

# **Energy and Exergy Analyses of Multigenerational Integrated Systems with Geothermal and Solar Energy Sources**

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## Abstract

The world population growth leads to a large demand of the different forms of energy. The challenges will be focusing on the discovery of new technologies that will satisfy to the demand and the production of energy that will have less impact to the environment. The global warming is now a real issue. The sustainability concept of producing energy has become a priority for many countries. Utilizing advanced technologies to increase the efficiency of producing energy by using renewable sources is now the new direction that many industries are taking to minimize their operating costs and maximize their profits without rapidly arming the environment. Among these technologies, they are multigeneration processes which are considered as a stand-alone system that is capable of producing multiple forms of energy at high efficiencies and low emission of the pollutant in the environment.

In this project, a multigenerational integrated systems is considered and analyzed for both energy and exergy. The geothermal and solar energy sources are used to produce electricity, cooling, heating and fresh distillate water through the desalination of seawater. From the steam rankine power cycle, the system is able to supply 25 MW of power. Through the absorber chiller, the system is able to produce a cooling load of 7329 kW. The cooling area can be calculated from the cooling load, the overall heat transfer coefficient (obtained from the insulation material used on the building) the inlet and outlet temperatures of the cooling space. The system generates a heat load of 3049 kW and 7021 m<sup>3</sup>/day of fresh distillate water. The overall energy and exergy efficiencies of the system is 22.83% and 13.02% respectively.

## **Acknowledgment**

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## Nomenclature

$A_e[j]$	Heat transfer area of $j^{\text{th}}$ effect, $\text{m}^2$
$C_p$	Specific heat of water, $\text{J}/(\text{kg K})$
$D_{1p}$	Absorber pipe interior diameter, m
$D_{2p}$	Absorber pipe exterior diameter, m
$D_{3gls}$	Glass cover interior diameter, m
$D_{4gls}$	Glass cover exterior diameter, m
$e_{gls}$	Glass cover wall thickness, m
$e_p$	Absorber pipe wall thickness, m
$ex$	Specific exergy, $\text{kJ}/\text{kg}$
$\dot{E}X$	Exergy rate, kW
$\dot{E}x_d$	Exergy of destruction, kW
$h$	Specific enthalpy, $\text{kJ}/\text{kg}$
$h_b[j]$	Enthalpy of brine exiting $j^{\text{th}}$ effect, $\text{kJ}/\text{kg}$
$h_{dv\_f}[j]$	Enthalpy of saturated distillate fluid in $j^{\text{th}}$ flash-chamber, $\text{kJ}/\text{kg}$
$h_{dv\_g}[j]$	Enthalpy of saturated distillate vapor in $j^{\text{th}}$ flash-chamber, $\text{kJ}/\text{kg}$
$h_{dv}[j]$	Enthalpy of condensed distillate vapor generated in $j^{\text{th}}$ effect, $\text{kJ}/\text{kg}$
$h_f[j]$	Enthalpy of feed seawater in $j^{\text{th}}$ effect, $\text{kJ}/\text{kg}$
$h_f$	Convection heat transfer coefficient, $\text{W}/\text{m}^2 \text{K}$
$h_{shv}[j]$	Enthalpy of superheated distillate vapor in $j^{\text{th}}$ effect, $\text{kJ}/\text{kg}$
$H_{P\#}$	Total head of the pump, m
$H_{PTC}$	Collector opening width, m
$h_{wind}$	Wind convection heat transfer coefficient, $\text{W}/\text{m}^2 \text{K}$
$I$	Solar available radiation, $\text{W}/\text{m}^2$
$ID_{Br}$	Hydraulic diameter of brine return piping, m
$ID_{sw}$	Seawater piping internal diameter, m
$k_{gls}$	Thermal conductivity of the glass, $\text{W}/\text{m K}$
$K_\theta$	Incidence angle modified
$k_p$	Thermal conductivity of the pipe, $\text{W}/\text{m K}$
$K_{PTC}$	Area factor
$L_{PTC}$	Collector length, m
$L_{sw}$	Total length of seawater piping, m
$\dot{m}$	Mass flow rate, $\text{kg}/\text{s}$
$\dot{m}_a$	Mass flow rate dry air, $\text{kg}/\text{s}$
$\dot{m}_b[j]$	Mass flow rate of brine exiting $j^{\text{th}}$ effect, $\text{kg}/\text{s}$
$\dot{m}_{b\_sec}[j]$	Mass flow rate of brine formed after flashing, $\text{kg}/\text{s}$
$\dot{m}_{dv\_gc}[j]$	Distillate vapor formed distillate formed via condensation in $j^{\text{th}}$ flash-chamber of the $\dot{m}_{dv}[j - 1]$ stream, $\text{kg}/\text{s}$
$\dot{m}_{dv\_gf}[j]$	Distillate vapor formed via flashing of the $\dot{m}_{dv}[j - 1]$ stream in $j^{\text{th}}$ flash-chamber, $\text{kg}/\text{s}$
$\dot{m}_{gb}[j]$	Distillate produce via boiling in the $j^{\text{th}}$ effect, $\text{kg}/\text{s}$
$\dot{m}_{gf}[j]$	Distillate vapor formed in $j^{\text{th}}$ effect via flashing of brine, $\text{kg}/\text{s}$
$\dot{m}_{d\_gc}[j]$	Distillate formed via condensation in $j^{\text{th}}$ flash-chamber of the $\dot{m}_d[j - 1]$ stream, $\text{kg}/\text{s}$

$\dot{m}_{d-gf}[j]$	Distillate vapor formed via flashing of the $\dot{m}_d[j - 1]$ stream in $j^{\text{th}}$ flash-chamber, kg/s
$\dot{m}_{av}[j]$	Mass flow rate of distillate vapor generate in $j^{\text{th}}$ effect, kg/s
$s$	Specific entropy, kJ/kg.K
$S$	Salinity, g/kg
$s[j]$	Specific entropy for $j^{\text{th}}$ effect, kJ/kg.K
$\dot{S}_{gen}$	Entropy generation, kJ/s.K
$t$	Wind, m/s
$T$	Temperature, °C
$T_a$	Atmospheric temperature, °C
$T_{dv}[j]$	Effect vapor temperature, °C
$T_f$	Arithmetic mean temperature, °C
$T_{f}[j]$	Effect feed seawater temperature, °C
$T_{gls,e}$	Exterior wall glass envelope temperature, °C
$T_{gls,i}$	Inside wall glass envelope temperature, °C
$T_0$	Reference temperature, °C
$T_{sky}$	Sky temperature, °C
$T_s$	Heating Source temperature, °C
$T_{sw}$	Temperature seawater, °C
$T_{p,e}$	Exterior wall absorber pipe temperature, °C
$T_{p,i}$	Inside wall absorber pipe temperature, °C
$\dot{Q}_{abs,p}$	Absorbed heat rate transmitted through the absorber pipe by conduction, kW
$\dot{Q}_{in,R}$	Heat partially transmitted through the glass, absorbed by the pipe and used to heat the seawater inside the receiver, kW
$\dot{Q}_{cd,p}$	Conduction heat rate through the tubular pipe, kW
$\dot{Q}_{loss,p-gls}$	Radiation heat loss between pipe and glass cover, kW
$\dot{Q}_{cd,gls}$	Heat rate passing through the glass cover by conduction, kW
$\dot{Q}_{loss,gls-a}$	Heat lost rate transmitted from the outer glass surface to ambient though wind convection and radiation, kW
$U_{eff}[j]$	Overall heat transfer coefficient of $j^{\text{th}}$ effect, kW/m <sup>2</sup> -K
$v_f$	Assumed design velocity for economical pumping, m/s
$\dot{W}$	Rate of work, kW
$X$	Steam quality, %
$X_f$	Seawater salinity, g/kg

### Subscripts

1, 2, ...i	State points
gls	Glass cover
Cond	Condenser
cw	Cooling water
sw	seawater
E	Evaporator
FV	Expansion valve
G	Generator
HE	Heat exchanger

HPT	High pressure turbine
Loss,p-gls	Losses from the piping absorber to the glass envelope
LPT	Low pressure turbine
MC	Mixing chamber
P	Pump
p	Absorber pipe
SF	Solar field
ST	Separator tank

### ***Acronyms***

COP	Coefficient of performance
CR	Concentration ratio
IW	Injection well
MED	Multi effect desalination
NCG	Non condensable gases
PW	Production well

### ***Greek Letters***

$\alpha_{\text{gls}}$	Absorptance of the glass cover
$\alpha_{\text{p}}$	Absorptance of the absorber pipe
$\delta$	Temperature increase in the last condenser, °C
$\Delta$	Difference
$\varepsilon$	Equivalent surface roughness, m
$\varepsilon_{\text{gls}}$	Emissivity of outer surface of the glass cover
$\varepsilon_{\text{p}}$	Emissivity of the absorber pipe
$\xi$	Concentration
$\eta_{\text{opt}}$	Optical losses efficiency of normal solar incident irradiation
$\sigma$	Stefan-Boltzmann constant, $\text{W/m}^2\text{-K}^4$
$\tau_{\text{gls}}$	Transmissivity of the glass cover

# **Chapter 1: Introduction**

## **1.1 Energy Perspectives**

The world population is continually growing in such way that it will reach 9 billions people in 2050 [1]. This growth will become a challenge for the earth on how land, food, water and energy can be redistributed among the population [2]. Under these circumstances, energy and water have direct influence in the well-being of the population across the globe. Large scale of the population requires an increase of the quantity of food, which is directly linked to the quality of water and energy. An insufficient of these two elements (water and energy) will have disastrous consequences on the population. The increase in energy demand is function of the available energy sources and they required processes technologies (e.g., generation of electricity, cooling, heating and fresh water) [4]. The conventional source of energy is usually extracted from the fossil fuel based on substances containing hydrocarbon material such as coal, crude & extra-heavy oil, natural bitumen and natural gas. Certain metallic elements such as uranium and thorium have the potential of providing energy [3]. The sources of hydrocarbon material are very limited, they are not renewable and the production of energy based on them generates pollutants material that negatively impact the environment. Renewable energy sources (e.g., Solar, wind, biomass, geothermal, tidal, wave and ocean thermal energy conversion) have become the domain of multiple studies that lead to a smart way of producing energy. These perpetual sources of energy lead to the sustainable development of multiples countries.

## **1.2 Sectorial Energy Usage**

Sectorial energy usage can be divided in four majors sectors of economy: commercial-residential, industrial, electrical power and transportation [46].

- **Residential and commercial sectors**

This sector involves the buildings where people can access. These buildings could be restaurants, private houses, offices, public building (such as hospitals, large shopping centers, schools etc.). These buildings utilize energy for lighting, heating, cooling, water heating and operating appliances. Nowadays in USA, residential and commercial building consume about 12% of the energy.

- **Industrial sector**

This sector is related to industrial process that utilized a large quantity of energy. This may involve steel manufacturing, petroleum manufacturing, cement manufacturing, paper manufacturing, chemical manufacturing; aluminum manufacturing and foods industry. In the USA, this sector consumes about 22% of energy

- **Transportation sector**

This sector can be divided in ground, air and water transportations. Ground transportation involves passengers' car, light trucks, commercial heavy duty truck, and rail road cars. However the air transportation includes passengers and cargo airliners. Water transportation is more reserve for large cargo containers. Generally, this section performs the transportation of the people and merchandises. It consumes a large quantity of energy and has a large carbon footprint. Fossil fuel is the main source of the energy that is used in the transpiration section. However, the improvement in the technology area has increased the efficiency of fuel consumption. The transportation is now being modernized by the implication of fuel cell and electrical cars. In the United State of the American, The transportation sector used more than 27 % of the energy.

### **1.3 Motivation and objectives**

The increase of greenhouse gases in the atmosphere is the primary cause of global warming. Thus that, the scientists have demonstrated that the rise of global temperature is related to the cumulative emissions of carbon dioxide over time [11]. Conventional fuel (great amount of carbon material in it) can be considered as the accelerator agent that led to the degradation of the environment. The improvement of the technologies in the energy system has driven me to find new solutions that will produce clean energy at low cost, protect our environment and prevent a global warming. The renewable energy sources have become the most viable production of energy without emitting molecules of carbon in the atmosphere.

The specific objectives of this project are listed as follows:

- To develop an integrated system that will produce the electricity, cooling, heating and fresh water by using different sources of renewable energy such as Geothermal, solar and seawater.
- To perform energy and exergy analyses for the proposed systems.
- To determine the exergy destruction for each component of the sub-systems.
- To conduct a parametric study for the proposed systems by varying the important parameters in the systems.

## Chapter 2: Background

### 2.1 Geothermal energy

Ever since the birth of geothermal power generator by an Italian scientist Piero Ginori Conti ( in 19<sup>th</sup> century) who discovered that natural steam can produce electrical energy [9] , the geothermal has become a domain of interest. The thermodynamic state of the geothermal reservoir is the most important aspect that provides the performance of geothermal plants [12]. The geothermal plant uses steam (from underground reservoir) as a working fluid. Most of geothermal working fluid contains non-condensable gases (NCGs). To prevent the rising of pressure in the condenser and decrease in power generation, the NCGs shall be removed from the system just before the inlet to the turbine [15]. To produce electricity from the plant, the steam under a certain temperature and pressure rotates the assembly made of the turbine and generator. They exist three categories of geothermal power plants [13].

- **Dry steam power plant**

This Plant operates with the steam extracted from the underground and directly supplied to the turbine-generator assembly

- **Binary cycle power plant**

This plant uses reservoir with hot water at low temperature between 107°C to 182°C. The heat from hot water boils a working fluid that has a low boiling point [14]. The working fluid is then vaporizer through a heat exchanger and used to drive the turbine –generator assembly. After vaporizing the working fluid, hot water is re-injected back into the reservoir. The heat exchanger is used to prevent hot water and the working fluid from mixing [14]. This is to prevent air from entering the working fluid.

