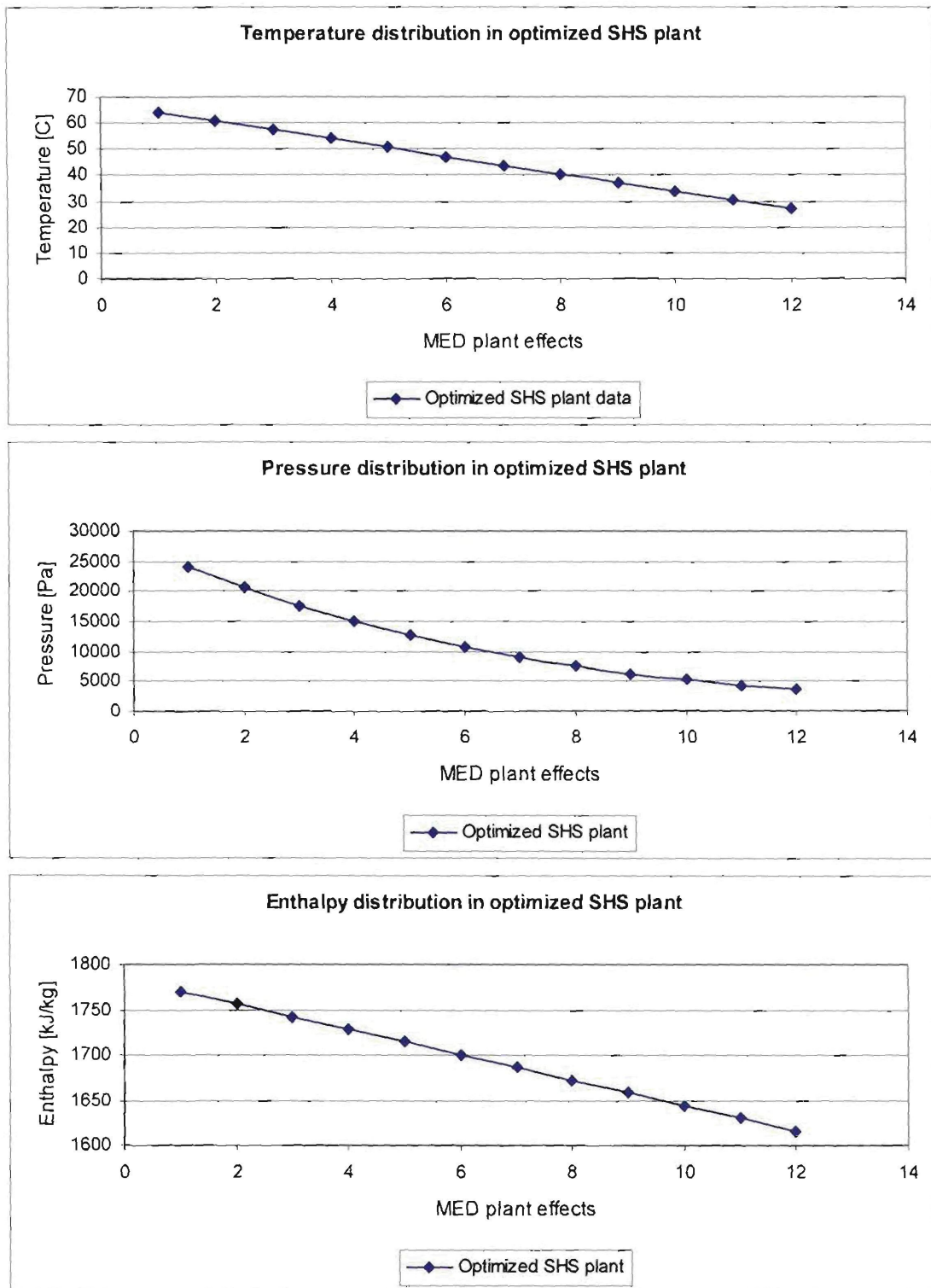


Figure 6-41: Optimized SHS saturated brine plant data

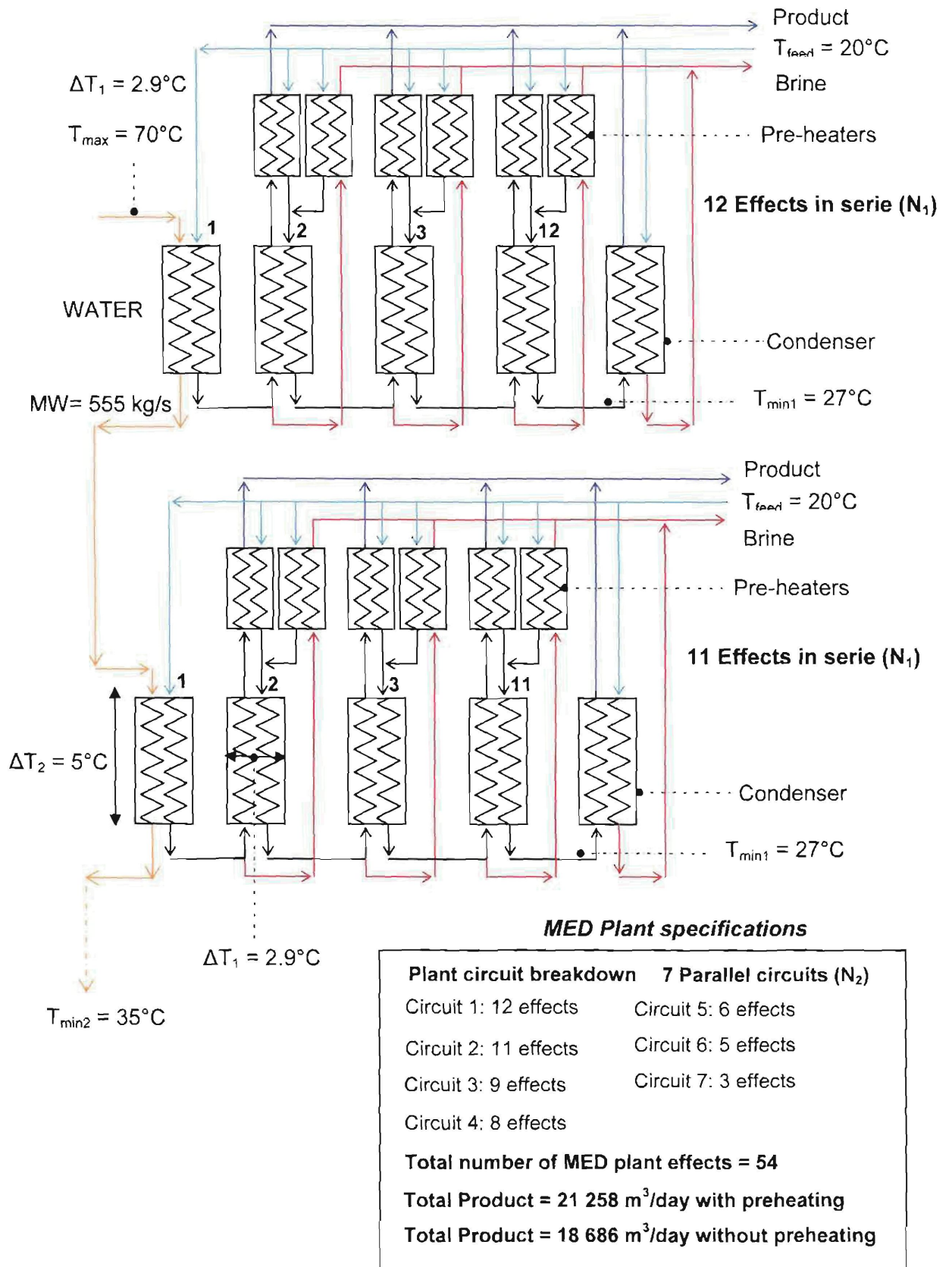


Figure 6-42: Optimized WHS plant

6.9 Conclusion

Preliminary MED process analyses were performed with each configuration in order to gain understanding into the effect of heat source utilization on plant production levels. First order analyses show that more product water can be obtained from a MED plant that utilizes high temperature steam as heat source rather than high temperature water in the secondary circuit. Less plant effects are needed in SHS-mode compared to WHS utilization. This leads to a decrease in cost of product water in SHS-mode. However, high temperature heating water is usually obtained as free waste heat from HTGR type power plants. Obtaining high temperature heating steam from conventional power plants involves costs since steam is either obtained from the plant boilers (or reactors) or bled off from the PCU turbines, which influences power generation. Thus the cost of product water in WHS mode can decrease even more when free waste heat is utilized, but the plant cost is significantly higher than a SHS-plant. Preheating increases water production levels and a first observation indicates that the PFC has the potential to generate the most product water. In the preliminary process analysis the system input parameters were fixed.

