MODELLING AND SIMULATION OF MULTISTAGE FLASH (MSF) DESALINATION PLANTS USING TDP, MEDRC AND MSTDP PROGRAMS

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Abstract

Desalination processes are playing a critical role in providing water for domestic and industrial usages in many places over the world. In this study, the benefits of the process modelling utilization in desalination plant design and operation are explored a case study on a real desalination plant is used to demonstrate of the concept.

A short-cut method of design and examine operation of Multi Stage Flash (MSF) Process is presented. Three Computer softwares were used and tested to demonstrate simulation of Multi stage Flash (MSF) plant which is operating in an industrial site in Libya. The first software (MSTDP) has been developed by the Authors under the name of " Modelling and Simulation of thermal desalination plants" is implemented as Excel Spreadsheet files while the second (TDP) developed by El-Dessouky and Ettouney (TDP - Thermal Desalination Processes) and the last one developed by Middle East Desalination Research Centre (MEDRC). Comparisons and Results obtained from this study are presented along with conclusions and recommendations.

Key words: Modelling and Simulation; Steady State Modelling; Multi Stage Flash; Plant Data Evaluation; Plant Productivity

1- Introduction

In many places in the world, there is a sever shortage of water from natural resources. Compensation this shortage is usually achieved by utilising desalination processes whenever that is feasible. Also, water may be needed at high quantity and quality for industrial usage such in the chemical and petrochemical plants and, in most cases, desalination can meet these requirements. Seawater is availability in large volumes on the earth (Fig. 1) and it is already the only source can provide water in some regions in the world such as the majority of Arab countries (see Table 1).

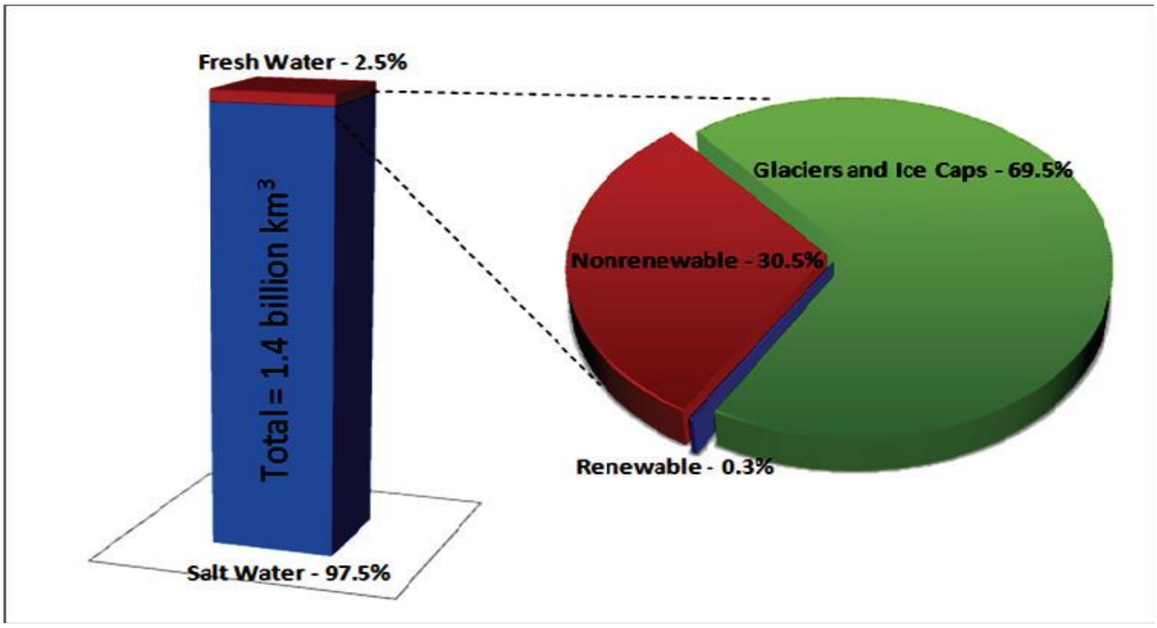

Fig. 1 World's Water Sharing Percentage [1]

Desalination processes are divided into two categories; Thermal and none-thermal processes. Thermal processes are utilising thermal energy sources such saturated steam and they are widely used (see Table 1) while the none-thermal processes are utilising any other sources such electrical energy (see Fig. 2).