- **Flash steam power plant**

DiPippo [17] presented the functionality of flash steam power plants. These plants use a working fluid from the geothermal reservoir totally dominated of nature pressurized hot water at the temperature greater than 180°C. This hot water flows from the reservoir to the upward piping under its own pressure. As it flows, its pressure decreases and a part of it boils into steam. The steam formed is then separated from and used to drive the turbine-generator assembly. After expanding through the turbine, the condensate steam is mixed with the leftover of the hot water and then re-injected into the geothermal reservoir. Thus that, the sustainability of the resource is maintained. The flash steam power plant is commonly used [14] in today power generation. However, there are two types of flash steam power plants. These are single flash and double flash. Single flash geothermal plant is the one where the geothermal energy is directly converted into electrical energy. The geothermal working fluid is considered to contain enough energy that can be separated into steam and liquid phases without presenting a major pressure drop [16]. Ozcan and Gokcen [15] have studied a single flash power plant and analyzed the effect of non-condensable gases on plant performance. They found that non-condensable gases have a direct impact on the plant by decreasing its net power, due to the increase of the pressure in the condenser. That why, the mechanism of removing non-condensable gases is usually integrated in the majority of the plants. However, Swandaru [16] stated that for the same geothermal fluid conditions, double flash steam power plant was able to generate 15 to 25 percentages more output power than the single flash plant. This means that double flash plants operate as the single flash plants, but they contain more improvement process stages that are related to the separated fluid leaving the primary separator and is used to generate additional steam at a lower pressure [17]. This low pressure steam is then used to spin the turbine-generator assembly and produced

more power. The down effects of the double flash power plants are the complexity of the system and the cost related to the type of the installation [18].

## **2.2 Solar energy**

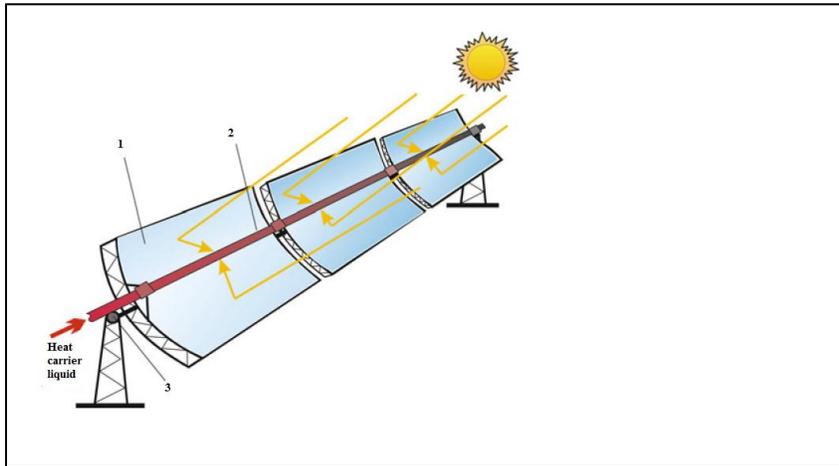
Every since in the 18th century when the first solar collector was discovered by the Swiss scientist Horace Benedict De Saussure [19]; many progresses were made in the design of the collectors. Nowadays, solar collectors are designed for a maximum efficiency. The materials used have the properties of absorbing, transmitting or reflecting the radiation from the sun. Solar energy can be extracted by using efficient thermal fluid with an elevated fusion temperature. However, even though the solar energy presents a greatest potential of renewable energy, it is very important to estimate the availability of solar radiation before installing the collectors which will be facilitate the conversion of solar energy to electricity. The evaluation of solar radiation depends on the direction of the sun and the layers of the atmosphere. The involving parameters are the latitude and altitude of the place, the date and the time [20]. Generally, solar energy concentrators contain three main components. The reflector which is in charge of receiving solar lights and directing them into the focus point; the receiver which located in the focus point and that turns the solar lights into heat; and the solar positioner which tracks the position of sun all days. Typically they are threes type of solar concentrators:

- **Cylindrical parabolic concentrator**

In this application, the receiver temperature can reach the range from 400°C to 500°C. This concentrator tracks only one coordinate from the sun elevation angle. In Figure 1 , the tracking is performed by rotating mirror (1) around the axis (3). The element (2) is the receiver representing a line crossing the optical focus point [6]

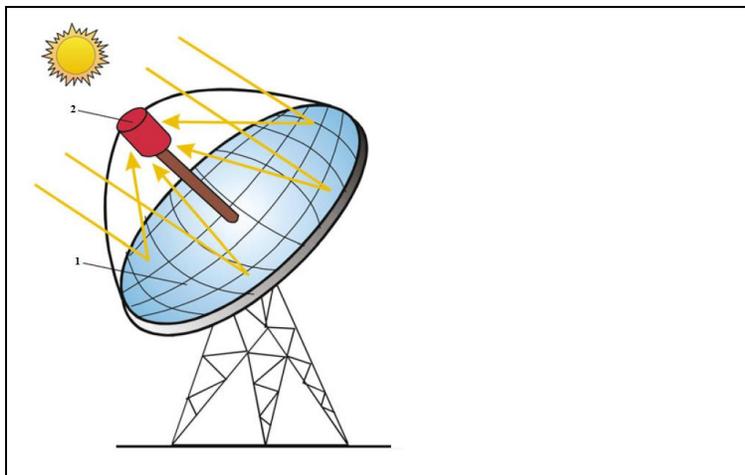
- **Paraboloidal concentrator**

In this application the receiver temperature can reach more than 1000°C. This concentrator tracks parameters such as the elevation angle and the azimuth angle.



**Figure 1:** Cylindrical parabolic reflective mirror [6]

In Figure 2, the element (1) represents the paraboloidal mirror that serves as a reflector and the element (2) is the receiver. It is installed in the focus point of the paraboloidal [6].

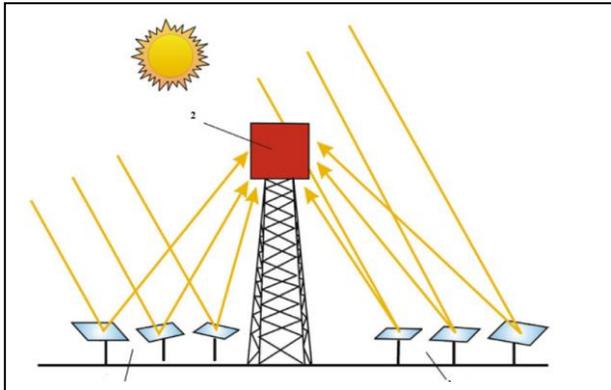


**Figure 2:** Solar concentrator with paraboloidal mirror [6]

- **Heliostat concentrator**

In this application, the receiver temperature can reach the range from 3000°C to 4000°C. Each heliostat is controlled such that it follows two coordinates of the sun position. In Figure 3, the elements (1) are flat reflected surface called heliostats. They are usually installed around the

circumference of the central tower. The element (2) is the reflector installed on the tower in the focus point [6].



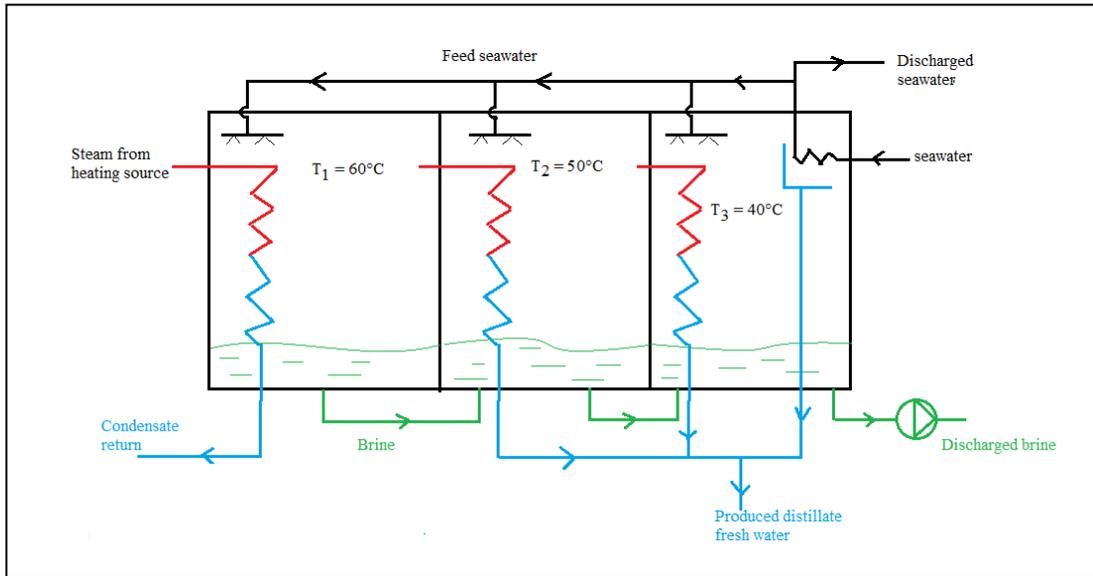
**Figure 3:** Solar concentrator with heliostat [6]

The main goal of solar concentrators is to increase temperature of the thermal fluid. Solar and geothermal sources are often used to power organic ranking cycle (ORC) and for the production of the electricity [21]. Hassoun and Dincer [22] performed the analysis of an ORC system powered by solar source. The study has showed that the energy efficiency at net power output of the ORC system are directly related to the temperature of the working fluid that is entering the ORC system. Cheng [23] demonstrated that under steady-state conditions, the ambient temperature, the geographic location, the solar irradiance and the geothermal fluid quality have an influence on the performance of an integrated system powered by solar and geothermal sources. His analysis has shown the power output of the ORC increases as both the geothermal reservoir temperature and the solar aperture area increase .

### **2.3 Multi effect desalination**

Multi effect desalination (MED) evaporator is the system that is formed of several consecutive single effect evaporators in which the pressure and temperature gradually decrease from the first effect to the last effect; and where the vapor formed in one effect is used in the next effect as a heating source. The basic principle of MED is that the energy is supplied from an external source

to the first effect only [34]. The main working fluid is the mixture of water and salt. The main goal of MED process is to produce fresh water from seawater. As showed in Figure 4 here below, cold seawater is vaporized at the first effect by the steam supplied by the boiler.

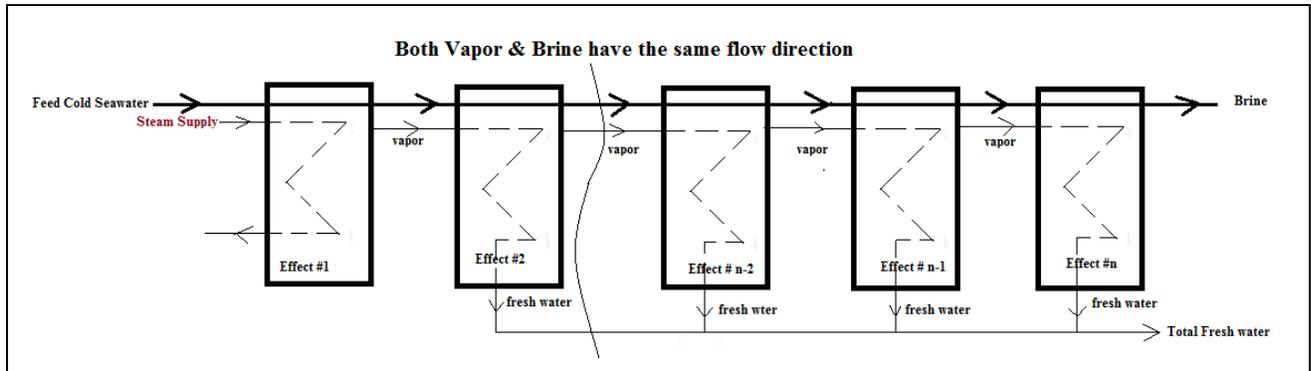


**Figure 4:** Multi effect desalination process [33]

The vapor (in the form of steam) formed in the first effect is then utilized as the heat source to vaporize the cold seawater at the following effect. Each effect is the combination of an evaporator and a condenser. The cold seawater plays also the role of the condensing fluid that transforms the state of the steam to fresh water. Each effect produces fresh water and the brine that is re-injected into seawater. MED process has the advantage of producing a very large volume of fresh water. However, this system required a large investment related to the cost associated to it. MED process can be represented in three different configurations: forward, backward and parallel cross feed. El-Dessouky et al. [35] stated that the main difference between the three configurations of the MED is the direction of the supply steam (heating source) and the evaporating brine.

- **Forward feed MED**

In forward feed MED configuration (Figure 5), both heating source vapor and feeding brine (feed seawater) have the same directions. The brine leaving the previous effect is successively introduced into the next effects as the feed brine.

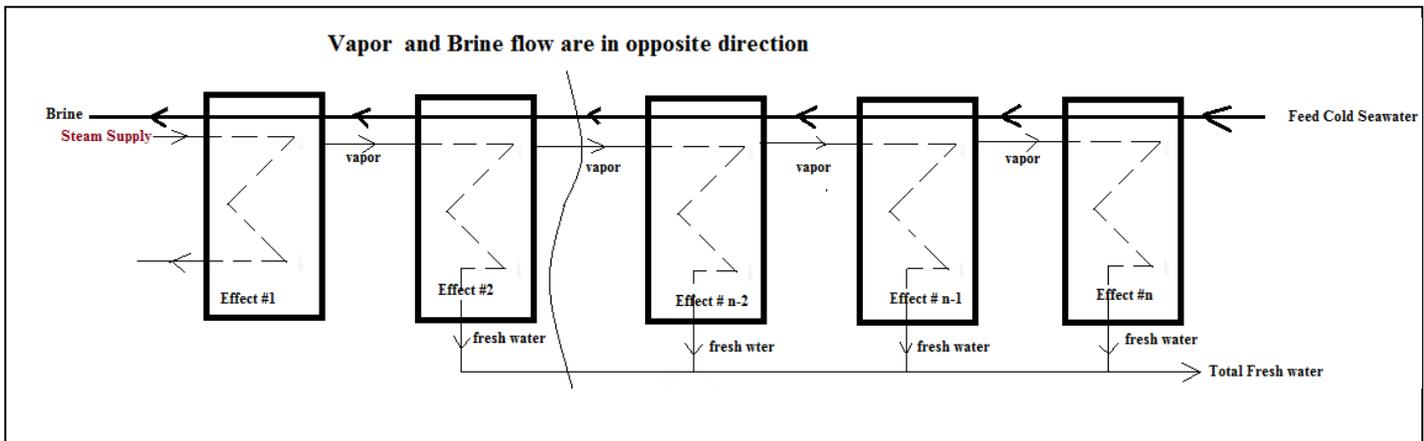


**Figure 5:** Forward feed MED configuration

Forward feed MED has the ability to operate at high brine temperature [33]. However, the last effects will receive brine containing high concentration of salt that will cause the formation of the scale inside and outside of the tubes (bundle) surface.