Different system simulations were performed with the MED analysis C++ model in order to evaluate the impact of different system parameters on a practical MED plant's performance. It was found that some parameters influence the MED plant design more than others. The PFC with preheating seems to be the most superior configuration in terms of water product production and performs well over a range of plant effects. Based on the sensitivity analysis an optimized PFC-MED plant design was proposed for SHS and WHS utilization. MED plant and water product costs were determined as well.

Chapter 7

Conclusion and Recommendations

"Water has become a highly precious resource. There are some places where a barrel of water costs more than a barrel of oil." - Lloyd Axworthy, Foreign Affairs Minister of Canada

"If there is magic on this planet, it is contained in water." – Loran Eisely, the Immense Journey, 1957

CHAPTER 7 CONCLUSION AND RECOMMENDATIONS

7.1 Summary

An overview of MED technology was discussed in Chapter 1 and the different MED plant design considerations were identified. It was concluded that many factors influence MED plant performance and these factors need to be evaluated as part of a system. The focus in Chapter 2 was on identifying energy sources for the MED process in order to produce fresh water economically and effectively. It was shown that interest in using nuclear energy to provide external process heat in the form of steam or water is growing worldwide since this energy leads to a lower environmental impact. Past and current MED plant experiences were discussed and it was seen that many countries worldwide are investing in desalination technologies and MED in particular. Different mathematical models have been generated and are used for MED plant modelling. These models are usually based on heat and mass balances.

The fundamental mechanism governing the MED process was shown in Chapter 3 and thermodynamic design considerations were evaluated. It was shown that the utilization of a particular process heat source, such as water and steam, determines or influences the performance, cost and layout of MED plants. In Chapter 4 three process flow configurations were identified namely the forward feed configuration (FFC), backward feed configuration (BFC) and parallel feed configuration (PFC) and the mode of operation of each configuration was discussed as well as possible advantages and disadvantages of each configuration.

A C++ MED model was developed in Chapter 5 to perform preliminary process and plant performance analyses. The C++ MED analysis model was discussed and also validated in order to perform investigation studies in the following chapters. The validation study was found satisfactory.

In Chapter 6 a preliminary process analysis was conducted in order to determine plant production levels with the different process flow configurations. The effect of preheating the feed streams was also shown. It was concluded that the PFC with preheating has the potential to achieve the highest production levels. Different plant performance case studies were also evaluated. Various system parameters were varied and the plant performance was studied across a range of plant effects for each process flow configuration. Based on these simulations an optimum steam-heat-source and water-heat-source plant was identified.

7.2 Conclusion of study

Based on this study the following conclusions can be made:

Fresh water resources are limited worldwide and desalination technologies, including multi-effect distillation, need to be well established. The use of nuclear power to supply the MED process heat source is gaining more interest.

MED plant efficiency:

Energy efficiency of a MED plant is determined by the Gained Output Ratio (GOR). In order to obtain maximum production levels, the GOR should be increased. The GOR is increased by:

1. Increasing the AU-value.
2. Avoiding temperature pinching.
3. Increasing the number of plant effects.
4. Utilize waste heat in product and brine streams to preheat feed water.

MED process heat source:

The available process heat source plays a major role in MED plant design. A SHS-plant produces 25-30% more product than a WHS-plant. A serie plant layout is favourable when steam is available and a serie-parallel layout is needed when water is available as external heat source. More plant effects are utilized in a WHS plant showing that the heat source also determines the cost per kg product.

MED process flow configuration:

Each process flow configuration has advantages and disadvantages and the choice for the optimum configuration involves making design decisions regarding component fouling, water production and plant costs. The backward feed configuration (BFC) produces the most product water when no feed water preheating is done. When preheating is done, the parallel feed configuration (PFC) seems to produce more product water. Preheating can increase production levels with up to 30%. The PFC also has the highest AU value which makes the PFC a more expensive option.

MED system parameters:

As the serie-effect temperature difference (ΔT_1) decreases, the number of plant effects increases leading to higher production levels for a SHS and WHS case. This causes the AU-value (plant cost) and GOR to increase. The relative performance ratio (α) also decreases as ΔT_1 decreases. In the ideal configuration (PF1) the GOR approaches the number of plant effects. Water performs better in a single circuit than steam since more WHS-plant effects are utilized at lower temperatures where less heat for evaporation is needed. The parallel circuit temperature difference, ΔT_2 , impacts the water production levels to a lesser extent and the plant performance is not as sensitive to a change in ΔT_2 . Inlet feed water temperature only impacts the

AU-value of the plant effects (plant cost). Product ratio and T_{min1} also influence system performance but to a lesser extent. The PFC performs the best over a wide range of plant effects. Thus, if waste heat from the PBMR is available as heat source for the MED process, as oppose to steam from conventional LWR nuclear power plants, less product water can be produced with the same energy input. More plant stages would also be needed, which increases the operating and maintenance costs of the MED plant. The product water costs for the PBMR MED desalination plant differs slightly from product water costs for a SHS MED plant, due to the nature of the heat source.

7.3 Recommendations for further studies

In this study only system simulations were performed in order to determine optimum plant configurations. Only lumped AU-values were determined and detail calculations of heat transfer coefficients should now be performed in order to determine the area (dimensions) of the MED plant stages (effects). It is also recommended that a techno-economic study be done on the use of different materials for the heat exchangers such as plastic. The use of cheaper materials would decrease the water product costs. Different heat exchangers such as plate type HX should be evaluated and considered for further research. Only then can detailed cost analyses be performed.

Temperature difference is the driving force for evaporator operation and is usually limited, as by compression ratio in vapour compression evaporators and by available steam-pressure and heat-sink temperature in single-and multiple-effect evaporators. A fundamental objective of evaporator design is to make as much of this total temperature difference available for heat transfer as is economically justifiable. Some losses in temperature difference, such as those due to boiling point elevation (BPE), are unavoidable. Thus, in MED systems the aim is to implement as many effects as economically possible in the temperature range between the heat source and heat sink, in this case $70^{\circ}\text{C} - 30^{\circ}\text{C} = 40^{\circ}\text{C}$. The main issue that has been omitted from this study is the effect of boiling point elevation (BPE) due to the salt in the feed, which increases with concentrating the water in additional effects. For seawater this is about $1 - 2^{\circ}\text{C}$ and on concentrating with a factor 5 this increases to $5 - 10^{\circ}\text{C}$ at the end of a MED train. This implies that there is a strong effect of the concentration factor on the economy of the process. Unfortunately it was realized at a rather late stage that BPE was not included in the study. However, due to the expected impact on time scales it was decided not to include this into the current study. Due to

conservative effect temperature differences chosen in the design, the BPE effect might not be too large. The BPE effect also only impacts the FFC and BFC where salinity changes in the feed occur. It is, however, suggested that the effect should be investigated further before implementing any of the results from this study in order to determine optimum number of effects. It is advised to include the composition of the seawater.

Other recommendations include:

1. Performing dynamic analyses of the MED system in order to predict system performance when a loss of load in the power plant occurs.
2. Investigate other MED systems such as MED with TVC and optimize double hybrid systems such as MED-RO and MED-TVC-RO.
3. Perform genetic optimization of the system.
4. Perform better validations with actual plant data.
5. Calculate the effect of pumping costs on the system.
6. In the case of the PBMR, a complete techno economic study of the WHS-MED plant needs to be done to evaluate the total plant costs involved and the water heat source nature, which decreases product costs and increases plant costs respectively. Evaluate different waste heat options in a MED plant such as the option of flashing in flash tanks to investigate efficiency advantages over water heating.
7. Perform a techno-economic study on the possibility of extracting salts and chlorine, for industrial purposes, from the brine stream at the MED plant outlet.

References

"Water is the driver of nature." - Leonardo da Vinci

"To live by a large river, is to be kept in the heart of things." – John Haines

REFERENCES

AMERICAN NUCLEAR SOCIETY, March 2005, "Use of Nuclear Energy for Desalination". (*Position Statement 62, Outreach Program (708-6611), Federal Affairs (202-312-7482), www.ans.org*)

ANDERSEN, B.J, MACIVER, A, HINGE, S, 2005, "New trend in desalination for Japanese nuclear power plants based on multiple effect distillation, with vertical titanium plate falling film heat transfer configuration". *Desalination 182 (2005) 221–228. (Paper presented at the Conference on Desalination and the Environment, Santa Margherita, Italy, 22–26 May 2005, European Desalination Society).*

ASHOUR, 2002, "Steady State analysis of the Tripoli West LT-HT-MED plant". *Desalination 152 (2002) 191–194. (Paper presented at the EuroMed 2002 conference on Desalination Strategies in South Mediterranean Countries)*

BLANCO J, 2002, "Advanced solar desalination: A feasible technology to the Mediterranean Area"

COLAK,U, 2005, "Coupling strategies for desalination plants with gas cooled reactors". *International Journal Nuclear Desalination, Vol 1, No. 4, pp 427-434.*

COLERIDGE, S, November/December 2001, "Gift of the Seas: Nuclear Desalination is an Economic, Clean Source of Drinking Water" (*NUCLEAR ENERGY INSIGHT magazine*).