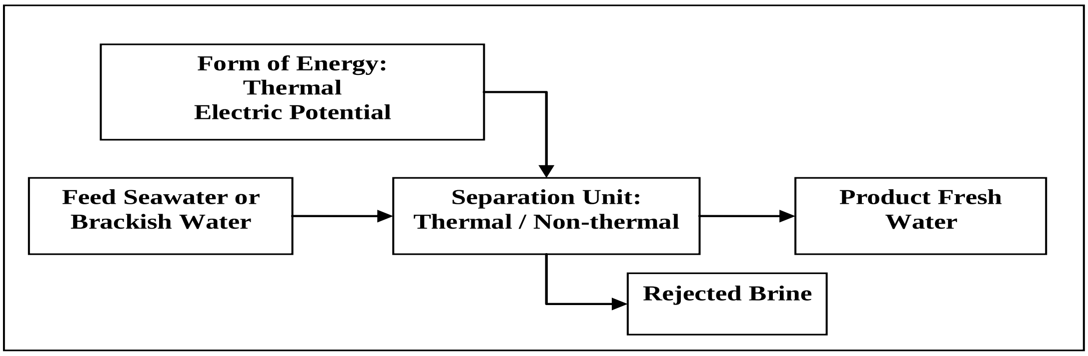

Fig. 2 Desalination Mechanisms

Thermal processes are used due to their potentional economic in term of production capacity capability and energy consumption. The steam energy is much cheaper than electrical and steam can be available as waste energy in some industrial sites. However, full economic feasibility study will show the best utilisation of energies with different scenarios of desalination technologies.

Table 1. Installed Desalination Capacity [2]

Country	Total Capacity (m^3/day)	% of Global Production	MSF	MEE	MVC	RO	ED
Saudi Arabia	5,253,200	25.9	65.7	0.3	1.2	31	1.9
United States	3,092,500	15.2	1.7	1.8	4.5	78	11.4
United Arab Emirates	2,164,500	10.7	89.8	0.4	3.0	6.5	0.2
Kuwait	1,538,400	7.6	95.5	0.7	0.0	3.4	0.3
Japan	745,300	3.7	4.7	2.0	0.0	86.4	6.8
Libya	683,300	3.4	67.7	0.9	1.8	19.6	9.8
Qatar	566,900	2.8	94.4	0.6	3.3	0.0	0.0
Spain	529,900	2.6	10.6	0.9	8.7	68.9	10.9
Italy	518,700	2.6	43.2	1.9	15.1	20.4	19.2
Bahrain	309,200	1.5	52.0	0.0	1.5	41.7	4.5
Oman	192,000	0.9	84.1	2.2	0.0	11.7	0.0
Total	**15,594,500**	**76.9**					

In Table 1 the first three processes are thermal processes which are MSF (Multi Stage Flashing), MEE (Multi Effect Evaporation) and MVC (Mechanical Vapor Compression). The reset two processes are non-thermal and they are RO (Reverse Osmosis) and ED (Electro-Dialysis). Multi stage flashing processes are used in the large commercial scale and they are divided into two types; Multi Stage Flashing-Once Through (MSF-OT) and Multi-Stage Flashing with Brine Recirculation (MSF-BR). MSF plants are known as massive productive processes , e.g. 50,000 m^3/day [3] comparing to others processes.

2- MSF Process Description

All MSF processes, at present state of art, are widely used all over the world; they are driving force for desalination, wherever seawater is converted into fresh water (Table 1). The objective of the MSF system is to overcome the main drawback of the single stage flash unit that is to improve the system performance ratio; by another word, improve the productivity and minimize energy consumption. This is achieved by dividing the flash range over a larger number of stages.

MSF commercial systems are divided into two process configurations. The first is called Multi Stage Flash Once Through, MSF-OT. The second is called Multi Stage Flash with Brine Circulation, MSF-BR.

2.1- MSF-OT Process

It is found on a very limited number in operation and small production capacity. The process is formed of the flashing stages (heat recovery section) and the brine heater; see Fig. 3. The feed seawater flows through the condenser tubes, where it absorbs the latent heat of condensation from the flashing vapor formed in each stage. This heat recovery process improves the overall system efficiency. The feed seawater is heated to the top brine temperature in the brine heater. Brine flashing takes place in the flashing chambers, where small amounts of distillate are formed in each stage with simultaneous increase in the brine salinity and decrease in its flow rate.