- **Backward feed MED**

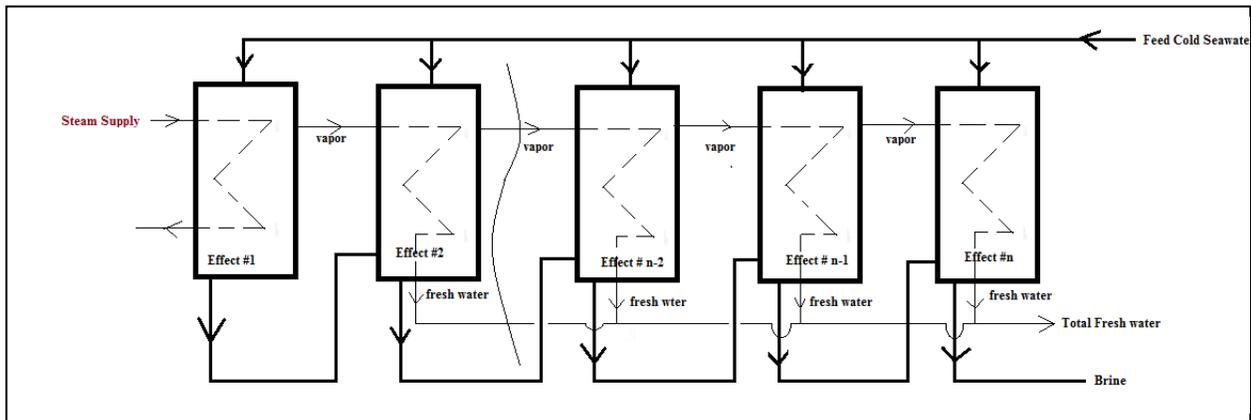
In backward feed MED, the vapor (steam) is in opposite direction with the feed brine (feed seawater). As shown in Figure 6, the particularity of this configuration is that the feed cold seawater is supplied from the last effect, which usually contains a low temperature and pressure. The brine leaving the effect is successively introduced into the next effects. This will allow the increase of temperature and pressure into the system, responsible of generate the scale of the tubes and the pressure drop. The moving of the brine from the last effect to effect the first effect will require a pumping system between the effects [35]. This will have an impact on the cost related to the operation of the system.



**Figure 6:** Backward feed MED configuration

- **Parallel cross feed MED**

In parallel cross feed MED, cold seawater is introduced from the top of each effect and the brine collecting at the bottom of the previous effect is introduced into the next effect, where it will combine with the feed seawater. El-Dessouky et al. [35] stated that this will allow the presence



**Figure 7:** Parallel cross feed MED configuration

of positive temperature difference at the effect between the income brine from the cold seawater and the brine coming from the previous effect. The positive temperature is also responsible of creating a flash of small portion of the brine at effect, improving the productivity and the thermal efficiency of the system [35]. However, the supply heat (vapor or steam) entering each effect is perpendicular to the feed cold seawater.

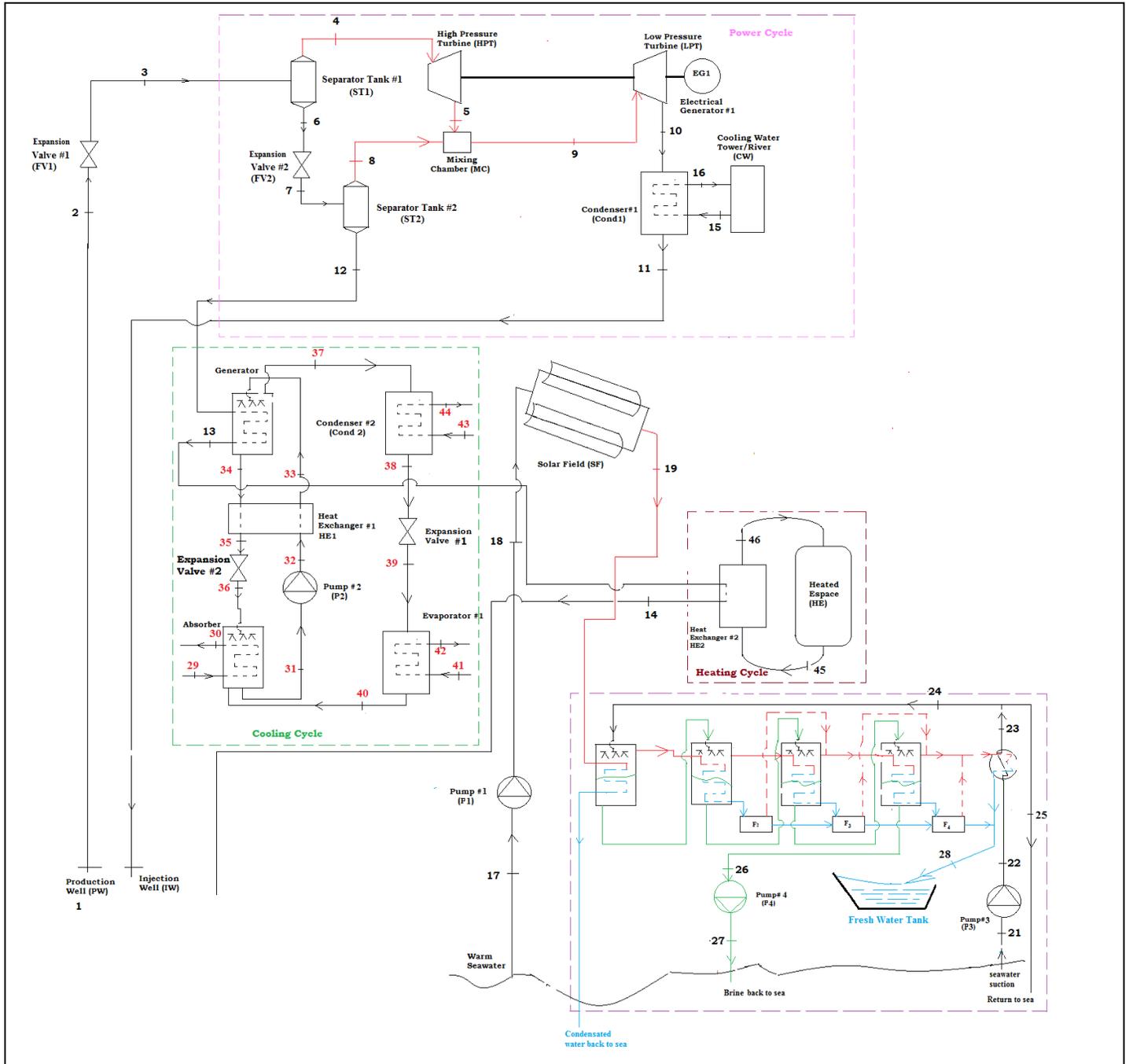
## Chapter 3: System Description

This multigeneration systems will produce electricity, cooling, heating and fresh water from the renewable energy sources such as geothermal, solar and seawater. The proposed system is represented in Figure 8 and can be described as the following:

### 3.1 Geothermal steam rankine power subsystem

A working fluid from the geothermal source will flow under the production well (PW) pressure to the surface. The fluid undergoes an evaporation process due to the decrease in pressure. The vapor obtained does not have enough energy to drive the assembly of the turbine and generator. A flashing process is performed to decrease the pressure of the working fluid at constant enthalpy. The meaning of the flashing is to find of an optimum value of pressure that would generate a maximum power of the turbine. For this sub-system, saturated pressurized liquid water flows from state (1) to state (2). The flashing of the fluid is done through the expansion valve (FV1) between the states (2) and (3). FV1 will generate a saturated mixture of water and vapor that will enter into the separator Tank (ST1) from state (3). The role of ST1 is to separate the superheated steam from the saturated hot water. The superheated steam will enter the high pressure turbine (HPT) at state (4) and saturated hot water will flow to the second expansion valve (FV2) at state (6). The superheated steam will expand through the HPT, drive the first generator which produces electricity, and enters the mixing chamber (MC) at state (5). The FV2 will create a saturated mixture of vapor and hot water at state (7) and the mixture will enter into the second separator tank (ST2) which will separate the surperheated steam from the saturated hot water. The superheated steam formed in ST2 enters MC at state (8). The low pressure turbine (LPT) is supplied by the steam exiting the MC at state (9). After expanding through LPT, driving the second generator which produces electricity, the saturated steam exiting the LPT at state

(10) is cooled through the condenser (Cond1) by water from the river or cooling tower (entering at state 15 and exiting at stage 16). The condense vapor will then exit the Cond1 at state (11), and flows back to the source through the injection well (IW).



**Figure 8:** Multigenerational integrated systems with geothermal and solar energy sources

However, the saturated hot water exiting ST2 at state (12) will flow first through the generator (state 13) for the coiling system and then through heat exchanger (HE2) between the states (13) and (14) for the heating space system. After exiting HE2, the flowing fluid is then re-injected back into the well (IW). This system will produce power at both the HPT and LPT. The composition of the thermal fluid the power cycle is described in Table-1

Table 1: State point and thermal fluid composition power cycle

State point	Thermal fluid composition
1	Water
2	Water
3	Mixture (vapor and water)
4	Superheated steam
5	Steam
6	Saturated hot water
7	Mixture (vapor and water)
8	Superheated steam
9	Superheated steam
10	Steam
11	Water
12	Saturated hot water
13	Saturated hot water
14	Saturated warm water
15	Saturated water
16	Saturated water

### 3.2 Cooling subsystem

An absorption chiller is usually used for cooling purposes. This system consumes less energy when compare to the conventional vapor -compression refrigeration systems. The absorption chiller uses two essential components: the absorber and the refrigerant. In this application, the refrigerant is usually water and the absorber is the mixture solution of LiBr-Water. This solution enters the generator at state (33), where it is heat up by the saturated hot water that is coming from the separator tank (ST2) at state (12). As the mixture of LiBr-Water is warmed up, it starts to vaporize at a high temperature by separating the Water (refrigerant) from the LiBr (absorber).

The weak brine solution of LiBr exits the generator at state (34), flows through a heat exchanger (HE1), where it releases heat (gained at the generator) to the incoming strong concentrated mixture of LiBr-Water at state (32). The weak mixture leaves HE1 at state (35) and enters the expansion valve#2 where its pressure decreases (state 36) before it starts flowing through the absorber unit. The vapor produced at the generator enters the condenser (cond 2) at state (37), where it is condensed by the flow of air (states 43 and 44). This vapor will become saturated water before entering the expansion valve#1 at state (38). Through the expansion valve #1, the saturated water is flashed at low pressure and low temperature. It will exit the expansion valve #1 at state (39) as a saturated vapor such that it can contain some energy allowing it to extract heat at the evaporator. This heat comes from the air-conditioned space (the air entering at state 41 and leaving at state 42). This saturated vapor will continue to flow to the absorber where it will be re-mixed with the solution of LiBr. Then, a new cycle will start at the suction of pump #2 (P2). This cycle can repeat itself over and over again. This system will provide the cooling at the evaporator unit. The composition of the thermal fluid at each state is represented in Table-2.

### **3.3 Multi effect distillation subsystem**

The multiple distillation effect is made of horizontal heat exchanger tubes. Seawater is pumped from state (17) to the inlet of the cylindrical parabolic concentrator (SF) at state (18). Seawater will be heated through the SF and exits at state (19) as hot seawater, which will be used as a heat source at the first effect of the desalination subsystem. However, the cold seawater pumped from states (21) to (22) will flow through the last condenser and exit at state (23). After condensing the vapor released at the last effect, cold seawater at state (23) will be separated between the states (24) and (25). At state (25), seawater will return back to the sea. However, the flow from state (24) is used as feed seawater for the first effect. This flow is sprayed on the top of the tube

bundles, where hot seawater from SF is flowing. Then, the feed seawater runs down the outside of the tube bundles at the first effect.

Table 2: State point and chemical composition at the cooling cycle

State Point	Thermal Fluid Composition
29	Saturated water
30	Saturated water
31	LiBr/Water
32	LiBr/Water
33	LiBr/Water
34	LiBr/Water
35	LiBr/Water
36	LiBr/Water
37	Saturated vapor
38	Saturated water
39	Saturated vapor
40	Saturated vapor
41	Air
42	Air
43	Saturated water
44	Saturated water

Feed seawater with the mass flow rate ( $\dot{m}_f[1]$ ) and the salinity ( $S_f$ ) entering the first effect is boiled by the latent heat of the hot seawater coming from the SF at state (19) and flowing inside the tube bundles . This boiling process will condense the hot seawater, which will exit the first effect at state (119) and generate the only distillate vapor that will be used as the source of heat for the second effect. After the boiling process, the remaining feed seawater called brine will exit the first effect (with an increase of its salinity) and supply as the feed seawater or brine for the second effect. For the effects 2 to N, the brine exiting the effect will be used as a feed seawater or brine for the following effect. This brine will be affected by two different processes:

- Flashing: This process will generate a certain quantity of distillate vapor. This process will only occur in the effect 2 and N, but not in the first effect because of the uniformity of the latent heat in the first effect.

- Boiling: After flashing process the feeding brine will be boiled by the latent heat of the distillate vapor formed in the previous effect. The boiling process will generate another quantity of the distillate vapor. The boiling process happens in all the effects.