DARDOUR, S & NISANA, S, 2005, "Development of a computer-package for MED plant dynamics". *Desalination 182 (2005) 229–237. (Paper presented at the Conference on Desalination and the Environment, Santa Margherita, Italy, 22–26 May 2005. European Desalination Society).*

DARDOUR, S, NISANA, S, CHARBIT, F, 2006, "Utilization of waste heat from GT-MHR and PBMR reactors for nuclear desalination." *Desalination 205 (2007) 254–268. (Paper presented at the EuroMed 2006 conference on Desalination Strategies in South Mediterranean Countries: Cooperation between Mediterranean Countries of Europe and the Southern Rim of the Mediterranean. France, 21–25 May 2006).*

DESWARE, 2007. Encyclopedia of Desalination and Water Resources.
<http://www.desware.net>. Date of access: Jan/Feb 2007

EL-DESSOUKY, H & ETOUNEY, H, 1999, "A simulator for thermal desalination processes, Kuwait." *Desalination 125 (1999) 277–291. (Paper presented at the Conference on Desalination and the Environment, Las Palmas, Gran Canaria, November 9–12, 1999. European Desalination Society and the International Water Association).*

EL-FIQI, A & ALY, N, 2003, "Thermal performance of seawater desalination systems" *Desalination 158 (2003) 127-142. (Paper presented at the European Conference on Desalination and the Environment: Fresh Water for All, Malta, 4-8 May 2003. European Desalination Society International Water Association).*

EL-FIQI, A & ALY, N, 2003, "Thermal performance of seawater desalination systems" *Desalination 158 (2003) 127-142. (Paper presented at the European Conference on Desalination and the Environment: Fresh Water for All, Malta, 4-8 May 2003.*

European Desalination Society International Water Association).

FAIBISH, R & KONISHI, T, February 2003, "Nuclear desalination, a viable option for producing freshwater." *Desalination* 157 (2003) 241-252. (Paper presented at the *European Conference on Desalination and the Environment: Fresh Water for All, Malta, 4-8 May 2003*)

FIORINI, P & SCIUBBA, E, 2005, "Modular simulation and thermo-economic analysis of a multi-effect distillation desalination plant." *Energy* 32 (2007) pp 459–466.

GEMMA, R, SERRA, L, UCHE, J, 2006, "Life cycle assessment of MSF, MED and RO desalination technologies." *Energy* 31 (2006) 2361–2372. (The results presented in this paper have been obtained in the frame of the development of the research project REN 2001-0292—included in the Spanish National Plan for Scientific Research and Technological Development and Innovation).

HANRA, M, 2000, "Desalination of seawater using nuclear heat." *Desalination* 132 (2000) 263-268. (Paper presented at the *Conference on Membranes in Drinking and Industrial Water Production, Paris, France, 3-6 October 2000*).

IAEA, 1995, "Non-electric applications for Nuclear energy." IAEA-TECDOC-923 (Proceedings of an Advisory Group meeting held in Jakarta, Indonesia, 21-23 November 1995)

IAEA, 2000a, "Introduction of nuclear desalination, a guide book, series 400 (Vienna)." *Technical reports series, ISSN 0074–1914 ; no. 400*

IAEA, 2000b, "Examining the economics of seawater desalination using the DEEP code." IAEA-TECDOC-1186 (The IAEA officer responsible for this publication was P.J. Gowin of the Division of Nuclear Power).

IAEA, 2001, "Safety aspects of nuclear plants coupled with seawater desalination units." IAEA-TECDOC-1186

IAEA, November 2002, "Design concepts of nuclear desalination plants." IAEA-TECDOC-1326

IAEA, 2006, "Nuclear Technology Review" 2006

IAEA, 2007, "International Atomic Energy Agency", <http://www.iaea.org>
Date of access: March/April 2007

INGERSOLL, D, BINDER, J, CONTI, D, May 2004, "Nuclear desalination options for the international reactor innovative and secure (IRIS) design." (Paper presented at the *5th International Conference on Nuclear Option in Countries with Small and Medium Electricity Grids Dubrovnik, Croatia, May 16-20, 2004*).

KRIEL, W, 2006, "PBMR for Desalination & Dry-cooling." (Presentation presented at the *ANS Water Panel Discussion – November 2006*).

MEGAHED, MOHAMED M, 2000, "Nuclear Desalination: History and Prospects." *Desalination* 135 (2001) 169–185. (Paper presented at the *International Conference on Sea Water Desalination Technologies on the Threshold of the New Millennium, Kuwait, 4–7 November 2000*).

METHNANI, M, 2007, "Fundamentals of Seawater Desalination Technologies" (*Short course presented at the North West University, Potchefstroom, 23-25 July 2007*).

MISRA, B & KUPITZ, J, 2004, "The role of nuclear desalination in meeting the potable water needs in water scarce areas in the next decades." *Desalination 166 (2004) 1-9 (Paper presented at the Euro Med 2004 conference on Desalination Strategies in South Mediterranean Countries: Marrakech, Morocco, 30 May-2 June, 2004)*.

NICHOLLS, D, 2005, "The pebble bed modular reactor, desalination challenges and options", *Int. J. Nuclear Desalination, Vol. 1, No. 4, 2005*.

NISSAN, S & DARDOUR, S, 2006, "Economic evaluation of nuclear desalination systems." *Desalination 205 (2007) 231-242. (Paper presented at Euro Med 2006 conference on Desalination Strategies in South Mediterranean Countries: Montpellier, France, 21-25 May 2006)*.

OLSSON J, 2005, "Stainless steels for desalination plants." *Desalination 183 (2005) 217-225. (Paper presented at the Conference on Desalination and the Environment, Santa Margherita, Italy, 22-26 May 2005. European Desalination Society)*.

OPHIR, A & LOKIEC, F, 2005, "Advanced MED process for most economic seawater desalination." *Desalination 182 (2005) 187-198. (Presented at the Conference on Desalination and the Environment, Santa Margherita, Italy, 22-26 May 2005. European Desalination Society)*.

PETERSON, P & ZHAO, H, January 2006, "An Optimized System for Advanced Multi-Effect Distillation (AMED) Using Waste Heat from Closed Gas Brayton Cycles" *U.C. Berkeley, Report UCBTH-05-003, Rev.E (This work was sponsored by US Department of Energy through NERI with award number DE-FC07-05ID14669)*.

RASHAD, I, HAWLADER, M, DEY, P, 2001, "Single phase heat transfer in multi-effect distillation (MED)." (*Authors from the Department of Mechanical Engineering, National University of Singapore*)

RAVIZKY, A & NADAV, N, January 2006, "Salt production by the evaporation of SWRO brine in Eilat: a success story" *Desalination 205 (2007) 374-279. (Paper presented at the EuroMed 2006 conference on Desalination Strategies in South Mediterranean Countries: Montpellier, France, 21-25 May 2006)*.

SCIUBBA, May 2007, "Systematic application of exergo-economic methods to the analysis and optimization of desalination processes" *Final Report TR-DMA-MEDRC-01-07*

SERRA, L & UCHE, J, 2006, "Simulation and Thermo-economic analysis of different configurations of gas turbine (GT)-based dual purpose power and desalination plants (DPPDP) and Hybrid Plants (HP)" *Energy 32 (2007) 1012-1023 (Department of Mechanical Engineering, University of Zaragoza, c/Mari'a de Luna 3, 50018 Zaragoza, Spain)*.

SERRA, L & ARTAL, J, 2002, "Comparisons of heat transfer coefficient correlations for thermal desalination units", *Desalination 152 (2002) 195-200. (Paper presented at the Euro Med 2002 conference on Desalination Strategies in South Mediterranean Countries)*.