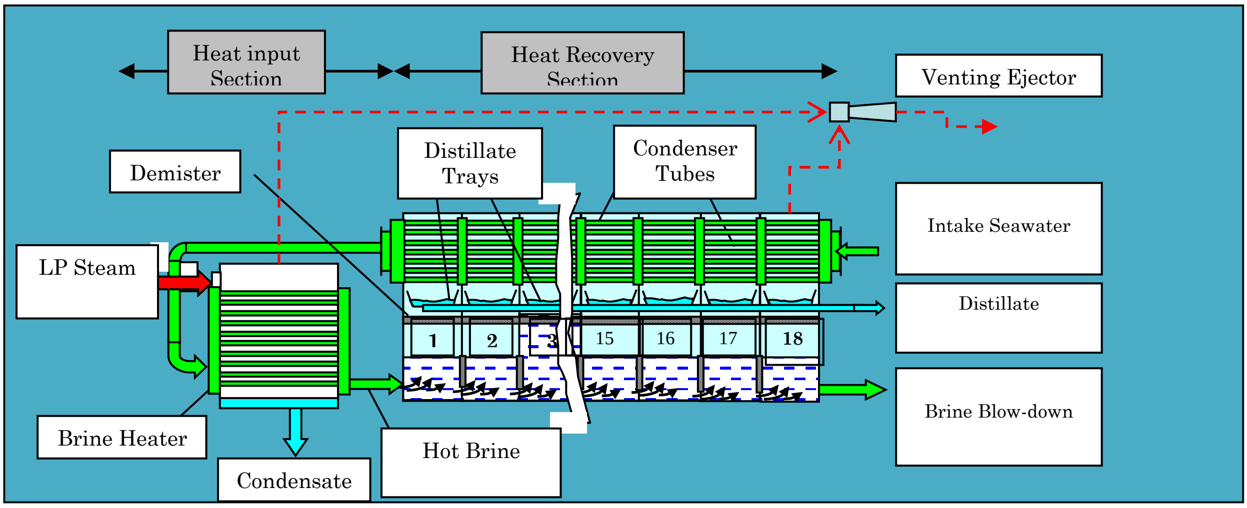

Fig. 3 MSF-OT Desalination Unit

There are many drawbacks for MSF-OT process. There is no control system on the feed seawater temperature. Therefore, reduction of the thermal performance ratio can be noticed {as low as 3 from 8 as the seawater temperature drops, from 25 oC (summer) to 15 °C (winter)}. Maintaining the thermal performance ratio at a value of 8 would require decrease in the brine blowdown temperature, which is associated with drastic increase in the stage dimensions. The flow rate ratio of the feed to product in the MSF-OT process is approximately 10:1. On the other hand, this ratio in the brine circulation MSF is 2.5:1. This increases the MSF-OT consumption rate scale and foam control chemicals.

On the other hand, there are also many advantages of MSF-OT. It is preferred to utilize where seawater temperature is constant along the year such as in equatorial regions with feed seawater almost constant at 28 °C all over the year. Reduction in the number of pumping units (MSF-OT has pumps for feed seawater, distillate product, and brine reject) and (MSF-BR has additional pumps for brine recycle and cooling seawater). Reduction in the number of pumps would reduce the number plant trips caused to the pumping units (50% of all MSF-BR plant trips). MSF-OT brine salinity is as high as 45,000 ppm that should affect the consumption rate of the antiscalent significantly. MSF-OT has lower boiling point elevation, which would increase the flashing vapor temperature and consequently the feed seawater temperature entering the brine heater. Other factors to be taken into considerations:

- The performance ratio of the MSF-OT is similar to the MSF-BR.
- The capacity of the MSF-OT is similar to the MSF-BR.
- The specific heat transfer area (defined as the total heat transfer area per unit product flow rate) of MSF-OT is similar to the MSF-BR.