After the boiling process, the remaining feeding brine will exit the effect with an increase of its salinity. The particularly of the effects 2 to N is that they contained flash chambers. The role of flash chambers is to receive the condensate distillate water coming from the slightly superheated distillate vapor. Flash chambers will receive both the condensate distillate vapor formed in the effect and condensate distillate water formed in the previous flash chamber. The mixture of these flow rates will allow the flash chambers to generate two processes:

- Flashing: This will generate the distillate vapor of the flashing chamber
- Boiling: This will generate the distillate fresh water of the flashing chamber.

Also, for the effects 2 to N the vapor formed in the previous effect will be used as a heat source for the next effect. The total distillate vapor of the effects 2 to N comes from the flashing of the feeding brine, the boiling of the remaining feeding brine and the flashing of the condensate distillate in the flashing chamber. The final remaining brine with a very high salinity is collected at state (26), and then pumped back into the sea at state (27). This system will produce the distillate fresh water. The total of water produce will be collected from the last flash chambers and the last condenser at state (28). The composition of the thermal fluid at each state of this subsystem is described in Table-3

### **3.4 Heating subsystem**

This sub-system receives heat from the geothermal at state (13). This heat source is introduced to the heat exchanger (HE2) and exit at state (14). After releasing hest through the HE2, the saturated warm water will be re-injected to the geothermal reservoir through the IW.

Table 3: State condition of seawater

State Point	Thermal fluid condition
21	Cold seawater
22	Cold seawater
23	Cold Feed seawater
24	Cold Feed seawater
25	Cold Feed seawater return
26	Total Brine return
27	Total Brine return
28	Total fresh water

Heat releases at HE2 is gained by the cold air that enters the exchanger at state (45) and exits at state (46). The system will produce the require heat to warm up the living space HE. The condition of the thermal fluid is described in Table-4.

Table 4: Conditions of air at the different state points

State Point	Thermal fluid condition
45	Cold air
46	Warm air

## Chapter 4: Energy and Exergy Analyses

This chapter describes the developed subsystems and provides their thermodynamics analysis.

They will include the mass, energy, entropy and exergy balance equations.

### ▪ Mass Balance Equation

Under steady state condition , the mass balance equation is defined as the sum of the mass flow rate that enter the control volume equal to the sum of the mass flow rate that exit the same control volume. The mass balance equation can be represented as per the following relation:

$$\sum_{int=1}^n \dot{m}_{int} = \sum_{out=1}^m \dot{m}_{out}$$

where  $\sum_{int=1}^n \dot{m}_{int}$  is the sum of mass flow rates entering the control volume and  $\sum_{out=1}^m \dot{m}_{out}$  is the sum of the mass flow rates exiting the control volume for each component.

### ▪ Energy Balance Equation

The equation is the balance of the energy that enters and exit the control volume. It can be expressed by the following equation:

$$\dot{Q}_{int} + \dot{W}_{int} + \sum_{int=1}^n \dot{m} \left( h + \frac{v^2}{2} + gz \right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out=1}^n \dot{m} \left( h + \frac{v^2}{2} + gz \right) \quad (4.1)$$

where  $\dot{Q}$  is heat transfer rate,  $\dot{W}$  is work rate,  $v$  is the velocity,  $g$  is the gravitational acceleration,  $h$  is the specific enthalpy and  $z$  is the elevation

### ▪ Entropy Balance Equation

This is the entropy balance of the control volume. It will include the entropy generated by the subsystem. The balance equation will be written as following:

$$\sum_{int=1}^n \dot{m}s + \dot{S}_{gen} + \sum \left( \frac{\dot{Q}_k}{T_k} \right) = \sum_{out=1}^m \dot{m}s \quad (4.2)$$

where  $s$  is the specific entropy,  $\dot{Q}_k$  is heat transfer from the system boundary and  $T_k$  is the temperature of the boundary

- **Exergy Balance Equation**

This will include the amount of the exergy destroyed by the control volume during its operation process. By assuming that the kinetic and potential exergies are negligible, the exergy balance equation can be written as follows:

$$\sum_{\text{int}=1}^n \dot{m} \text{ex} + \sum \left(1 - \frac{T_0}{T_s}\right) \dot{Q} = \sum_{\text{out}=1}^m \dot{m} \text{ex} + \dot{W} + \dot{E}X_{\text{dest}} \quad (4.3)$$

where  $T_0$  is the reference temperature,  $T_s$  is the source temperature,  $\text{ex}$  is the specific exergy. It may contain the physical exergy ( $\text{ex}_{ph}$ ), the chemical exergy ( $\text{ex}_{ch}$ ), the potential exergy ( $\text{ex}_{pt}$ ) and kinetic exergy ( $\text{ex}_{kn}$ ). The specific exergy can be expressed as follows:

$$\text{ex} = \text{ex}_{ph} + \text{ex}_{ch} + \text{ex}_{pt} + \text{ex}_{kn} \quad (4.4)$$

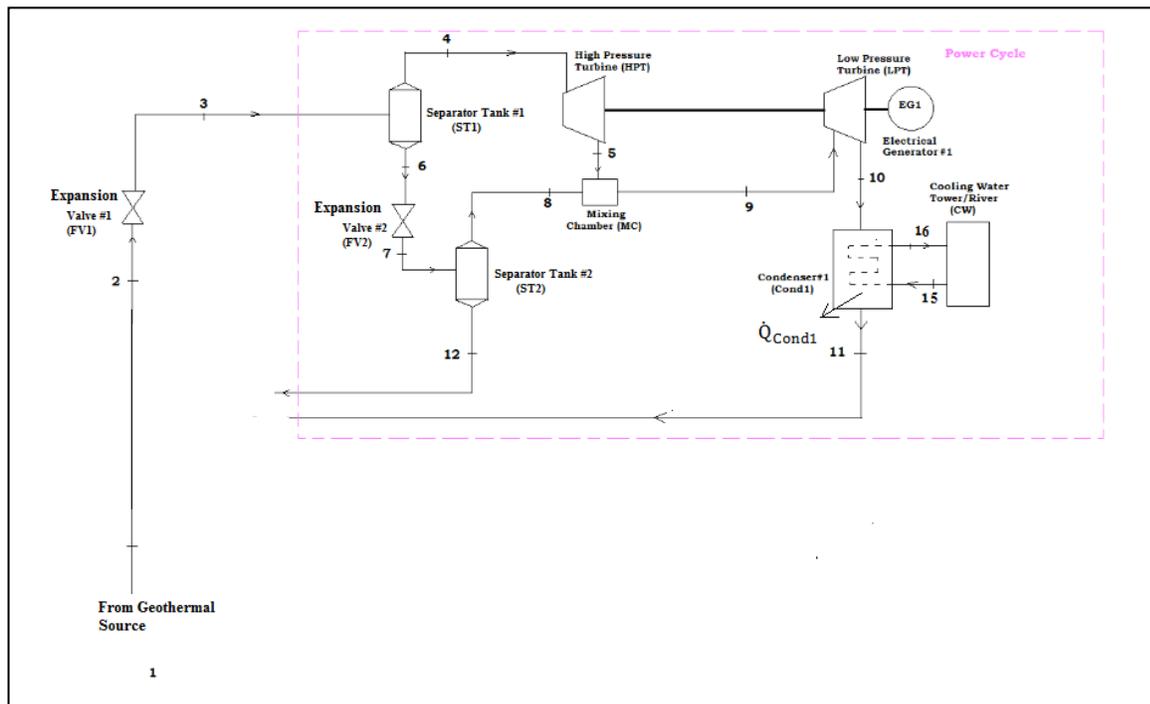
For this project the chemical exergy ( $\text{ex}_{ch}$ ), the potential exergy ( $\text{ex}_{pt}$ ) and kinetic exergy ( $\text{ex}_{kn}$ ) will be neglected. Only the physical exergy ( $\text{ex}_{ph}$ ) will be considered. The physical exergy is defined by the following relation:

$$\text{ex}_{ph} = (h - h_0) - T_0(s - s_0) \quad (4.5)$$

#### **4.1 Steam Rankine Power Cycle**

A working fluid from the geothermal source will flow under the production well (PW) pressure to the surface. The fluid undergoes an evaporation process due to the decrease in pressure. The vapor obtained does not have enough energy to drive the assembly of the turbine and generator. A flashing process is performed to decrease the pressure of the working fluid at constant enthalpy. The meaning of the flashing is to find an optimum value of pressure that would generate a maximum power of the turbine. For this sub-system, saturated pressurized liquid water flows from state (1) to state (2). The flashing of the fluid is done through the expansion valve (FV1) between the states (2) and (3). FV1 will generate a saturated mixture of water and vapor that will enter into the separator Tank (ST1) from state (3). The role of ST1 is to separate

the superheated steam from the saturated hot water. The superheated steam will enter the high pressure turbine (HPT) at state (4) and saturated hot water will flow to the second expansion valve (FV2) at state (6). The superheated steam will expand through the HPT, drive the first generator which produces electricity, and enters the mixing chamber (MC) at state (5). The FV2 will create a saturated mixture of vapor and hot water at state (7) and the mixture will enter into the second separator tank (ST2) which will separate the superheated steam from the saturated hot water. The superheated steam formed in ST2 enters MC at state (8). The low pressure turbine (LPT) is supplied by the steam exiting the MC at state (9). After expanding through LPT, driving the second generator which produces electricity, the saturated steam exiting the LPT at state (10) is cooled through the condenser (Cond1) by water from the river or cooling tower (entering at state 15 and exiting at stage 16). The condense vapor will then exit the Cond1 at state (11), and flows back to the source through the injection well (IW). The steam rankine power cycle subsystem is represented in Figure-9.



**Figure 9:** Steam rankine power cycle

Each component of geothermal steam rankine power cycle was analyzed separately. Four balance equations were written for each component, including mass, energy, entropy and exergy as the following:

- **Expansion valve #1 (FV1)**

Assuming that the first flash happen at state (3)

*Mass balance equation*

$$\dot{m}_2 = \dot{m}_3 \quad (4.6)$$

*Energy balance equation*

$$\dot{m}_2 h_2 = \dot{m}_3 h_3 \quad (4.7)$$

*Entropy balance equation*

$$\dot{m}_2 s_2 + \dot{S}_{\text{gen\_FV1}} = \dot{m}_3 s_3 \quad (4.8)$$

*Exergy balance equation*

$$\dot{m}_2 ex_2 = \dot{m}_3 ex_3 + \dot{E}_{\text{XdFV1}} \quad (4.9)$$

The specific exergies at state (3) can be expressed as the following:

$$ex_3 = (h_3 - h_o) - T_o (s_3 - s_o) \quad (4.10)$$

- **Separator tank #1 (ST1)**

*Mass balance equation*

$$\dot{m}_3 = \dot{m}_4 + \dot{m}_6 \quad (4.11)$$

$$\dot{m}_4 = x_3 \dot{m}_3 \quad (4.12)$$

$$\dot{m}_6 = (1 - x_3) \dot{m}_3 \quad (4.13)$$

where  $x_3$  is the quality of the steam entering ST1 and it is defined as the following:

$$x_3 = \frac{h_3 - h_6}{h_4 - h_6} \quad (4.14)$$

*Energy balance equation*

$$\dot{m}_3 h_3 = \dot{m}_4 h_4 + \dot{m}_6 h_6 \quad (4.15)$$

*Entropy balance equation*

$$\dot{m}_3 s_3 + \dot{S}_{\text{gen\_ST1}} = \dot{m}_4 s_4 + \dot{m}_6 s_6 \quad (4.16)$$

*Exergy balance equation*

$$\dot{m}_3 ex_3 = \dot{m}_4 ex_4 + \dot{m}_6 ex_6 + \dot{E}_{\text{xdST1}} \quad (4.17)$$

The specific exergies at states (4) and (6) can be expressed as the following:

$$ex_4 = (h_4 - h_o) - T_o (s_4 - s_o) \quad (4.18)$$

$$ex_6 = (h_6 - h_o) - T_o (s_6 - s_o) \quad (4.19)$$

- **High pressure turbine (HPT)**

*Mass balance equation*

$$\dot{m}_4 = \dot{m}_5 \quad (4.20)$$

*Energy balance equation*

$$\dot{m}_4 h_4 = \dot{m}_5 h_5 + \dot{W}_{\text{HPT}} \quad (4.21)$$

where,  $\dot{W}_{\text{HPT}}$  is the HPT power

$$\dot{W}_{\text{HPT}} = x_3 \dot{m}_3 (h_4 - h_5) \quad (4.22)$$

*Entropy balance equation*

$$\dot{m}_4 s_4 + \dot{S}_{\text{gen\_HPT}} = \dot{m}_5 s_5 \quad (4.23)$$

*Exergy balance equation*

$$\dot{m}_4 ex_4 = \dot{m}_5 ex_5 + \dot{W}_{\text{HPT}} + \dot{E}_{\text{xdHPT}} \quad (4.24)$$

The specific exergies at state (5) can be expressed as the following:

$$ex_5 = (h_5 - h_o) - T_o (s_5 - s_o) \quad (4.25)$$

The isentropic efficiency of high pressure turbine is defined as the following:

$$\eta_{\text{HPT}} = \frac{h_4 - h_5}{h_4 - h_{5s}} \quad (4.26)$$

- **Expansion valve #2 (FV2)**

Assuming that the second flash happen at state (7)

*Mass balance equation*

$$\dot{m}_6 = \dot{m}_7 \quad (4.27)$$

*Energy balance equation*

$$\dot{m}_6 h_6 = \dot{m}_7 h_7 \quad (4.28)$$

*Entropy balance equation*

$$\dot{m}_6 s_6 + \dot{S}_{\text{gen\_FV2}} = \dot{m}_7 s_7 \quad (4.29)$$

*Exergy balance equation*

$$\dot{m}_6 ex_6 = \dot{m}_7 ex_7 + \dot{E}_{\text{xdFV2}} \quad (4.30)$$

The specific exergies at state (7) can be expressed as the following:

$$ex_7 = (h_7 - h_o) - T_o (s_7 - s_o) \quad (4.31)$$

- **Separator tank #2 (ST2)**

*Mass balance equation*

$$\dot{m}_7 = \dot{m}_8 + \dot{m}_{12} \quad (4.32)$$

$$\dot{m}_8 = (1 - x_3) x_7 \dot{m}_3 \quad (4.33)$$

$$\dot{m}_{12} = (1 - x_3) (1 - x_7) \dot{m}_3 \quad (4.34)$$

where  $x_7$  is the quality of the steam at state (7) and it is defined as the following:

$$x_7 = \frac{h_7 - h_{12}}{h_g - h_{12}} \quad (4.35)$$

*Energy balance equation*

$$\dot{m}_7 h_7 = \dot{m}_8 h_8 + \dot{m}_{12} h_{12} \quad (4.36)$$

*Entropy balance equation*

$$\dot{m}_7 s_7 + \dot{S}_{\text{gen\_ST2}} = \dot{m}_8 s_8 + \dot{m}_{12} s_{12} \quad (4.37)$$