- TANG, Y, WANG, Y, TIAN, L, 2004, "Economic evaluation of seawater desalination for a nuclear heating reactor with multi-effect distillation" *Desalination 180 (2005)* 53-61. (Institute of Nuclear Energy Technology, Energy Science building, Tsinghua University Beijing, P.R. China).
- TEWARI, P & RAO, I, 2002, "LTE desalination utilizing waste heat from a nuclear research reactor", *Desalination 150 (2002)* 45-49. (Desalination Division Bhabha Atomic Research Centre, Trombay, Mumbai, 400 085 India)
- TIAN L, WANG Y, GUO, J, 2002, "Economic analysis of a 2x200 MW nuclear heating reactor for seawater desalination by multi-effect distillation (MED)", *Desalination 152 (2002)* 223–228. (Paper presented at the Euro Med 2002 conference on Desalination Strategies in South Mediterranean Countries)
- VAN DER BRUGGEN, B & VANDECASTEELE, C, 2002, "Distillation vs. membrane filtration: overview of process evolutions in seawater desalination." *Desalination 143 (2002)* 207-218. (Department of Chemical Engineering, University of Leuven, WI de Croylaan 46, B - 3001 Heverlee, Belgium)
- VIDALI, R, KOUSI, P, HATZIKIOSEYIAN, A, 2004, "Modelling and thermodynamic analysis of a multi-effect distillation (MED) plant for sea water desalination" (National Technical University of Athens (NTUA), School of Mining and Metallurgical Engineering Laboratory of Environmental Science and Engineering, Athens).
- VOROSMARTY, C.J, 2000, "Global Water Resources: Vulnerability from Climate Change and Population Growth." *Science, Volume 289, pp 284-288.*
- WATERAID, 2007, <http://www.wateraid.org> Date of access: October 2007
- WU, S & ZHENG, Z, 2001, "Coupling of nuclear heating reactor with desalination processes", *Desalination 142 (2002)* 187-193. (Institute of Nuclear Energy Technology, Energy Science building, Tsinghua University Beijing, P.R. China).
- WU, S, DU, X, CHENG, L. 2001. Thermal hydraulic performance of a seawater desalination system coupled with a nuclear heating reactor. *Desalination 140 (2001)* 297-307. (Institute of Nuclear Energy Technology, Energy Science building, Tsinghua University Beijing, P.R. China).
- WU, S & ZHENG, Z, 2002, "An approach to improve the economy of desalination plants with a nuclear heating reactor by coupling with hybrid technologies." *Desalination 155 (2003)* 179-185. (This paper is based on research work supported by the CRP of the International Atomic Energy Agency).
- WU, S. 2005, "Analysis of water production costs of a nuclear desalination plant with a nuclear heating reactor coupled with MED processes." *Desalination 190 (2006)* 287–294. (The investigation presented in this paper was supported by a CRP project of the International Atomic Energy Agency).

Appendices

"Water is the best of all things." - PINDAR (438 BC)

"Life originated in the sea, and about eighty percent of it is still there." – Isaac Asimov, 1988

Appendix A MEE program description

In this section the MEE program, used as validation tool, is described. This program simulates the steady state behaviour of the Multiple Effect Evaporation (MEE) process (academic version) and provides cost analyses (commercial version). MEE is part of four programs distributed freely under the copy write agreement put out by the Middle East Desalination Research Centre (MEDRC). In this study the academic version was used.

The MEE computer program provides the desalination community with a useful design tool that can be used to perform system design simulate system performance and calculate process economics. MEE is user friendly and includes a large number of input design data as well as default values. Parameters such as unit capacity and system temperatures can be varied by the user. The MEE program only allows for steam heat sources such as in conventional MED systems, but no allowance is made for water heat source type plants. This program can operate in stand-alone mode or TVC (thermal vapour compression) mode. In Figure A-1 the stand-alone type layout is shown. As seen in Figure A-2, the TVC type layout utilizes compressed vapour as heating medium in order to increase the GOR of the MED plant. An additional steam jet ejector is used. This steam jet ejector is shown in Figure A-3.