2.2- MSF-BR Process

The process is formed of brine heater and flashing stages of the heat rejection and heat recovery sections, see Fig. 4. The intake seawater stream flows in the condenser tubes of the heat rejection section. The warm stream of intake seawater is divided into two parts: the first is the cooling seawater which is rejected back to the sea and the second is the feed seawater which is deaerated, chemically treated and then fed to the brine pool of the last flashing stage in the heat rejection section. The brine recycle stream is extracted from the brine pool of the last stage in the heat rejection section and is introduced into the condenser tubes of the last stage in the heat recovery section.

The temperature of the brine recycle is increased inside the condenser tubes in the heat rejection section to a temperature 5-10ºC lower than the top brine temperature. The brine recycle stream is heated to the top brine temperature in the brine heater, where its value depends on the type of chemicals used to control the scale formation. The hot brine enters the flashing stages in the heat recovery section and then in the heat rejection section, where a small amount of fresh water vapor is formed by brine flashing in each stage. The flashing process takes place due to the decrease in the stage saturation temperature that causes reduction in the stage pressure. The condensed fresh water vapor outside the condenser tubes accumulates across the stages and forms the distillate product stream.

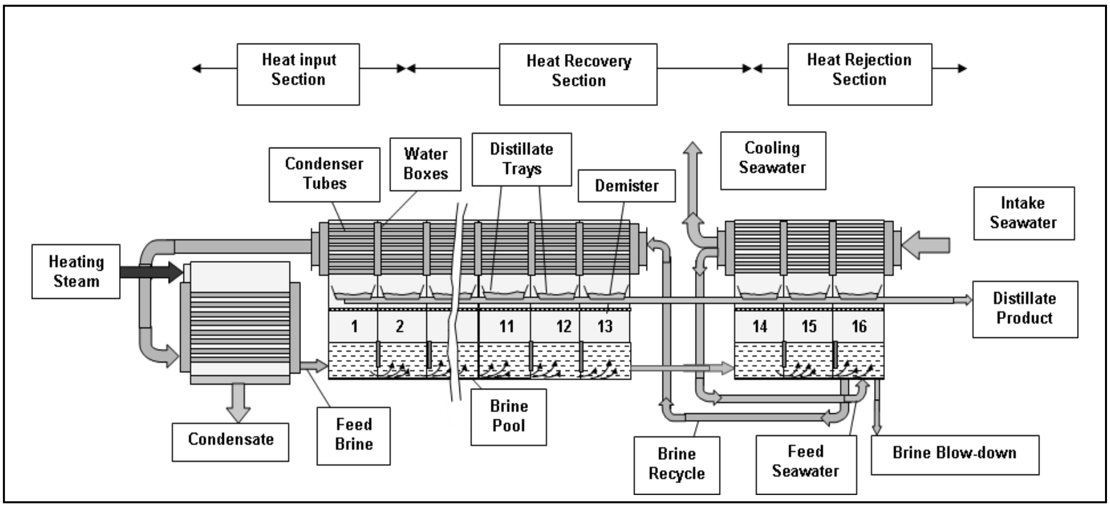

Fig 4 MSF-BR Desalination Unit

The flashing process and vapor formation is limited by increase in the specific vapor volume at lower temperatures and difficulties encountered for operation at low pressures. Common practice limits the temperature of the last stage to range of 30 to 40ºC, for winter and summer operation, respectively. In MSF, most of the flashing stages operate at temperatures below 100ºC and have vacuum pressure. This increases the possibilities of in-leakage of the outside air. Also, trace amounts of dissolved gases in the flashing brine, which are not removed in the deaerator or formed by decomposition of $CaHCO_3$.

Presence of non-condensable gases results in severe reduction in the heat transfer rates within the chamber, increase of the tendency for corrosion, and reduction of the flashing rates. Proper venting of non-condensable gases is necessary to enhance the flashing process and to improve the system efficiency. Treatment of the intake seawater is limited to simple screening and filtration. On the other hand, treatment of the makeup seawater is more extensive and it includes deration and addition of chemicals to control scaling and foaming.

2.3- Case Study: MSF-BR Plant

MSF-BR plant was used in this study for demonstration, this plant has been working for more than 20 years and it has a production capacity of 6,000 m^3/day [4]. It consists of 13 stages as heat recovery section and extra 3 stages as heat rejection section. The energy supplied to the process in its brine heater and then it is removed in heat rejection section mostly. All of the heat recovery stages are identical in construction as well as heat rejection section. Fig 4 and table 2 shows a schematic diagram and the main specification data of the MSF-BR desalination Plant respectively.