*Exergy balance equation*

$$\dot{m}_7 \text{ex}_7 = \dot{m}_8 \text{ex}_8 + \dot{m}_{12} \text{ex}_{12} + \dot{E}_{\text{xdST2}} \quad (4.38)$$

The specific exergies at states (8) and (12) can be expressed as the following:

$$\text{ex}_8 = (h_8 - h_o) - T_o (s_8 - s_o) \quad (4.39)$$

$$\text{ex}_{12} = (h_{12} - h_o) - T_o (s_{12} - s_o) \quad (4.40)$$

- **Mixing chamber (MC)**

*Mass balance equation*

$$\dot{m}_5 + \dot{m}_8 = \dot{m}_9 \quad (4.41)$$

*Energy balance equation*

$$\dot{m}_5 h_5 + \dot{m}_8 h_8 = (\dot{m}_5 + \dot{m}_8) h_9 \quad (4.42)$$

The enthalpy at state (9) which is the mixture of a saturated vapor and steam would be calculated as following :

$$h_9 = \frac{x_3 h_5 + (1-x_3) x_7 h_8}{x_3 + (1-x_3)x_7} \quad (4.43)$$

*Entropy balance equation*

$$\dot{m}_5 s_5 + \dot{m}_8 s_8 + \dot{S}_{\text{gen\_MC}} = \dot{m}_9 s_9 \quad (4.44)$$

*Exergy balance equation*

$$\dot{m}_5 \text{ex}_5 + \dot{m}_8 \text{ex}_8 = \dot{m}_9 \text{ex}_9 + \dot{E}_{\text{xdMC}} \quad (4.45)$$

The specific exergies at state (9) can be expressed as the following:

$$\text{ex}_9 = (h_9 - h_o) - T_o (s_9 - s_o) \quad (4.46)$$

- **Low pressure turbine (LPT)**

*Mass balance equation*

$$\dot{m}_9 = \dot{m}_{10} \quad (4.47)$$

*Energy balance equation*

$$\dot{m}_9 h_9 = \dot{m}_{10} h_{10} + \dot{W}_{LPT} \quad (4.48)$$

where  $\dot{W}_{LPT}$  is the power of LPT

$$\dot{W}_{LPT} = (\dot{m}_5 + \dot{m}_9) (h_9 - h_{10}) \quad (4.49)$$

*Entropy balance equation*

$$\dot{m}_9 s_9 + \dot{S}_{gen\_LPT} = \dot{m}_{10} s_{10} \quad (4.50)$$

*Exergy balance equation*

$$\dot{m}_9 ex_9 = \dot{m}_{10} ex_{10} + \dot{W}_{LPT} + \dot{E}^{Xd}_{LPT} \quad (4.51)$$

The specific exergies at state (10) can be expressed as the following:

$$ex_{10} = (h_{10} - h_o) - T_o (s_{10} - s_o) \quad (4.52)$$

The isentropic efficiency of low pressure turbine is defined as the following:

$$\eta_{LPT} = \frac{h_9 - h_{10}}{h_9 - h_{10s}} \quad (4.53)$$

$$\text{where, } h_{10s} = h_{11} + (h_{g10} - h_{11}) \left[ \frac{s_9 - s_{11}}{s_{g10} - s_{11}} \right] \quad (4.54)$$

- **Condenser#1 (Cond1)**

*Mass balance equation*

$$\dot{m}_{10} = \dot{m}_{11} \quad (4.55)$$

$$\dot{m}_{16} = \dot{m}_{17} \quad (4.56)$$

*Energy balance equation*

$$\dot{m}_{10} h_{10} = \dot{m}_{11} h_{11} + \dot{Q}_{Cond1} \quad (4.57)$$

$$\dot{Q}_{Cond1} = \dot{m}_{17} h_{17} - \dot{m}_{16} h_{16} \quad (4.58)$$

*Entropy balance equation*

$$\dot{m}_{10} s_{10} + \dot{S}_{gen\_Cond1} = \dot{m}_{11} s_{11} + \frac{\dot{Q}_{Cond1}}{T_o} \quad (4.59)$$

*Exergy balance equation*

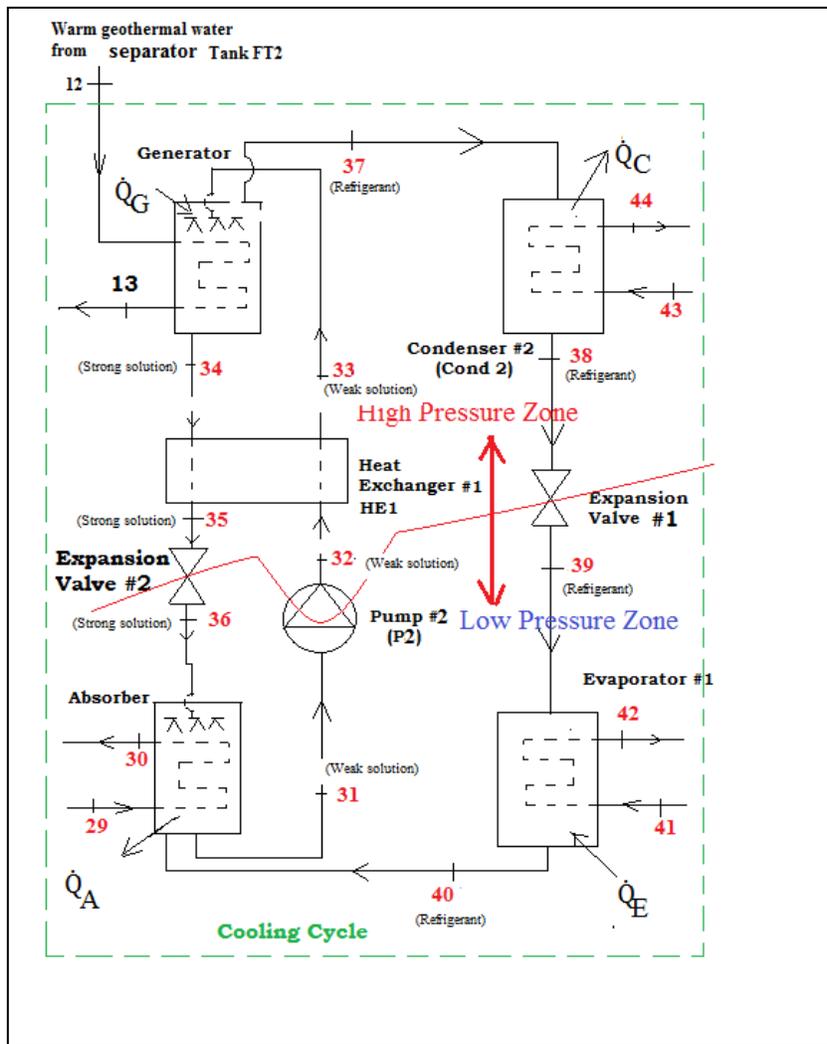
$$\dot{m}_{10} ex_{10} = \dot{m}_{11} ex_{11} + \dot{Q}_{\text{Cond1}} \left(1 - \frac{T_0}{T_3}\right) + \dot{E}_{\text{xdCond1}} \quad (4.60)$$

The specific exergies at state (11) can be expressed as the following:

$$ex_{11} = (h_{11} - h_0) - T_0 (s_{11} - s_0) \quad (4.61)$$

## 4.2 Absorption chiller cooling cycle

This solution enters the generator at state (33), where it is heat up by the saturated hot water that is coming from the separator tank (ST2) at state (12). As the mixture of LiBr-Water is warmed up, it starts to vaporize at a high temperature by separating the Water (refrigerant) from the LiBr (absorber). The weak brine solution of LiBr exits the generator at state (34), flows through a heat exchanger (HE1), where it releases heat (gained at the generator) to the incoming strong concentrated mixture of LiBr-Water at state (32). The weak mixture leaves HE1 at state (35) and enters the expansion valve#2 where its pressure decreases (state 36) before it starts flowing through the absorber unit. The vapor produced at the generator enters the condenser (cond 2) at state (37), where it is condensed by the flow of air (states 43 and 44). This vapor will become saturated water before entering the expansion valve#1 at state (38). Through the expansion valve #1, the saturated water is flashed at low pressure and low temperature. It will exit the expansion valve #1 at state (39) as a saturated vapor such that it can contain some energy allowing it to extract heat at the evaporator. This heat comes from the air-conditioned space (the air entering at state 41 and leaving at state 42). This saturated vapor will continue to flow to the absorber where it will be re-mixed with the solution of LiBr. Then, a new cycle will start at the suction of pump #2 (P2). This cycle can repeat itself over and over again. This system will provide the cooling at the evaporator unit. The control volume of this subsystem is represented in Figure 10.



**Figure 10:** Absorption chiller cooling cycle

Each component of the absorber chiller cooling cycle was analyzed separately. Four balance equations were written for each component, including mass, energy, entropy and exergy as the following:

- **Absorber**

*Mass balance equation*

$$\text{Refrigerant: } \dot{m}_{40} + \dot{m}_{36} = \dot{m}_{31} \quad (4.62)$$

In equation (4.62),  $\dot{m}_{31}$  is the mass flow rate of the weak solution (LiBr-Water);  $\dot{m}_{36}$  is the mass flow rate of the strong solution (LiBr-Water) and  $\dot{m}_{40}$  is the mass flow of the refrigerant (Pure Water). When divided the (4.62) by  $\dot{m}_{40}$ , the following will happen :

$$1 + \frac{\dot{m}_{36}}{\dot{m}_{40}} = \frac{\dot{m}_{31}}{\dot{m}_{40}} \quad (4.63)$$

Let  $\lambda$  be the circulation ratio that can be defined as the mass flow rate of the strong solution (LiBr-Water) over the mass flow rate of refrigerant (pure water)

$$\lambda = \frac{\dot{m}_{36}}{\dot{m}_{40}} \quad (4.64)$$

The equation (4.63) will be come:

$$\dot{m}_{31} = (1 + \lambda) \dot{m}_{40} \quad (4.65)$$

*The concentration balance equation*

$$\dot{m}_{40} \xi_{40} + \dot{m}_{36} \xi_{36} = \dot{m}_{31} \xi_{31} \quad (4.66)$$

$$\text{Here } \xi_{40} = 0 \text{ (Pure water)} \quad (4.67)$$

The equation (4.66) will become:

$$\dot{m}_{36} \xi_{36} = \dot{m}_{31} \xi_{31} \quad (4.68)$$

By substituting the equations (4.64) and (4.65) into (4.68), the following relation is obtained:

$$\lambda = \frac{\xi_{31}}{\xi_{36} - \xi_{31}} \quad (4.69)$$

*Energy balance equation*

$$\dot{m}_{36} h_{36} + \dot{m}_{40} h_{40} = \dot{m}_{31} h_{31} + \dot{Q}_A \quad (4.70)$$

By substituting the equations (4.64) and (4.65) into (4.70), the following relation will be obtained:

$$\dot{Q}_A = \dot{m}_{40} h_{40} + \lambda \dot{m}_{40} h_{36} - (1 + \lambda) \dot{m}_{40} h_{31} \quad (4.71)$$

$\dot{Q}_A$  can also be obtained from the following relation:

$$\dot{Q}_A = \dot{m}_{30} h_{30} - \dot{m}_{29} h_{29} \quad (4.72)$$

where  $\dot{Q}_A$  (kW), is rate of heat to the Absorber rejected from the system

*Entropy balance equation*

$$\lambda \dot{m}_{40} s_{36} + \dot{m}_{40} s_{40} + \dot{S}_{\text{gen}_A} = (1 + \lambda) \dot{m}_{40} s_{31} + \frac{\dot{Q}_A}{T_0} \quad (4.73)$$

*Exergy balance equation*

$$\lambda \dot{m}_{40} ex_{36} + \dot{m}_{40} ex_{40} = (1 + \lambda) \dot{m}_{40} ex_{31} + \dot{Q}_A \left(1 - \frac{T_0}{T_A}\right) + \dot{E}_{x d_A} \quad (4.74)$$

The specific exergies at states (29), (30), (31), (36) and (40) can be expressed as the following:

$$ex_{29} = (h_{29} - h_o) - T_o (s_{29} - s_o) \quad (4.75)$$

$$ex_{30} = (h_{30} - h_o) - T_o (s_{30} - s_o) \quad (4.76)$$

$$ex_{31} = (h_{31} - h_o) - T_o (s_{31} - s_o) \quad (4.77)$$

$$ex_{36} = (h_{36} - h_o) - T_o (s_{36} - s_o) \quad (4.78)$$

$$ex_{40} = (h_{40} - h_o) - T_o (s_{40} - s_o) \quad (4.79)$$

- **Heat exchanger# 1 (HE1)**

*Mass balance equation*

$$\text{Weak solution LiBr-Water: } \dot{m}_{32} = \dot{m}_{33} \quad (4.80)$$

By substituting the equations (4.65) into (4.80) the following equations would be used for the mass flow rate calculation:

$$\dot{m}_{32} = (1 + \lambda) \dot{m}_{40} \quad (4.81)$$

$$\dot{m}_{33} = (1 + \lambda) \dot{m}_{40} \quad (4.82)$$

$$\text{Strong solution LiBr-Water: } \dot{m}_{34} = \dot{m}_{35} \quad (4.83)$$

By substituting the equations (4.64) into (4.83) the following equations would be used for the mass flow rate calculation:

$$\dot{m}_{34} = \lambda \dot{m}_{40} \quad (4.84)$$

$$\dot{m}_{35} = \lambda \dot{m}_{40} \quad (4.85)$$

*Concentration balance equation*

$$\text{Weak solution LiBr-Water: } \xi_{32} = \xi_{33} \quad (4.86)$$

For the weak solution, the following equations are also true:

$$\xi_{32} = \xi_{31} \quad (4.87)$$

$$\xi_{33} = \xi_{31} \quad (4.88)$$

$$\text{Strong solution LiBr-Water: } \xi_{34} = \xi_{35} \quad (4.89)$$

For the strong solution, the following equations are also true:

$$\xi_{34} = \xi_{36} \quad (4.90)$$

$$\xi_{35} = \xi_{36} \quad (4.91)$$

*Energy balance equation*

$$\dot{m}_{32} h_{32} + \dot{m}_{34} h_{34} = \dot{m}_{33} h_{33} + \dot{m}_{35} h_{35} \quad (4.92)$$