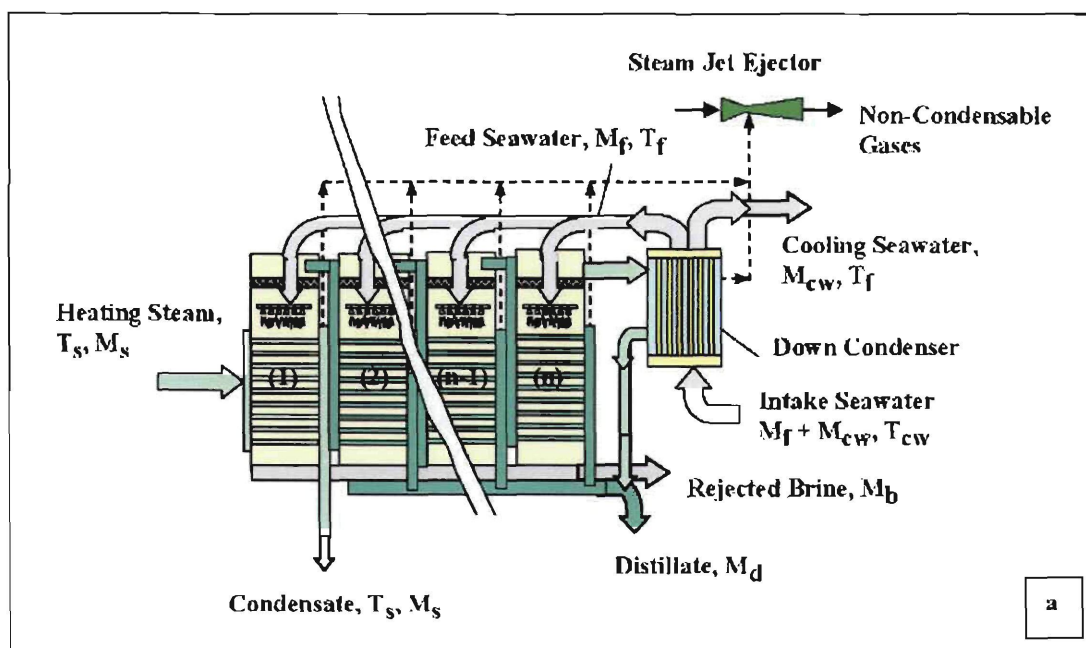


Figure A-1: Schematic of MEE stand-alone layout

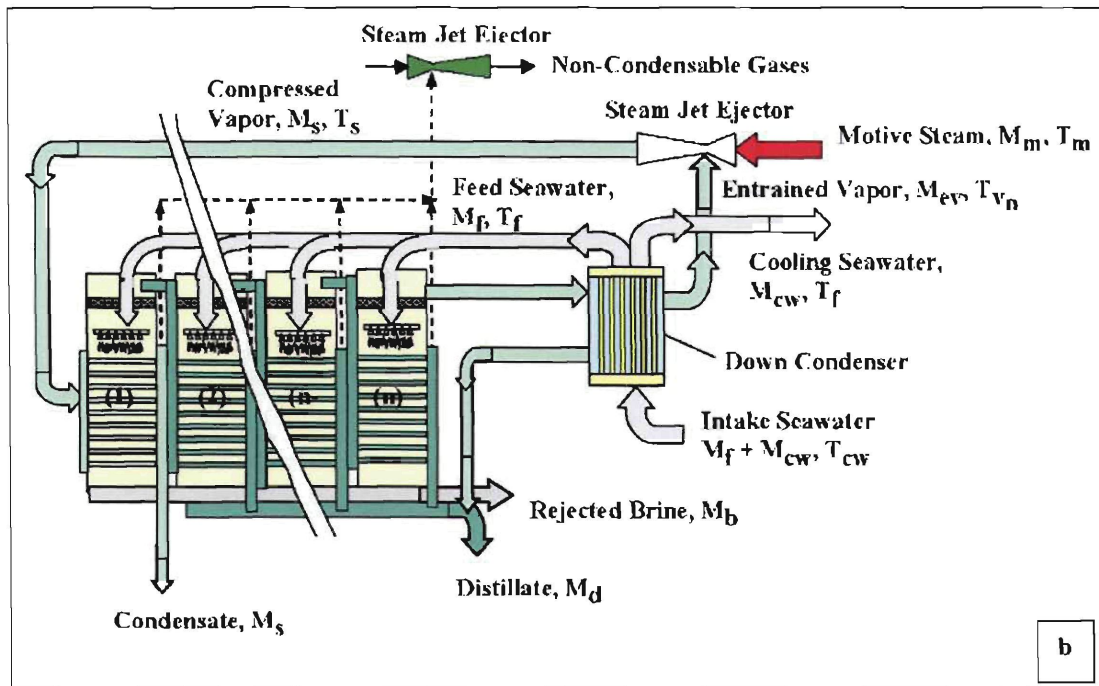


Figure A-2: Schematic of MEE thermal vapour compression (TVC) layout

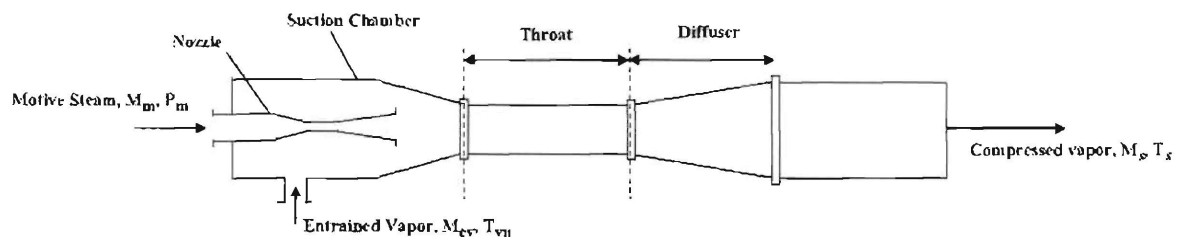


Figure A-3: Steam jet ejector including suction chamber, nozzle and throat

As mentioned in Section 5.3, the MED stage layout and process flow configuration used in the MEE-TVC software differs from the layout identified in this study. As seen from Figure A-4, brine is collected at the bottom of the tube bundles and allowed to flash inside the evaporator shell. This flashing leads to additional product being produced. Brine is used for flashing and rather than for preheating of feed water. From Figure A-6 it is seen that the distillate formed by distillate flashing increases from the first to the last stage, since the brine flow rate (kg/s) increases.

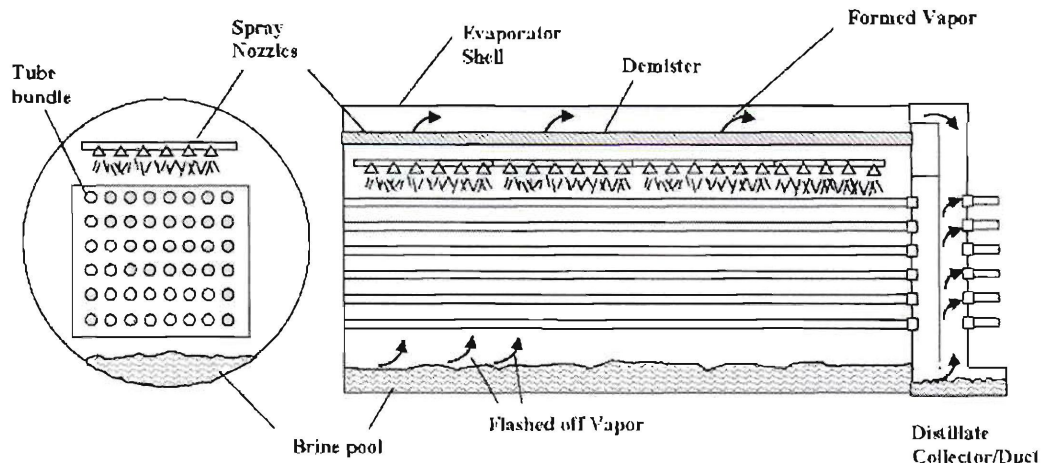


Figure A-4: Evaporator layout including shell, tube bundle and spray nozzles

Assumptions made during development of the MEE-TVC model include:

1. Steady state operation
2. Heat losses to the surroundings are negligible.
3. Equal heat transfer area in each effect.
4. The heat capacities for feed seawater, brine and distillate depend on temperature and composition.
5. The overall heat transfer coefficients in the evaporators depend on the following parameters:
 - a. Flow rate of the condensing vapour.
 - b. Flow rate of the brine film on the outside surface of the evaporator tubes.
 - c. Temperatures of the condensing vapour and brine film.
 - d. Physical properties of the condensing vapour and brine film which includes thermal conductivity, viscosity, density and specific heat.
 - e. The tube material, diameter and wall thickness.
 - f. Fouling resistance.
6. The overall heat transfer coefficient is the sum of the thermal resistances expressed in terms of the inside and outside heat transfer coefficient, the fouling resistance and the thermal resistance of the evaporator tubes.
7. The latent heat of formed/condensed vapour depends on temperature.
8. Thermodynamic losses include the boiling point elevation (BPE), the non-equilibrium allowance (NEA) and demister losses.
9. The distillate product is salt free.

10. The driving force for heat transfer in the evaporators is assumed constant and equal to the difference between the vapour condensation saturation temperature and the brine boiling temperature.

Design input data is specified by the user in a data sheet as seen in Figure A-5. The number of plant effects is specified by the user and the brine temperature distribution is calculated. In this study, the developed C++ MED model allows the user to specify a desired temperature difference across the MED stage, in order to determine the number of stages. It is thus seen that different approaches, regarding user specification, were followed in the C++ MED model and the MEE-TVC software.

A typical MEE-TVC system result sheet is shown in Figure A-6 as well as the nomenclature for the result sheet

Number of Effects	<input type="text"/>	Wall Thickness of Condenser Tubes(m)	<input type="text"/>
Plant Capacity (m ³ /d)	<input type="text"/>	Outer diameter of Condenser Tubes(m)	<input type="text"/>
Heating Steam Temperature (°C)	<input type="text"/>	Thermal Conductivity of Evaporator Tubes(kW/m°C)	<input type="text"/>
Rejected Brine Temperature (°C)	<input type="text"/>	Thermal Conductivity of Condenser Tubes(kW/m°C)	<input type="text"/>
Feed Temperature (°C)	<input type="text"/>	Fouling Resistance in Evaporator (°C/kW)	<input type="text"/>
Intake Seawater Temperature (°C)	<input type="text"/>	Fouling Resistance in Condenser (°C/kW)	<input type="text"/>
Feed Salinity (ppm)	<input type="text"/>	Length of Evaporator Tubes (m)	<input type="text"/>
Salinity of Brine Leaving each Effect(ppm)	<input type="text"/>	Length of Condenser Tubes (m)	<input type="text"/>
Compression Ratio	<input type="text"/>	Vapor velocity in demister (m/s)	<input type="text"/>
Pressure of Motive Steam (kPa)	<input type="text"/>	Demister Thickness (m)	<input type="text"/>
Wall Thickness of Evaporator Tubes(m)	<input type="text"/>	Demister Density (kg/m ³)	<input type="text"/>
Outer diameter of Evaporator Tubes(m)	<input type="text"/>		

Figure A-5: MEE-TVC Design data input sheet

N	TB	TV	D	DD	DB	F	B	XB	U	HIN	HOUT	BPE	NEA	LMTD
1	58.812	58.040	13.9			31.838	17.909	64000	2.842	277.853	10.663	0.771		1.186
2	56.935	56.170	12.8	0.046	0.0551	29.295	34.387	64000	2.798	283.810	10.057	0.765	0.831	1.105
3	55.129	54.371	12	0.085	0.102	27.351	49.772	64000	2.760	289.662	9.569	0.758	0.840	1.041
4	53.378	52.627	11.3	0.119	0.142	25.897	64.339	64000	2.728	295.452	9.184	0.751	0.853	0.993
5	51.669	50.924	10.9	0.151	0.179	24.858	78.322	64000	2.702	301.221	8.887	0.745	0.870	0.956
6	49.989	49.251	10.6	0.18	0.214	24.179	91.922	64000	2.682	307.004	8.668	0.739	0.891	0.935
7	48.329	47.597	10.4	0.209	0.248	23.822	105.322	64000	2.669	312.837	8.519	0.732	0.916	0.921
8	46.679	45.953	10.4	0.238	0.281	23.764	118.690	64000	2.661	318.754	8.435	0.726	0.946	0.916
9	45.030	44.310	10.5	0.268	0.316	23.993	132.185	64000	2.659	324.788	8.411	0.720	0.981	0.923
10	43.373	42.660	10.7	0.3	0.353	24.505	145.970	64000	2.663	330.976	8.443	0.713	1.021	0.937
11	41.700	40.993	11.1	0.334	0.393	25.311	160.207	64000	2.672	337.357	8.531	0.707	1.069	0.960
12	40.000	39.300	11.6	0.373	0.438	26.428	175.073	64000	2.687	343.973	8.673	0.701	1.124	0.993

Figure A-6: MEE-TVC System results

Nomenclature in Figure A-6 includes:

N: Stage number

TB: Brine saturation temperature [°C]

TV: Vapour saturation temperature [°C]

D: Distillate formed by evaporation [kg/s]

DD: Distillate formed by distillate flashing [kg/s]

DB: Distillate formed by brine flashing [kg/s]

F: Feed flow rate [kg/s]

B: Brine flow rate [kg/s]

XB: Brine salinity [ppm]

U: Overall heat transfer coefficient [kW/m²K]HIN: Inside heat transfer coefficient for vapour condensation [kW/m²K]HOUT: Outside heat transfer coefficient for falling film [kW/m²K]

BPE: Boiling point elevation [°C]

NEA: Non equilibrium allowance [°C]

LMTD: Logarithmic mean temperature difference [°C]

For model equations, correlations, range of input parameters and system approach visit <http://www.medrc.org/> and download software.