The feed seawater is drawn through intake pipes located into deep sea. A pre-treatment for seawater includes pre-chlorination and removal of suspended solids by filtration are applied. Then cold seawater enters the condenser tubes in the last stage of the process at an initial temperature (heat rejection section). The feed stream divides into two streams. The 45% of warm seawater leaving the rejection section is discharged to the effluent line and about 55% of this warm water is diverted as make – up feed water to the evaporator in order to maintain a constant salt concentration in the evaporator.

Seawater and brine circulation are heated generatively by condensing water vapour until it exits at a temperature. Then it is heated to top brine temperature by an external source of heat (LP steam) and enters the first-stage-flashing chamber. After successive flashing, the brine finally leaves the unit with a reject concentration around 7 wt% at blowdown temperature. The difference between top brine temperature and brine blowdown temperature is called the flash range.

Dissolved CO_2 and air must be removed (by deaerator and venting ejectors) from seawater make-up stream to a very low level, to prevent corrosion, and to minimize the amount of non-condensable gases which would impair the heat transfer rate. Anti-scale chemical is injected to seawater make up stream to eliminate scale formation.

The major parts of the desalination units are described briefly:

- **Evaporator/Condenser**

A single stage contains the evaporator / condenser heat exchanger. The lower section of the stage is a large room called the flash chamber where brine water passes, and then part of it vaporizes and passes through demisters to the upper section. The evaporated steam enters the upper section of the flash chamber, which consists of condensing tubes on which steam condenses to form the distillate water. The distillate water is collected in a distillate tray in each stage. The stages are separated with walls; each wall has outlet for the brine water (orifice) to pass to the next stage.

- **Brine heater**

The function of this heater is to heat the brine water to a maximum temperature of 88^{0}C or 90^{0}C by using saturated low-pressure steam. It is a shell and tube heat exchanger where brine flows through the tubes and steam on the shell side. The condensed steam is collected in withdrawn pool located under the heater.

- **Pumps**

There are a number of pumps are included in the unit: seawater feed pump, brine blowdown pump, distillate water pump, circulating venting water pump, condensate pump, and chemicals dosing pumps.

- **Venting system**

Air leakage through manholes and other flanged connections, together with the non-condensable gases and the small amount of entrained vapour are vented from each stage of the evaporator to the ejector system (venting system).

Table 2 Main Plant Specification Data

Plant design data	Units	Case 1	Case 2	Case 3
Seawater feed temp.	ºC	16	24	27
Maximum brine temp.	ºC	90	90	90
Distillate production	t/hr	277	250	240
Performance ratio*	--	6.26	6.25	6.23
Cooling water	t/hr	832.1	890	911.5
Make-up water	t/hr	673	614.4	593.5
Brine blowdown	t/hr	395.2	364.37	353.2
Heat Transfer Area, Rejection Section	m^2	1,482		
Heat Transfer Area, Recovery Section	m^2	13,726		
Heat Transfer Area, Brine Heater	m^2	1,313		
Distillate Purity (TDS)	ppm	< 3.0	< 3.0	< 3.0

* **Performance ratio = distillate production / steam consumption**

3- Thermal Desalination Process Simulation with TDP and MEDRC Programs

In recent years, many desalination softwares are available to plant designers and operators. Among them two softwares were used in this study. The first package was used had been developed by the Chemical Engineering Department at Kuwait University under name of "Thermal Desalination Processes, TDP". It contains mostly all thermal desalination processes models such as Multi Stage Flash with/without brine circulation (MSF-OT or MSF-BR) and Multi Effect Evaporators with/without thermo compression ejector (MEE or MEE-TVC). TDP can also used to estimate thermodynamic properties for steam and seawater.

The second software package (MEDRC package) was developed by the Middle East Desalination Research Centre (MEDRC) in Oman. This package includes four sub-softwares for simulation and each one concern a special desalination process. These sub-softwares are Multi Stage Flash, Multi Effect Evaporators, Mechanical Vapor compression, and Reverse Osmosis.