By substituting the equations (4.81), (4.82), (4.84) and (4.85) into (4.92), the following equation will be used for the energy calculation:

$$(1+\lambda) h_{32} + \lambda h_{34} = (1+\lambda) h_{33} + \lambda h_{35} \quad (4.93)$$

*Entropy balance equation*

$$(1+\lambda) \dot{m}_{40} s_{32} + \lambda \dot{m}_{40} s_{34} + \dot{S}_{\text{gen\_EX1}} = (1+\lambda) \dot{m}_{40} s_{33} + \lambda \dot{m}_{40} s_{35} \quad (4.94)$$

*Exergy balance equation*

$$(1+\lambda) \dot{m}_{40} ex_{32} + \lambda \dot{m}_{40} ex_{34} = (1+\lambda) \dot{m}_{40} ex_{33} + \lambda \dot{m}_{40} ex_{35} + \dot{E}_{\text{xdEX1}} \quad (4.95)$$

The specific exergies at states (32), (33), (34) and (35) can be expressed as the following:

$$ex_{32} = (h_{32} - h_o) - T_o (s_{32} - s_o) \quad (4.96)$$

$$ex_{33} = (h_{33} - h_o) - T_o (s_{33} - s_o) \quad (4.97)$$

$$ex_{34} = (h_{34} - h_o) - T_o (s_{34} - s_o) \quad (4.98)$$

$$ex_{35} = (h_{35} - h_o) - T_o (s_{35} - s_o) \quad (4.99)$$

*Temperature balance equation*

The temperature at state (35) can be calculated as following:

$$\epsilon_{HE1} = \frac{T_{34} - T_{35}}{T_{34} - T_{32}} \quad (4.100)$$

where,  $\epsilon_{HE1}$  is the effectiveness of the heat exchanger.

Assuming that the temperatures at the states (31) and (32) are equal

$$T_{31} = T_{32} \quad (4.101)$$

▪ **Generator**

*Mass balance equation*

$$\text{For geothermal: } \dot{m}_{12} = \dot{m}_{13} \quad (4.102)$$

$$\text{For the chiller fluid: } \dot{m}_{33} = \dot{m}_{34} + \dot{m}_{37} \quad (4.103)$$

*Concentration balance equation*

$$\text{For LiBr-Water : } \dot{m}_{33} \xi_{33} = \dot{m}_{34} \xi_{34} + \dot{m}_{37} \xi_{37} \quad (4.104)$$

$$\text{where } \xi_{37} = 0 \text{ (state 37 is a vapor)} \quad (4.105)$$

The concentration ratio (CR) is:

$$CR = \frac{\xi_{34}}{\xi_{33}} = \frac{1+\lambda}{\lambda} \quad (4.106)$$

*Energy balance equation*

$$\dot{m}_{33} h_{33} + \dot{Q}_G = \dot{m}_{34} h_{34} + \dot{m}_{37} h_{37} \quad (4.107)$$

$$\text{where } \dot{Q}_G = \dot{m}_{40} h_{37} + \lambda \dot{m}_{40} h_{34} - (1+\lambda) \dot{m}_{40} h_{33} \quad (4.108)$$

and,  $h_{37}$  can be evaluated as the following:

$$h_{37} = h(P_{34}, x_{37}=1, \xi_{37}=0) \quad (4.109)$$

Here  $P_{34}$  and  $x_{37}$  and are the pressure and quality of the vapor states (34) and (37) respectively and  $\dot{Q}_G$  is the rate of heat to the generator of an absorption system. It can also be calculated as the following:

$$\dot{Q}_G = \dot{m}_{12} \times C_{p_{gf}} \times (T_{12} - T_{13}) = \dot{m}_{12} h_{12} - \dot{m}_{13} h_{13} \quad (4.110)$$

*Entropy balance equation*

$$\dot{m}_{33} s_{33} + \dot{S}_{gen\_G} + \frac{\dot{Q}_G}{T_0} = \dot{m}_{34} s_{34} + \dot{m}_{37} s_{37} \quad (4.111)$$

*Exergy balance equation*

$$\dot{m}_{33} ex_{33} + \dot{Q}_G \left(1 - \frac{T_0}{T_G}\right) = \dot{m}_{34} ex_{34} + \dot{m}_{37} ex_{37} + \dot{E}x_{dG} \quad (4.112)$$

The specific exergy at state (37) can be expressed as the following:

$$ex_{37} = (h_{37} - h_0) - T_0 (s_{37} - s_0) \quad (4.113)$$

*Temperature balance equation*

The temperature at states (34) and (37) shall be calculated as following:

$$T_{34} = T_G \quad (4.114)$$

$$T_{37} = T_{34} \quad (4.115)$$

where  $T_G$  is the generator Temperature.

- **Condenser#2**

*Mass balance equation*

For the Refrigerant:

$$\dot{m}_{37} = \dot{m}_{38} \quad (4.116)$$

These masses flow rates are the refrigerant mass flow rate. This means that:

$$\dot{m}_{37} = \dot{m}_{40} \quad (4.117)$$

$$\dot{m}_{38} = \dot{m}_{40} \quad (4.118)$$

For cooling water:

$$\dot{m}_{43} = \dot{m}_{44} \quad (4.119)$$

*Energy balance equation*

$$\dot{m}_{37} h_{37} = \dot{m}_{38} h_{38} + \dot{Q}_C \quad (4.120)$$

$$\text{where } \dot{Q}_C = \dot{m}_{44} h_{44} - \dot{m}_{43} h_{43} \quad (4.121)$$

$\dot{Q}_C$  is the he rate of heat to the condenser #2 of an absorption system

*Entropy balance equation*

$$\dot{m}_{37} s_{37} + \dot{S}_{\text{gen}_C} = \dot{m}_{38} s_{38} + \frac{\dot{Q}_C}{T_0} \quad (4.122)$$

*Exergy balance equation*

$$\dot{m}_{37} ex_{37} = \dot{m}_{38} ex_{38} + \dot{Q}_C \left(1 - \frac{T_0}{T_C}\right) + \dot{E}x_{dC} \quad (4.123)$$

The specific exergies at states (46), (51) and (52) can be expressed as the following:

$$ex_{38} = (h_{38} - h_o) - T_o (s_{38} - s_o) \quad (4.124)$$

$$ex_{43} = (h_{43} - h_o) - T_o (s_{43} - s_o) \quad (4.125)$$

$$ex_{44} = (h_{44} - h_o) - T_o (s_{44} - s_o) \quad (4.126)$$

▪ **Evaporator #1**

*Mass balance equation*

$$\text{Refrigerant: } \dot{m}_{39} = \dot{m}_{40} \quad (4.127)$$

$$\text{Chilled Water: } \dot{m}_{41} = \dot{m}_{42} \quad (4.128)$$

*Energy balance equation*

$$\dot{m}_{39} h_{39} + \dot{Q}_E = \dot{m}_{40} h_{40} \quad (4.129)$$

$$\text{where } h_{40} = h(T_E, X_{40}=1) \quad (4.130)$$

$$\text{and } \dot{Q}_E = \dot{m}_{41} h_{41} - \dot{m}_{42} h_{42} = \dot{m}_{39} h_{39} - \dot{m}_{40} h_{40} \quad (4.131)$$

$\dot{Q}_E$  is the rate of heat to the Evaporator #1 of an absorption system

*Entropy balance equation*

$$\dot{m}_{39} s_{39} + \dot{S}_{\text{gen}_E} + \frac{\dot{Q}_E}{T_0} = \dot{m}_{40} s_{40} \quad (4.132)$$

*Exergy balance equation*

$$\dot{m}_{39} \text{ex}_{39} + \dot{Q}_E \left(1 - \frac{T_0}{T_E}\right) = \dot{m}_{40} \text{ex}_{40} + \dot{E}_{\text{Xd}_E} \quad (4.133)$$

The specific exergies at states (47), (49) and (50) can be expressed as the following:

$$\text{ex}_{39} = (h_{39} - h_0) - T_0 (s_{39} - s_0) \quad (4.134)$$

$$\text{ex}_{41} = (h_{41} - h_0) - T_0 (s_{41} - s_0) \quad (4.135)$$

$$\text{ex}_{42} = (h_{42} - h_0) - T_0 (s_{42} - s_0) \quad (4.136)$$

- **Expansion valve #1**

*Mass balance equation*

$$\dot{m}_{38} = \dot{m}_{39} \quad (4.137)$$

*Energy balance equation*

$$\dot{m}_{38} h_{38} = \dot{m}_{39} h_{39} \quad (4.138)$$

*Entropy balance equation*

$$\dot{m}_{38} s_{38} + \dot{S}_{\text{gen}_\text{ExpV1}} = \dot{m}_{39} s_{39} \quad (4.139)$$

*Exergy balance equation*

$$\dot{m}_{38} \text{ex}_{38} = \dot{m}_{39} \text{ex}_{39} + \dot{E}_{\text{Xd}_\text{ExpV1}} \quad (4.140)$$

- **Expansion valve #2**

*Mass balance equation*

$$\dot{m}_{35} = \dot{m}_{36} \quad (4.141)$$

*Energy balance equation*

$$\dot{m}_{35} h_{35} = \dot{m}_{36} h_{36} \quad (4.142)$$

*Entropy balance equation*

$$\dot{m}_{35} s_{35} + \dot{S}_{\text{gen\_ExpV2}} = \dot{m}_{36} s_{36} \quad (4.143)$$

*Exergy balance equation*

$$\dot{m}_{35} ex_{35} = \dot{m}_{36} ex_{36} + \dot{E}x_{d\text{ExpV2}} \quad (4.144)$$

- **Pump #2 (P2)**

*Mass balance equation*

$$\dot{m}_{31} = \dot{m}_{32} \quad (4.145)$$

*Energy balance equation*

$$\dot{m}_{31} h_{31} + \dot{W}_{P2} = \dot{m}_{32} h_{32} \quad (4.146)$$

*Entropy balance equation*

$$\dot{m}_{31} s_{31} + \dot{S}_{\text{gen\_P2}} = \dot{m}_{32} s_{32} \quad (4.147)$$

*Exergy balance equation*

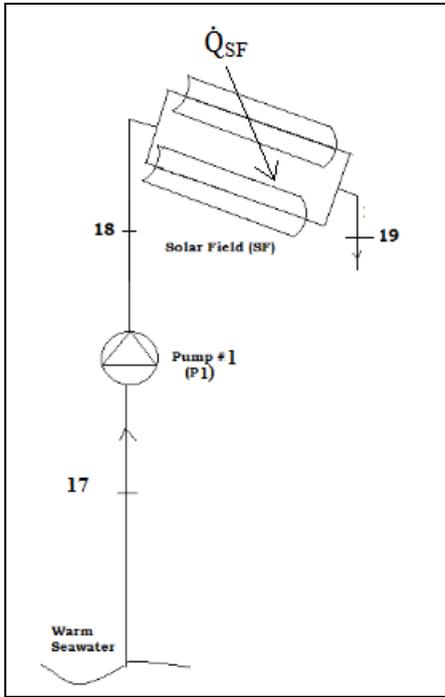
$$\dot{m}_{31} ex_{31} + \dot{W}_{P2} = \dot{m}_{32} ex_{32} + \dot{E}x_{dP2} \quad (4.148)$$

### 4.3 Cylindrical parabolic concentrator solar field

Seawater is pumped from state (17) to the inlet of the cylindrical parabolic concentrator (SF) at state (18). Seawater will be heated through the SF by solar radiations and exits at state (19) as hot seawater, which will be used as a heat source at the first effect of the desalination subsystem.

The control volume of this subsystem is represented in Figure 11.

Each component of the cylindrical parabolic concentrator solar field was analyzed separately. Four balance equations were written for each component, including mass, energy, entropy and exergy as the following:



**Figure 11:** Cylindrical parabolic concentrator solar field

▪ **Pump #1 (P1)**

*Mass balance equation*

$$\dot{m}_{17} = \dot{m}_{18} \quad (4.149)$$

*Energy balance equation*

$$\dot{m}_{17} h_{17} + \dot{W}_{P1} = \dot{m}_{18} h_{18} \quad (4.150)$$

*Entropy balance equation*

$$\dot{m}_{17} s_{17} + \dot{S}_{gen\_P1} = \dot{m}_{18} s_{18} \quad (4.151)$$

*Exergy balance equation*

$$\dot{m}_{17} ex_{17} + \dot{W}_{P1} = \dot{m}_{18} ex_{18} + \dot{E}_{xdP1} \quad (4.152)$$

where the specific exergies at states (17) and (18) can be expressed as the following:

$$ex_{17} = (h_{17} - h_o) - T_o (s_{17} - s_o) \quad (4.153)$$

$$ex_{18} = (h_{18} - h_o) - T_o (s_{18} - s_o) \quad (4.154)$$

And the power ( $\dot{W}_{P1}$ ) of the pump (P1) can be calculated by using the following:

$$\dot{W}_{P1} = \frac{\dot{m}_{17} \Delta H_{P1} g}{\eta_{P1}} \quad (4.155)$$

Here, the specific enthalpies and entropies at the states (17) and (18) will be evaluated by using Sharqawy [38] correlations defined as per the equations (4.193) and (4.198) respectively. However; the temperature and the salinity of the seawater will be defined at each specific state.