A.1 Validation Test Case 1 system results

Results from Test Case 1 are shown in this section. Design input parameters, for the MEE-TVC simulation, are shown in Figure A-7. These values correspond with the design input parameters used in the C++ MED model, as seen in Table 5-3 and Table 5-4. Note that the same plant capacity (10 921.5 m³/day) and number of plant effects (8) are used for both the C++ MED model and MEE-TVC simulations.

User Name :**Case No. :****Printed On: 2007/09/03**

Multiple Effect Evaporation

Heat Transfer Areas and Overall Heat Transfer Coefficients

Evaporator Heat Transfer Area =	4649.085 m ²
Brine Heater Heat Transfer Area =	4621.875 m ²
Distillate Heater Heat Transfer Area =	3856.514 m ²
Evaporator Overall Heat Transfer Coefficient =	3.127328 kW/(m ² K)
Brine Heater Overall Heat Transfer Coefficient =	1.939673 kW/(m ² K)
Distillate Heater Overall Heat Transfer Coefficient =	1.949342 kW/(m ² K)

Temperature Distribution

Intake Seawater Temperature =	20 °C
Feed Seawater Temperature =	42 °C
Brine Temperature =	43 °C
Heating Steam Temperature =	70 °C
Motive Steam Pressure =	31 C

Streams Flow Rates, Temperatures, and Salinity

Distillate Flow Rate =	10921.5 m ³ /d	}
Brine Flow Rate =	10712.32 m ³ /d	
Feed Seawater Flow Rate =	21424.64 m ³ /d	
Motive Steam Flow Rate =	1359.958 m ³ /d	
Entrained Vapor Flow Rate =	246.6621 m ³ /d	

 Page No. (1 / 4)

Figure A-7: Test Case 1 system input data

In Figure A-8 the performance parameters, stream flow rates and feed salinity are given. Detail characteristics of the evaporator and condenser, such as tube diameter and heat transfer areas are also given, which can be used to determine the plant capital cost. Cost analyses can also be done with the MEE-TVC commercial version.

Multiple Effect Evaporation	
Heating Steam Flow Rate =	1606.62 m ³ /d
Distillate Salinity =	0 ppm
Brine Salinity =	70000 ppm
Feed Seawater Salinity =	35000 ppm
} Recovery ratio (or PR) = 0.5	
Performance Parameters	
Performance Ratio for MEE =	6.797813
Specific Heat Transfer Area for MEE =	330.795 m ² /k
Specific Flow Rate of Cooling Water for MEE =	1.855085 m ³ /d
Performance Ratio for MEE-TVC =	8.030766
Specific Heat Transfer Area for MEE-TVC =	324.7402 m ² /k
Specific Flow Rate of Cooling Water for MEE-TVC =	1.23892 m ³ /d
Evaporator Design Characteristics	
Evaporator Shell Diameter =	3.539436 m
Number of Evaporator Tubes =	12918.73
Evaporator Tube Outer Diameter =	0.025 m
Evaporator Tube Inner Diameter =	0.015 m
Wall Thickness of the Evaporator Tubes =	0.005 m
Evaporator Tube Length =	7 m
Thermal Conductivity of the Evaporator Tube =	0.042 kW/(m K)
Fouling Resistance of the Evaporator =	0.1 m ² K/kW
Condenser Design Characteristics	
Condenser Shell Diameter for MEE =	3.676164 m
Number of Condenser Tubes for MEE =	14011.32

Figure A-8: Test Case 1 system results (1)

Multiple Effect Evaporation

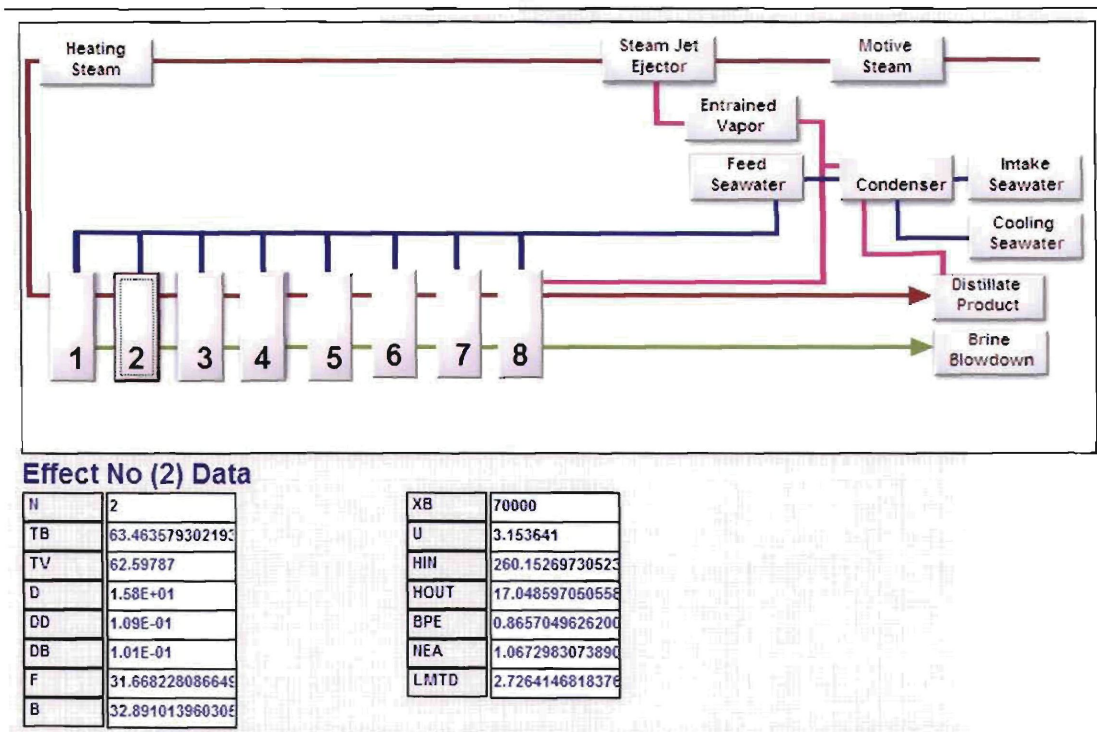
Condenser Shell Diameter for MEE-TVC =	2.661451 m
Number of Condenser Tubes for MEE-TVC =	7014.666
Condenser Tube Outer Diameter =	0.025 m
Condenser Tube Inner Diameter =	0.015 m
Wall Thickness of the Condenser Tubes =	0.005 m
Condenser Tube Length =	7 m
Thermal Conductivity of the Condenser Tube =	0.042 kW/(m K)
Fouling Resistance of the Condenser =	0.1 m ² K/kW

Condenser Design Characteristics

Number of Ejectors in Series =	2
Nozzle Diameter (first ejector) =	7 m
Nozzle Outlet Diameter (first ejector) =	0.042 m
Diffuser Diameter (first ejector) =	0.1 m
Nozzle Diameter (second ejector) =	n/a m
Nozzle Outlet Diameter (second ejector) =	n/a m
Diffuser Diameter (second ejector) =	n/a m

Figure A-9: Test Case 1 system results (2)

The plant layout used in the MEE-TVC simulation is shown in Figure A-10 as well as fluids property profiles in the MED plant.