These packages are very helpful for beginners as well as for professionals in modelling of desalination processes. In practical application, the first package (TDP) suffers from many limitations which minimize their utilization and reliability as well as the MEDRC package but is not in the same extent. Moreover, TDP prediction for design or operation a plant is very conservative when compare to actual plant data (see Table 3) while MEDRC package overestimated it.

It seems that these softwares either built on basis of typical design values which might not valid for an actual plant, or their assumption of calculations are conservative, or they were designed for large plant which can hide some small deviation of parameters in its calculations. Therefore, programmers need to check the basis of calculations, assumptions, mathematical algorithms, and maximum and minimum limitations. They also might need to develop two separate softwares to consider large variation in plant size and parameters, i.e. for large units and small units. However, there is a need to review these packages (especially TDP) and validate them to give prediction better for real plant.

Table 3 Soft wares Comparison on Designing of a 6,000 t/day MSF-BR*

	Seawater Temp., ºC	Production, t/hr	Brine Heater Heating Surface, m^2
Reference Plant Data	24	250.0	1,313.00
TDP package*	24	363.6	1,792.30
MEDRC Package*	24	250	933.43

* Seawater temperature and production are input parameter for TDP and MEDRC Package.

4- MSF-BR Short-Cut Method for Production Estimation

This is a preliminary method to estimate the productivity of a MSF-BR unit at design stage or even in operation [2]. The method is actually based on the overall mass & energy balance concept of MSF processes (both MSF-BR and MSF-OT). The concept is that the temperature profiles across MSF unit are indication to maximum temperature that the seawater can be heated which can affect the capital costs and the energy costs of water production. Accordingly, the thermal efficiency of the unit is then dependent on the temperature range that is the flashing is flash range which is driving force for all MSF processes.

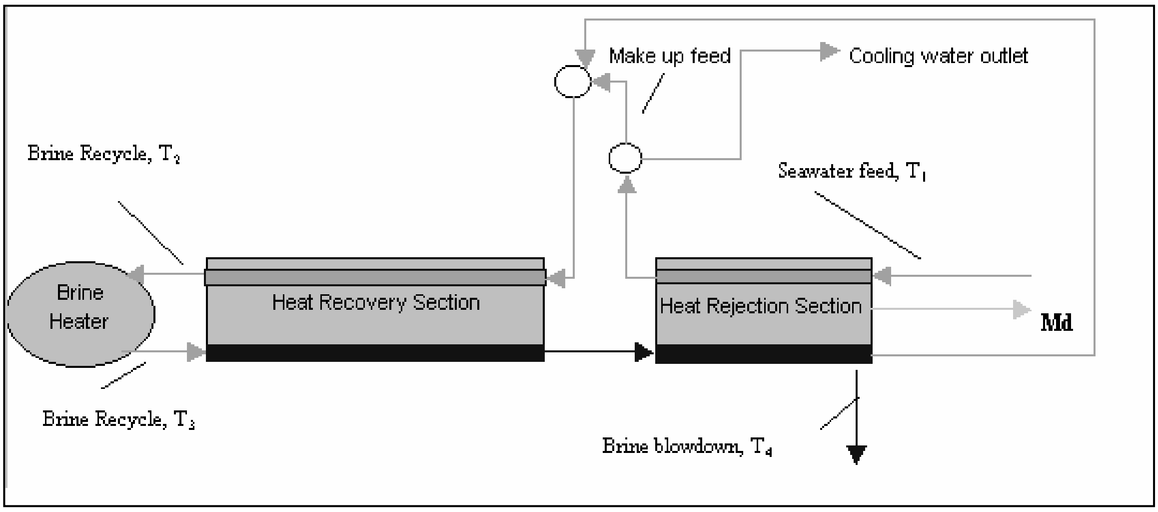

Fig. 5 MSF-BR with Parameters of Short-Cut Method

This method assume ideal situation and ignores boiling point elevation (BPE), non-equilibrium allowance loss (NEA), temperature and pressure losses in demisters and tube bundles, and heat loss from the process to environment.