$\dot{m}_{17}$  is the mass flow rate of warm sea water

$\Delta H_{P1}$  ; is the total pump head difference of the warm sea water piping, in meter (m)

$\eta_{P1}$  ; is pump (P1) efficiency warm sea water

$$\Delta H_{P1} = (\Delta H_{P1})_{SH} + [(\Delta H_{P1})_{SP} + (\Delta H_{P1})_M] \quad (4.156)$$

where  $(\Delta H_{P1})_{SH}$  is static head of the pump (P1) and It is in (m),  $(\Delta H_{P1})_{SP}$  is Minors losses due to warm seawater straight pipe (SP) section and it is in (m),  $(\Delta H_{P1})_M$  is minor losses due to the entrance, bending, valves and exit on the seawater piping and it is in (m).

$$(\Delta H_{P1})_{SH} = h_{L1} - h_{L01} \quad (4.157)$$

$h_{L1}$  is the top seawater level

$h_{L01}$  is the bottom seawater level

$$(\Delta H_{P1})_{SP} = \sum \frac{f_{SW} L_{SW} V_{SW}^2}{ID_{SW} 2g} \quad (4.158)$$

$$(\Delta H_{P1})_M = \sum k_{SW} \frac{V_{SW}^2}{2g} \quad (4.159)$$

where  $f_{SW}$  is a friction factor coefficient of seawater suction piping,  $L_{SW}$  is the length of the suction piping,  $V_{SW}$  is the velocity in the suction piping of seawater (m/s),  $g$  is gravitational acceleration constant ( $9.81 \text{ m/s}^2$ ),  $ID_{SW}$  is the hydraulic diameter (m) of the suction piping for seawater

$\eta_{P1}$  : The efficiency of pump P1

For turbulent flow:

$$f_{SW} = \left\{ -0.782 \ln \left[ \frac{6.9}{Re_{SW}} + \left( \frac{\varepsilon}{3.7 ID_{SW}} \right)^{1.11} \right] \right\}^{-2} \quad (4.160)$$

where  $\varepsilon$  is the roughness of the pipe. For Commercial steel,  $\varepsilon = 4.6 \times 10^{-5}$  m,  $Re_{SW}$  is the Reynolds Number seawater

$$Re_{SW} = \frac{\rho v_{SW} ID_{SW}}{\mu} = \frac{4 \dot{m}_{17}}{\mu \pi ID_{SW}} \quad (4.161)$$

**Table 5:** Total minor losses for pump (P1)

Components	Quantity	Minor losses	Total minor losses
		For $25 \text{ mm} \leq ID_{SW} < 500 \text{ mm}$	$(\sum k_{SW})$
90° Elbow	$\alpha_2$	$0.21 (ID_{SW})^{-0.23}$	$0.21 \alpha_2 (ID_{SW})^{-0.23}$
Tee	$\beta_2$	$0.061 (ID_{SW})^{-0.46}$	$0.061 \beta_2 (ID_{SW})^{-0.46}$
Gate Valve	$\gamma_2$	$0.02 (ID_{SW})^{-1.14}$	$0.02 \gamma_2 (ID_{SW})^{-1.14}$

$$\sum k_{SW} = 0.21 \alpha_2 (ID_{SW})^{-0.23} + 0.061 \beta_2 (ID_{SW})^{-0.46} + 0.02 \gamma_2 (ID_{SW})^{-1.14} \quad (4.162)$$

▪ **Cylindrical parabolic concentrator solar field (SF)**

*Mass balance equation*

$$\dot{m}_{18} = \dot{m}_{19} \quad (4.163)$$

*Energy balance equation*

$$\dot{m}_{18} h_{18} + \dot{Q}_{SF} = \dot{m}_{19} h_{19} \quad (4.164)$$

*Entropy balance equation*

$$\dot{m}_{18} s_{18} + \frac{\dot{Q}_{SF}}{T_0} + \dot{S}_{gen\_SF} = \dot{m}_{19} s_{19} \quad (4.165)$$

*Exergy Balance Equation*

$$\dot{m}_{18} e_{x18} + \dot{Q}_{SF} \left(1 - \frac{T_0}{T_{SF}}\right) = \dot{m}_{19} e_{x19} + \dot{E}_{xd_{SF}} \quad (4.166)$$

where the specific exergy at state (19) can be expressed as the following:

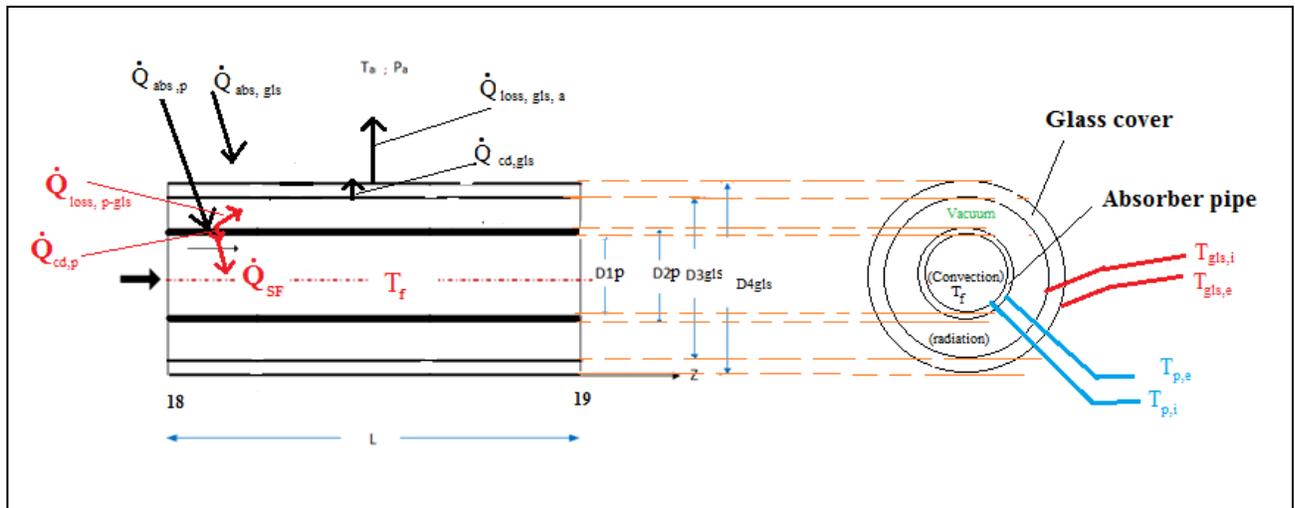
$$e_{x19} = (h_{19} - h_0) - T_0 (s_{19} - s_0) \quad (4.167)$$

Here the specific enthalpy and entropy at the states (19) will be evaluated by using Sharqawy [38] correlations defined as per the equations (4.193) and (4.198) respectively. However, the temperature and the salinity of the seawater will be defined at state (19);  $T_{SF}$  is the sun 's surface temperature , which is equal to 6000K , as per Dincer [43] and  $\dot{Q}_{SF}$  is the useful solar energy gain by the collector through state (18) to (19). This can write as:

$$\dot{Q}_{SF} = \dot{m}_{18} C_{p_{wsw}} (T_{19} - T_{18}) \quad (4.168)$$

On the other hand,  $\dot{Q}_{SF}$  can be determined from the energy balances equations of Figure 12.

These equations will determine the temperature ( $T_{19}$ ) at state (19) [44]:



**Figure 12:** Modeling of the parabolic concentrator and the tubular receiver [44]

The modeling equations of Figure 12 can be found in Table 6:

Table 6: Modeling equation for the solar field [44]

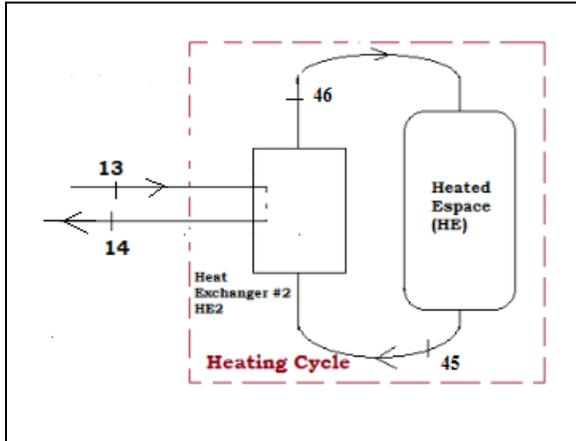
Description	Equations	Number
Absorbed heat rate transmitted through the absorber pipe by conduction	$\dot{Q}_{abs,p} = \tau_{gls} \alpha_p \dot{Q}_{in,R}$	(4.169)
Heat partially transmitted through the glass, absorbed by the pipe and used to heat the seawater inside the receiver	$\eta_{env} = \eta_{opt} k_{\theta}$ $\dot{Q}_{in,R} = \eta_{env} H_{PTC} L_{PTC} G_B = \eta_{opt} H_{PTC} L_{PTC} G_{Bt}$	(4.170)
Energy balance equation on the inner pipe surface	$\dot{Q}_{SF} = \dot{Q}_{cd,p}$	(4.171)
Conduction heat rate through the tubular pipe	$\dot{Q}_{cd,p} = 2\pi L_{PTC} k_p \frac{T_{p,e} - T_{p,i}}{\ln(\frac{D_{2p}}{D_{1p}})}$	(4.172)
Heat received by seawater by thermal convection	$\dot{Q}_{SF} = \pi D_{1p} L_{PTC} h_f (T_{p,i} - T_f)$	(4.173)
Arithmetic mean temperature between $T_{18}$ and $T_{19}$	$T_f = \frac{T_{18} + T_{19}}{2}$	(4.174)
Convection heat transfer coefficient	$h_f = \frac{Nu_f \lambda_f}{D_1}$ ; Where the Nusselt Number is $Nu_f = 0.023 Re^{0.8} Pr^{0.4}$	(4.175)
Energy balance equation on the pipe exterior surface	$\dot{Q}_{abs,p} = \dot{Q}_{SF} + \dot{Q}_{loss,p-gls}$	(4.176)
Radiation heat loss between pipe and glass cover	$\dot{Q}_{loss,p-gls} = \pi D_{1p} L_{PTC} \sigma \frac{T_{p,e}^4 - T_{gls,i}^4}{\frac{1}{\epsilon_p} + (\frac{1 - \epsilon_{gls}}{\epsilon_{gls}}) \frac{D_{2p}}{D_{3gls}}}$	(4.177)
Energy balance equation on the inner surface of the glass cover	$\dot{Q}_{loss,p-gls} = \dot{Q}_{cd,gls}$	(4.178)
Heat rate passing through the glass cover by conduction	$\dot{Q}_{cd,gls} = 2\pi L_{PTC} k_{gls} \frac{T_{gls,i} - T_{gls,e}}{\ln(\frac{D_{4gls}}{D_{3gls}})}$	(4.179)
Energy balance equation on the outer surface of the glass cover	$\dot{Q}_{cd,gls} + \dot{Q}_{abs,gls} = \dot{Q}_{loss,gls-a}$	(4.180)
Heat lost rate transmitted from the outer glass surface to ambient though wind convection and radiation	$\dot{Q}_{loss,gls-a} = \pi D_{4gls} L_{PTC} h_{wind} (T_{gls,e} - T_a)$ $+ \pi D_{4gls} L_{PTC} \epsilon_{gls} \sigma (T_{gls,e}^4 - T_{sky}^4)$	(4.181)
Wind convection heat transfer coefficient	$h_{wind} = 5.7 + 3.8t$ Where, t is wind velocity in m/s	(4.182)

#### 4.4 Heating cycle

Saturated hot water from the geothermal source will enter the heat exchanger (HE2) at state (13).

Heat releases at HE2 is gained by the cold air that enters the exchanger at state (45) and exits at

state (46) as hot air to heat up the leaving space. After releasing its heat, the geothermal will be at HE2 at state (14) and flows back to the geothermal reservoir through the injection well (IW). The control volume of this subsystem is represented in Figure 13.