N	TB	TV	D	DD	DB	F	B	XB	U	HIN	HOUT	BPE	NEA	LMTD
1	67.069	66.190	17.1			34.114	17.057	70000	3.185	250.042	18.094	0.879		2.931
2	63.464	62.598	15.8	0.109	0.101	31.668	32.891	70000	3.154	260.153	17.049	0.866	1.067	2.726
3	60.004	59.151	15.1	0.201	0.186	30.131	47.956	70000	3.130	270.223	16.304	0.853	1.104	2.594
4	56.630	55.790	14.7	0.286	0.263	29.345	62.629	70000	3.113	280.411	15.810	0.840	1.155	2.521
5	53.291	52.464	14.6	0.37	0.339	29.228	77.243	70000	3.104	290.871	15.531	0.827	1.221	2.499
6	49.939	49.125	14.9	0.457	0.418	29.747	92.116	70000	3.103	301.766	15.448	0.814	1.307	2.525
7	46.525	45.725	15.5	0.555	0.506	30.921	107.577	70000	3.109	313.281	15.546	0.800	1.418	2.600
8	43.000	42.214	16.4	0.668	0.608	32.817	123.985	70000	3.122	325.637	15.822	0.786	1.563	2.725

Figure A-10: Test Case 1 system profile

Appendix B MED plant cost

Cost of product is the most important and useful economic criterion. It is evaluated in terms of cost per unit product for a given plant [IAEA, 2000a:137]. Product water cost is evaluated by summing all cost components for desalted water, which include:

- i. The capital cost of desalination plant, including interest during construction.
- ii. Cost of energy for the desalination plant.
- iii. Operation and maintenance (O&M) costs.

Experience from most desalination plants show capital cost to be 30-50% of total water product cost, energy cost 50-30% and O&M cost 15-25% [IAEA, 2000a:138]. Interest and insurance rates have a large effect on a nuclear desalination plant's product water cost. The load factor (LF) represents the fact that the plant or unit produces annually less product than its theoretical potential at full nominal production rate (P_N) and typical LF values for MED plants are 0.7-0.8 [IAEA, 2000a:142]. Higher contributions from capital costs, for nuclear desalination plants, exist. Therefore, the load factor plays an important role. The annual average production rate is given by:

$$P_{avg} = 365 \cdot P_N \times L_F \quad (B.1)$$

The capital recovery factor (CRF), for a given present capital worth value, is given by:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (B.2)$$

where i is the annual interest rate and n is the lifetime of the plant. An economic lifetime of 25 years for a desalination plant is assumed [IAEA, 2000a:141]. The annual capital worth value is then determined by:

$$C_{ca} = C_{cp} \times CRF \quad (B.3)$$

Capital costs include direct cost, indirect cost, base cost and total cost. Direct costs include the nuclear reactor system, turbine system, steam generation system, desalination plant and coupling system. Desalination plant costs include *component costs*, such as heat exchangers, piping, valves, pumps, and *fixed costs*, such as manufacturing of the various components. In this section the costs of the heat exchangers are calculated in order to determine the total capital cost. Since detail costs are not known, for a specific nuclear plant site, certain values will be assumed in order to determine a cost per product for each optimized plant type (SHS, WHS).

Plant economics are important in order to make quality decisions regarding different MED desalination technologies.

Optimized SHS plant

As seen from Table 6-6, the total heat load of the SHS-MED plant is 81.2 MW. The MED plant consists of 12 effects in serie, producing 32,492 m³/day of product water. The annual average production rate is:

$$P_{avg} = 365 \times P_N \times L_F = 365 \times (32,492) \times 0.8 = 9,487,664 \text{ m}^3 \quad (\text{B.4})$$

The total AU-value of the SHS plant is:

$$AU_{total} = AU_1 + AU_2 = 287,323.41 \text{ [kW/K]} \quad (\text{B.5})$$

Assume an overall heat transfer coefficient (U) of 3 kW/m²K. The evaporator heat transfer area becomes:

$$A_{evap} = 95,774.47 \text{ m}^2 \quad (\text{B.6})$$

The heat transfer area per stage is then:

$$A_{effect} = A_{evap} / 12 = 7,981.2 \text{ m}^2 \quad (\text{B.7})$$

Currently Copper-Nickel and Copper-Zink are used as tube material in MED plants. However, aluminium as material should be investigated in the future. Seamless evaporator tubes in CuNi10Fe1Mn (ASTM C68700-061 annealed) are chosen as tube material, in order to make a cost comparison. Tube dimensions are chosen as 25.4 x 1.0 x 6100 mm. The heat transfer area of a single pipe is calculated as:

$$A_{tube} = \pi \cdot D_i \cdot L = \pi \cdot (0.0254 - (0.002)) \times 6.1 = 0.448 \text{ m}^2 \quad (\text{B.8})$$

The number of evaporator tubes in the MED plant is:

$$\# \text{ tubes} = \frac{A_{evap}}{A_{tube}} = 213,782.3 \quad (\text{B.9})$$

The number of tubes per stage is 17,816. A quotation obtained from Wolverine Tube Europe BV in the Netherlands, 2007-06, regarding the tube material cost, states that:

Item	Quantity	Dimensions	Price/piece	Extension per stage
1	17,816	25.4 x 1.0 x 6100 mm	USD 63.95	USD 1,139,333.2

In order to determine the total capital cost of any MED size plant, a cost prediction is made for SHS type plants. MED plant cost is given by (3.26). The b-value is calculated, assuming a cost-function through the origin, according to:

$$b = \text{cost} / A = 1,139,333.2 / 7,981 = 142.75 \quad (\text{B.10})$$

It is assumed that the fixed cost is 10% of the MED plant. This value can now be divided among the total heat exchangers to obtain the a-value. Then, the a-value is determined according to:

$$a = [0.1 \times \text{cost}] / 12 = [0.1 \times 1,139,333.2] = 113,933.32 \quad (\text{B.11})$$

A cost prediction for the SHS plant can now be made and the total desalination plant cost determined.

$$\begin{aligned} \text{Cost [\$]} &= N \times (113,933.32 + 142.75 A_{\text{effect}}) \\ &= 12 \times (113,933.32 + 142.75(7,981.2)) \\ &= 15,038,995.44 \end{aligned} \quad (\text{B.12})$$

Assume that the heat exchanger tube cost represents the desalination plant cost and that the desalination plant cost presents 30% of the total capital cost. When extrapolating the desalination plant cost, a total capital cost for the SHS-MED plant of USD 50,129,984.80 is obtained.

When using an annual interest rate of 8%, the annual capital cost becomes:

$$C_{ca} = C_{cp} \times \frac{0.08(1.08)^{25}}{(1.08)^{25} - 1} = \$ 4,696,119.94 \quad (\text{B.13})$$

Assuming capital cost to be 30% of the total water product cost, the water product cost is then approximately \$ 15,653,733.14 per year. The water product cost, using (B.4), becomes:

$$\text{Water product cost} = \$ 15,653,733.14 / P_{\text{avg}} = \$1.65/\text{m}^3 \quad (\text{B.14})$$

The capital cost becomes \$1,542.84 per m³/d capacity. The capital cost, based on the annual value, is \$0.49/m³.

Optimized WHS plant

As seen from Table 6-6, the total heat load of the SHS-MED plant is 81.2 MW. The MED plant consists of 54 effects in serie and parallel, producing 21,258 m³/day of product water. The annual average production rate is:

$$P_{\text{avg}} = 365 \times P_N \times L_F = 365 \times (21,258) \times 0.8 = 6,207,336 \text{ m}^3 \quad (\text{B.15})$$

The total AU-value of the WHS plant is:

$$AU_{\text{total}} = AU_1 + AU_2 = 193,074 \text{ [kW}/\Delta\text{T}] \quad (\text{B.16})$$

Assume an overall heat transfer coefficient (U) of 3 kW/m²K. The evaporator heat transfer area becomes:

$$A_{\text{evap}} = 64,358 \text{ m}^2 \quad (\text{B.17})$$

The heat transfer area per stage is then:

$$A_{\text{effect}} = A_{\text{evap}} / 54 = 1,191.81 \text{ m}^2 \quad (\text{B.18})$$

Tube dimensions are chosen as 25.4 x 1.0 x 6100 mm. The heat transfer area of a single pipe is calculated as:

$$A_{\text{tube}} = \pi \cdot D_i \cdot L = \pi \cdot (0.0254 - (0.002)) \times 6.1 = 0.448 \text{ m}^2 \quad (\text{B.19})$$

The number of evaporator tubes in the MED plant is:

$$\# \text{ tubes} = \frac{A_{\text{evap}}}{A_{\text{tube}}} = 143,656.25 \quad (\text{B.20})$$

The number of tubes per stage is 2,661. A quotation obtained from Wolverine Tube Europe BV in the Netherlands, 2007-06, regarding the tube material cost, states that:

Item	Quantity	Dimensions	Price/piece	Extension
1	2,661	25.4 x 1.0 x 6100 mm	USD 63.95	USD 170,170.95

The b-value is calculated, assuming a cost-function through the origin, according to:

$$b = \text{cost} / A = 170,170.95 / 1,191.82 = 142.78 \quad (\text{B.21})$$

It is assumed that the fixed cost is 10% of the MED plant. This value can now be divided among the total heat exchangers to obtain the a-value. Then, the a-value is determined according to:

$$a = (0.1 \times \text{cost}) / 54 = (0.1 \times 170,170.95) = 17,017.1 \quad (\text{B.22})$$