However, there is a benefit from using this method; easily it can show any indication of deviation in water productivity using just few plant parameters (i.e. temperatures and flow rates). The model equations (Eqn I and II) are as follows;

Md = {Mr × Cp × Flash range} / λ ----- **(1)**

Qin = (((T3-T2) x λ) / Flash range) × Md ----- **(2)**

Where:

T1 = inlet seawater temperature (^oC)

T2 = hot seawater temperature inlet to brine heater (^oC)

T3 = top brine temeprature (^oC)

T4 = brine blowdown temeprature (^oC)

Flash range = T3 – T4 (^oC)

Md = product water (t/hr)

Mr = seawater feed flow rate (t/hr)

Cp = average seawater specific heat of seawater across evaporator (kJ/kg.^oC)

λ = average latent heat of vaporization across evaporator (kJ/kg)

Q_{in} = heat input, Brine heater load (kW)

Note that the only way to reduce the external energy requirements is to increase the flashing range (T3-T4). However, this means increase in temperature which is constrained by technical and economical factors such as pressure losses and plant size. Increasing the flash range reduces the amount of seawater that can be brought through the process, and thus decreasing flow rates and hence reducing the operating cost of the plant. This method is used to predict the production rate of distillate water using design and actual operation data for demonstrated plant. Table 4 summarized the results obtained for four case studies (at design and operational conditions).

As can be seen from Table 4, the predicted results of design case are in agreement with values were recorded by plant operator. The deviations (shown in the table) are due of ignoring all types of losses mentioned previously. This method can be a great help tool for operators after check their validation tolerance error between design and prediction to consider all thermodynamics losses.

Table 4 Example on Using Short-Cut Method on MSF-BR Unit

	Item	Design			Operation Case
		Case 1	Case 2	Case 3	
Input	Seawater feed temperature, T1 (oC)	16	24	26.7	25
	Seawater feed temperature, T2 (oC)	81.8	82.7	82.9	80
	Top brine temperature, T3 (oC)	90	90	90	88
	Brine blowdown temperature, T4 (oC)	33.2	39.2	41.3	40.61
	Average seawater temp. across evaporator (oC)	61.6	64.6	65.65	64.305
	Average latent heat of vaporization, λ (kJ/kg)	2383.5	2383.5	2383.5	2383.5
	Seawater salinity (ppm)	65380	65380	65380	65380
	Average seawater specific heat , C_p (kJ/kg.oC)	3.89	3.89	3.89	3.89
	Seawater feed flow rate, Mr (t/hr)	3098	3098	3098	2400
	Flash range (oC)	56.8	50.8	48.7	47.39
Output	Water production, Md (t/hr)	287.18	256.85	246.23	185.6233
	Brine Heater load, Qin (kW)	27450	24437.2	23767.68	20746.67
Reference	Production reference capacity, Md (t/hr)	277.7	250	240.7	182
	Heat load reference, Qin (kW)	27744.44	25222.22	23961.11	21505
Deviation	Deviation of Water production, %	3.42%	2.74%	2.30%	1.99%
	Deviation of Heat load, %	1.06%	3.11%	0.807%	3.526%

5- MSF-BR Process Simulation with MSTDP Program

MSTDP program has been developed by the Authors under the name of " Modelling and Simulation of thermal desalination plants" is implemented as Excel Spreadsheet files and has developed a number of Excel spreadsheets to increase capability in analysiing process parameters of desalination processes. One spreadsheet is designed for modelling of MSF-BR. The mathematical model and themrmodynamic carrolations of steam and water used are taken from reference number [3],[5],[6],[7],[8]. We found that spreadsheet model is more reliable than the previous Short-Cut Method for specially the calculation of prodcutivity and energy consumption. It performs analysis as stage-by-stage and it takes account of the most of thermodynamic losses that affect the flashing process. Further more, the calculation of heat transfer charactericès for the process are included.

The calculations start from the hot side in the processes (i.e. Brien heater) and it is based on temperature rise of brine and seawater inside the condenser tubes in order to simplify starting of analysis. the results of production rate, all flow rate streams and temperature of all streams are calculated and found to be very close to design values. A small variation has been noted between calculated values (i.e. temperature profile) and design specifications. This is because of the assumption used within the model such as using typical stage dimensions, brine levels, space between brine levels and demisters, orifice gate geometry, ignoring presence of non-condensable gases, and ignoring heat loss form stage to surrounding.

5.1- Design Conditions

The MSTDP Program is capable to predict the production capacity of a plant at different operating condition. Table 5 summaries the prediction data by using MSTDP Program for a given plant and Fig. 6 shows the main streams technical information for MSF-BR at seawater temperature of 24^{o}C using MSTDP Program.