A cost prediction for the WHS plant can now be made and the total desalination plant cost determined.

$$\begin{aligned} \text{Cost [\$]} &= N \times (17,017.1 + 142.78 A_{\text{effect}}) \\ &= 54 \times (17,017.1 + 142.78(1,191.81)) \\ &= 10,107,921.24 \end{aligned} \quad (\text{B.23})$$

When extrapolating the desalination plant cost, a total capital cost for the WHS-MED plant of USD 33,693,070.82 is obtained. When using an annual interest rate of 8%, the annual capital cost becomes:

$$C_{\text{ca}} = C_{\text{cp}} \times \frac{0.08(1.08)^{25}}{(1.08)^{25} - 1} = \$ 3,156,325.84 \quad (\text{B.24})$$

Assuming capital cost to be 30% of the total water product cost, the water product cost is then approximately \$ 10,521,086.14 per year. The water product cost, using (B.4), becomes:

$$\text{Water product cost} = \$ 10,521,086.14 / P_{\text{avg}} = \$1.7/\text{m}^3 \quad (\text{B.25})$$

The capital cost becomes \$1,584.95 per m³/d capacity. The capital cost, based on the annual value, is \$0.56/m³. Both the capital cost and water product cost corresponds well with predicted MED costs, calculated by the IAEA, mentioned in Section 1.2.

Appendix C MED model configuration layouts

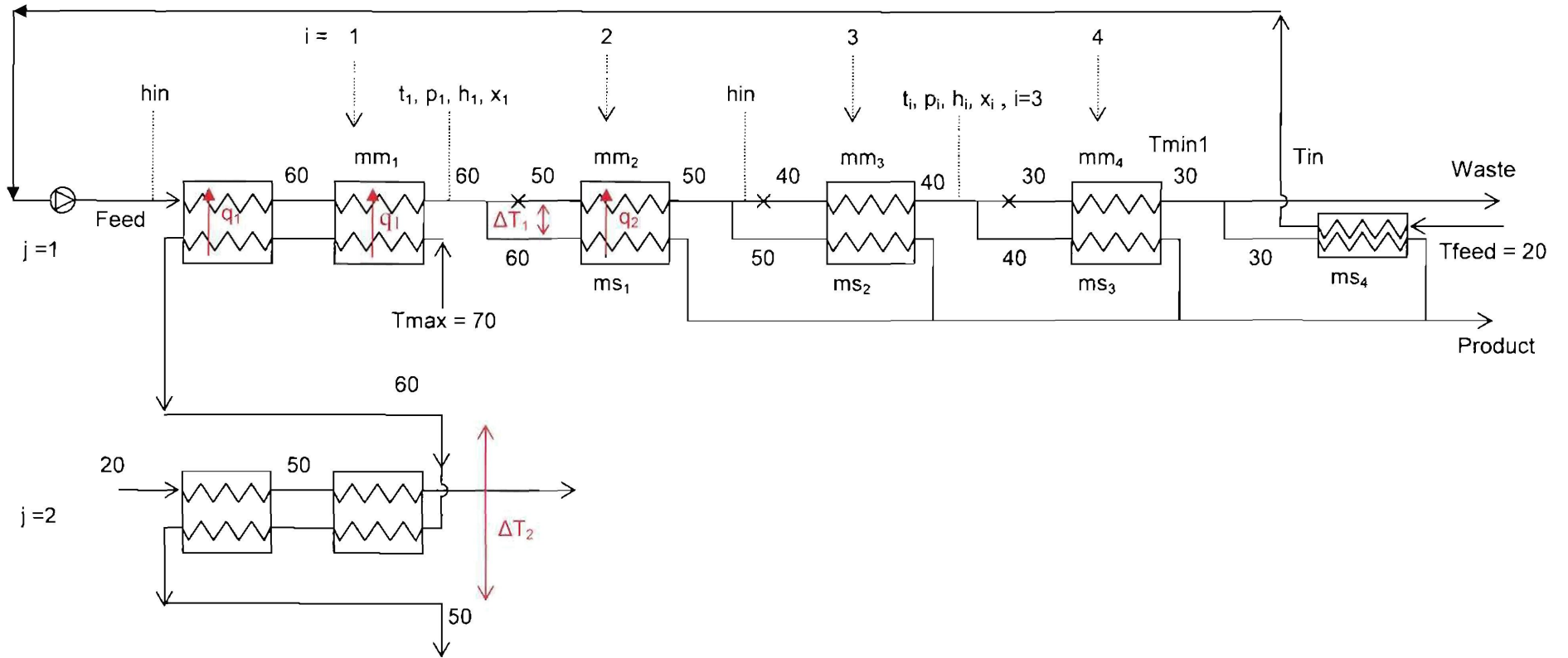


Figure C-1: Analysis model of FFC layout

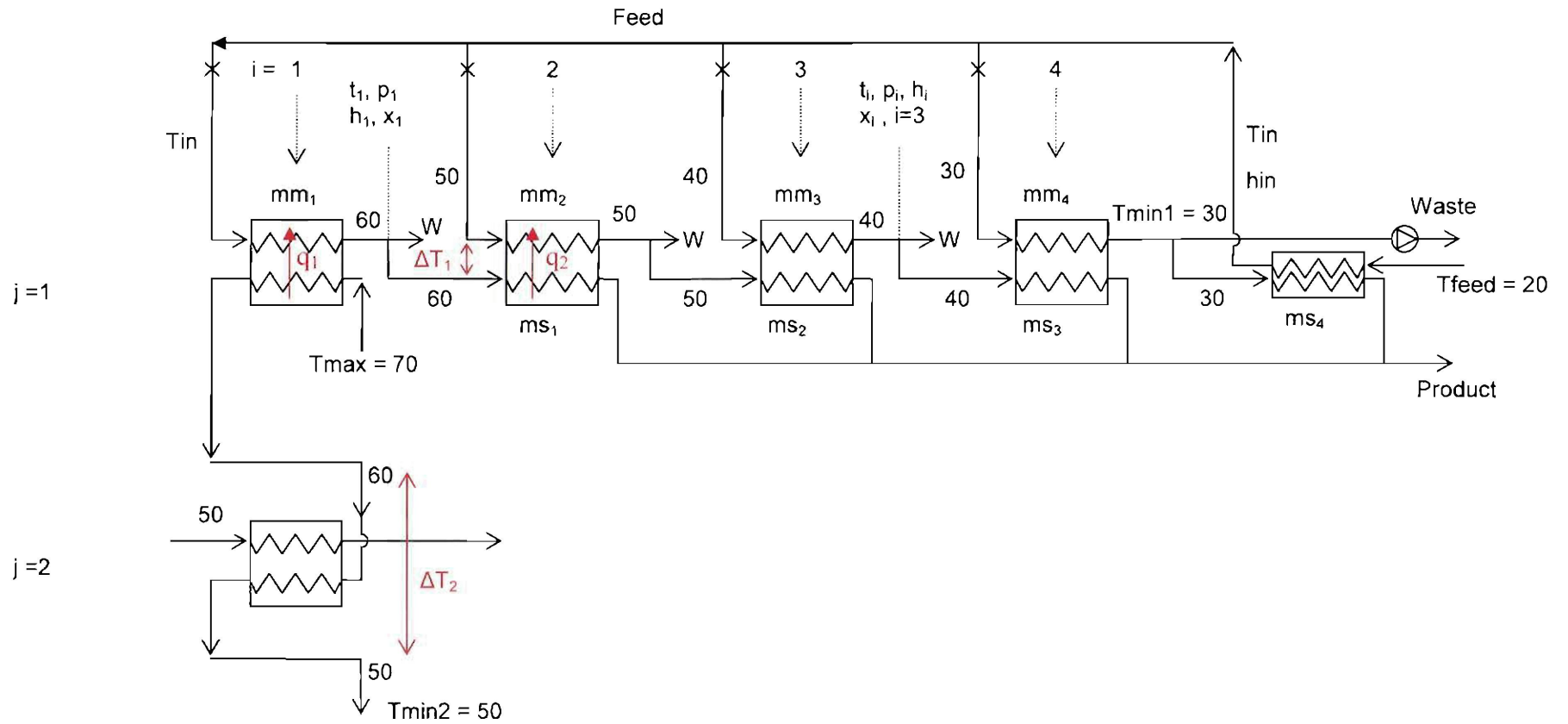


Figure C-3: Analysis model of PFC layout