Table 5 Production Capacity at Design conditions and Prediction by using MSTDP Program at different operating cases

	Case 1	Case 2	Case 3
Seawater Temperature, ºC	16	24	27
Production Capacity, t/hr (Design)	277	250	240
Production Capacity, t/hr (Prediction using MSTDP Program)	275	249	238

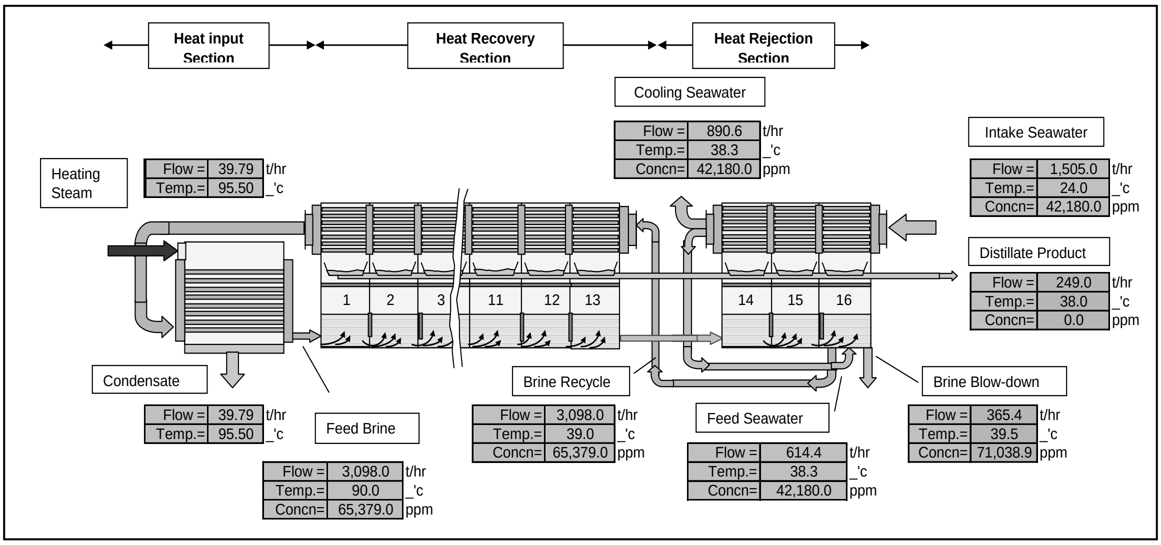

Fig. 6 Design Operation using MSTDP Program at Seawater Temperature 24ºc

5.2- Operational Conditions

This case is a real operation case which involves un-tested measurement device, after long time of operation, for a distillate stream. The readings of the plant capacity was recorded around 220 t/hr and the plant operators were in doubt of reliability of this flow meter since the received quantities are not matching the measured one in control room and it was estimated to be below 200 t/hr. An examination MSTDP Program revealed that the plant capacity was around 182 t/hr. The correction action was taken to fix the malfunctioning of measurement device and the real capacity was matched with the simulation results. On regular basis, the company process engineers carry out check on the plant mass and energy balances.

6- Comments and Recommendations

1. Process modelling and simulation for MSF desalination plants is an important tool in which it can help to identify the main process parameters and variables,
2. Process modelling simulation can be used to check different operational scenarios before to be applied on the real plant operation,
3. Desalination softwares developed by the Kuwait University and MEDRC can be utilised for designing MSF processes; however, they should be evaluated and compared against real plant data,

4. Steady state modelling and Dynamic simulation is recommended to be used as a tool for checking difference operational strategies, and could be used as a training tool for new engineers and technicians,
5. MSTDP Program can be used for assess the design and operation of MSF plant. Further improvements on spreadsheet will be done to include more calculation options, coupling cost data and make spreadsheet user friendly,
6. Attentions should be paid to the fouling factor since this playing a critical rule in the calculation of heat transfer; therefore, there is a need to improve and review old fouling factor values speeding in designing new desalination plant,
7. It is recommended to modify the process configuration through managing the unit seawater temperature for unit by mixing cooling water and seawater intake in order to stabilize operation, water production, and steam consumption

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