**Figure 13:** Heating cycle

Each component of the heating cycle was analyzed separately. Four balance equations were written for each component, including mass, energy, entropy and exergy as the following:

- **Heating space (HE)**

*Mass balance equation*

From geothermal water source:  $\dot{m}_{13} = \dot{m}_{14}$  (4.183)

For air:  $\dot{m}_{45} = \dot{m}_{46}$  (4.184)

*Energy balance equation*

$$\dot{m}_{45} h_{45} + \dot{Q}_{HE} = \dot{m}_{46} h_{46}$$
 (4.185)

The rate of heat to the heating space system is provided the heat exchanger #2

and is calculated by using the following equation:

$$\dot{Q}_{HE} = \dot{m}_{13} h_{13} - \dot{m}_{14} h_{14}$$
 (4.186)

*Entropy balance equation*

$$\dot{m}_{45} s_{45} + \frac{\dot{Q}_{HE}}{T_0} + S_{genHE} = \dot{m}_{46} s_{46} \quad (4.187)$$

*Exergy balance equation*

$$\dot{m}_{45} ex_{45} + \dot{Q}_{HE} \left(1 - \frac{T_0}{T_{HE}}\right) = \dot{m}_{46} ex_{46} + \dot{E}x_{destHE} \quad (4.188)$$

The specific exergies at state (45) and (46) can be expressed as the following:

$$ex_{45} = (h_{45} - h_o) - T_o (s_{45} - s_o) \quad (4.189)$$

$$ex_{46} = (h_{46} - h_o) - T_o (s_{46} - s_o) \quad (4.190)$$

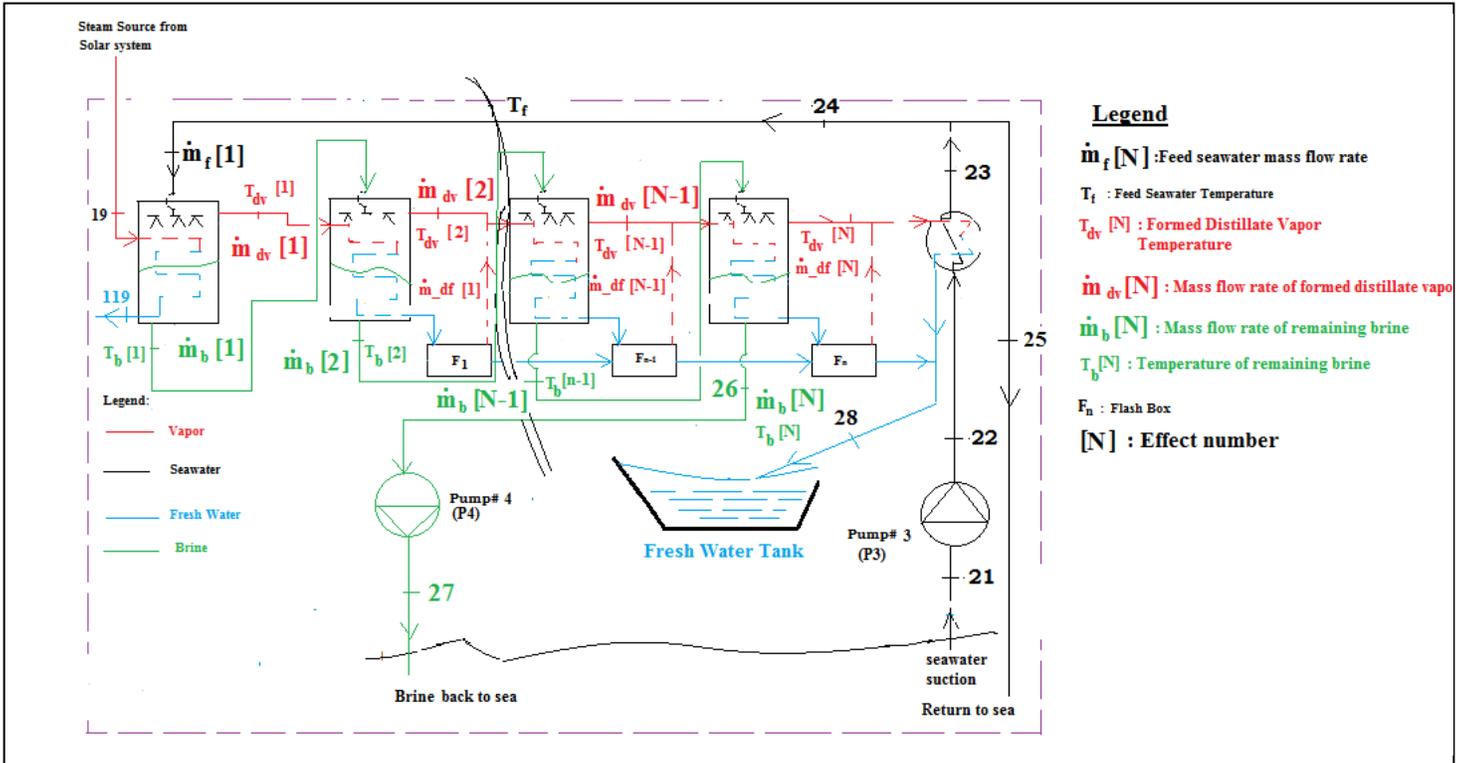
#### 4.5 MED fresh water cycle

The analysis will be based under the following assumptions:

- Vapor formed at each effect is assumed to be a saturated vapor that is free of salt
- Assuming that the quantity of non-dissolved gases and particles are negligible
- Steady state condition
- Non-Equilibrium (NEA) is negligible [45]
- No heat exchange with the surrounding (the system is adiabatic)
- The potential and kinetic energies are negligible
- Distillate vapor and brine leave each effect at that effect's temperature [45]
- Seawater properties are only a function of temperature and salinity
- The final reject salinity is slightly higher than the salinity of the feed seawater
- The temperature of the seawater remains constant
- Heat transfer area of evaporators 2 to N is the same
- The difference of temperatures ( $\Delta T$ ) between the effects is equal and constant
- The energy losses to the environment are negligible [45]
- The pressure losses are negligible

- The mass flow rates of the feed seawater entering at the top of each effect are equal
- Heat transfer area is sufficient to condensate vapour to saturated liquid at the pressure of the previous effect
- The distillate water generated is free from salinity

The operational principal of Figure 14 is described in section 3.3



**Figure 14:** Fresh water cycle (MED)

Each component of fresh water cycle was analyzed separately. Four balance equations were written for each component, including mass, energy, entropy and exergy as the following:

- **Pump #3 (P3)**

*Mass balance equation*

$$\dot{m}_{21} = \dot{m}_{22} \quad (4.191)$$

*Energy balance equation*

$$\dot{m}_{21} h_{21} + \dot{W}_{P3} = \dot{m}_{22} h_{22} \quad (4.192)$$

The specific enthalpies are evaluated by using the following Sharqawy [38] correlations:

$$h_{21} = h_{w21} - S_{21} ( a_1 + a_2 S_{21} + a_3 S_{21}^2 + a_4 S_{21}^3 + a_5 T_{21} + a_6 T_{21}^2 + a_7 T_{21}^3 + a_8 S_{21} T_{21} + a_9 S_{21}^2 T_{21} + a_{10} S_{21} T_{21}^2 ) \quad (4.193)$$

$$h_{w21} = 141.355 + 4202.070 T_{21} - 0.535 T_{21}^2 + 0.004 T_{21}^3 \quad (4.194)$$

$$h_{22} = h_{w22} - S_{22} ( a_1 + a_2 S_{22} + a_3 S_{22}^2 + a_4 S_{22}^3 + a_5 T_{22} + a_6 T_{22}^2 + a_7 T_{22}^3 + a_8 S_{22} T_{22} + a_9 S_{22}^2 T_{22} + a_{10} S_{22} T_{22}^2 ) \quad (4.195)$$

$$h_{w22} = 141.355 + 4202.070 T_{22} - 0.535 T_{22}^2 + 0.004 T_{22}^3 \quad (4.196)$$

where  $a_1 = -2.348 \times 10^4$ ,  $a_2 = 3.152 \times 10^5$ ,  $a_3 = 2.803 \times 10^6$ ,  $a_4 = -1.446 \times 10^7$ ,  
 $a_5 = 7.826 \times 10^3$ ,  $a_6 = -4.417 \times 10^1$ ,  $a_7 = 2.139 \times 10^{-1}$ ,  $a_8 = -1.991 \times 10^4$ ,  
 $a_9 = 2.778 \times 10^4$  and  $a_{10} = 9.728 \times 10^1$

$h_{21}$ ,  $h_{22}$ ,  $h_{w21}$  and  $h_{w22}$  are (J/kg K)

These correlations are validated for the seawater belong between 10 and 120 °C; The salinity (S) shall be between 0 and 120 g/kg

*Entropy balance equation*

$$\dot{m}_{21} s_{21} + \dot{S}_{gen\_P3} = \dot{m}_{22} s_{22} \quad (4.197)$$

Sharqawy [38] correlations can also be used to evaluate the specific entropies at the states (21) and (22):

$$s_{21} = s_{w21} - w_{21} (\partial_1 + \partial_2 w_{21} + \partial_3 w_{21}^2 + \partial_4 w_{21}^3 + \partial_5 T_{21} + \partial_6 T_{21}^2 + \partial_7 T_{21}^3 + \partial_8 w_{21} T_{21} + \partial_9 w_{21}^2 T_{21} + \partial_{10} w_{21} T_{21}^2) \quad (4.198)$$

where,  $w_{21}$  represents the salt concentration of seawater at state (21);  $s_{w21}$  (J/kg K) represents the specific entropy of pure water at state (21) and can be calculated from the following equation:

$$s_{w21} = 0.1543 + 15.383 T_{21} - 2.996 \times 10^{-2} T_{21}^2 + 8.193 \times 10^{-5} T_{21}^3 - 1.370 \times 10^{-7} T_{21}^4 \quad (4.199)$$

$$s_{22} = s_{w22} - w_{22}(\partial_1 + \partial_2 w_{22} + \partial_3 w_{22}^2 + \partial_4 w_{22}^3 + \partial_5 T_{22} + \partial_6 T_{22}^2 + \partial_7 T_{22}^3 + \partial_8 w_{22} T_{22} + \partial_9 w_{22}^2 T_{22} + \partial_{10} w_{22} T_{22}^2) \quad (4.200)$$

Where  $w_{22}$  represents the salt concentration of seawater at state (22),  $s_{w22}$  (J/kg K) represents the specific entropy of pure water at state (22) and can be calculated from the following equation:

$$s_{w22} = 0.1543 + 15.383 T_{22} - 2.996 \times 10^{-2} T_{22}^2 + 8.193 \times 10^{-5} T_{22}^3 - 1.370 \times 10^{-7} T_{22}^4 \quad (4.201)$$

The constants  $\partial$ 's can be evaluated from the following relations:

$$\begin{aligned} \partial_1 &= -4.231 \times 10^{-2}, \partial_2 = 1.463 \times 10^4, \partial_3 = -9.880 \times 10^4, \partial_4 = 3.095 \times 10^5, \partial_5 = 2.562 \times 10^1, \\ \partial_6 &= -1.443 \times 10^{-1}, \partial_7 = 5.879 \times 10^{-4}, \partial_8 = -6.111 \times 10^1, \partial_9 = 8.041 \times 10^1 \text{ and} \\ \partial_{10} &= 3.035 \times 10^{-1} \end{aligned}$$

These correlations can only be used by assuring that the temperature of seawater is between 10 and 120 °C and the salt concentration in seawater is between 0 and 120 g/kg

*Exergy balance equation*

$$\dot{m}_{21} C_{Pcs} [(T_{21} - T_{22}) - T_0 \ln \frac{T_{21}}{T_{22}}] + \dot{W}_{P4} = \dot{E}X_{dP4} \quad (4.202)$$

where  $C_{Pcs}$  is the specific heat of cold seawater. It is evaluated at the average temperature ( $T_{CPcs}$ ), which can be calculated as the following equation:

$$T_{CPcs} = \frac{T_{21} + T_{22}}{2} \quad (4.203)$$

$C_{Pcs}$  (kJ/kg k) is calculated from El-Dessouky and Shaban [36] correlations:

$$C_{Pcs} = (A_{1cs} + A_{2cs} T_{CPcs} + A_{3cs} T_{CPcs}^2 + A_{4cs} T_{CPcs}^3) \times 10^{-3} \quad (4.204)$$

$$\text{where } A_{1cs} = 4206.8 - 6.6197 S_{22} + 1.2288 \times 10^{-2} S_{22}^2 \quad (4.205)$$

$$A_{2cs} = -1.1262 + 5.4178 \times 10^{-2} S_{22} - 2.2719 \times 10^{-4} S_{22}^2 \quad (4.206)$$

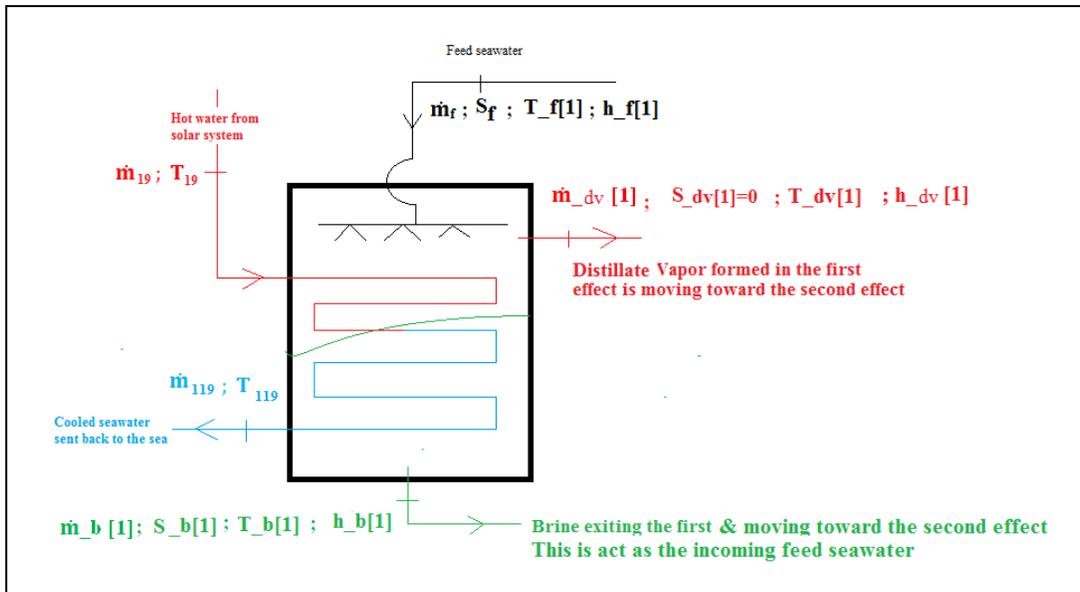
$$A_{3cs} = 1.2026 \times 10^{-2} - 5.3566 \times 10^{-4} S_{22} + 1.8906 \times 10^{-6} S_{22}^2 \quad (4.207)$$

$$A_{4cs} = 6.87774 \times 10^{-7} + 1.517 \times 10^{-6} S_{22} - 4.4268 \times 10^{-9} S_{22}^2 \quad (4.208)$$

Here  $S_{22}$  (g/kg) represents the salinity of seawater at state (22)

- **First effect**

Feed seawater with the mass flow rate ( $\dot{m}_f[1]$ ) and the salinity ( $S_f$ ) entering the first effect is boiled by the latent heat of the hot seawater (mass flow rate  $\dot{m}_{19}$ ) coming from solar system at state (19). This boiling process will condensate the seawater (mass flow rate  $\dot{m}_{119}$ ) exiting the effect at state (119) and generates the only distillate vapor (mass flow rate  $\dot{m}_{dv}[1]$ ) that will be used as the source of heat for the second effect. After the boiling process, the remaining feed seawater called brine (mass flow rate  $\dot{m}_b[1]$ ) will exit the first effect with an increase of its salinity ( $S_b[1]$ ). Figure 15 below describes the control volume of the first effect



**Figure 15:** First effect control volume

Four balance equations including mass, energy, entropy and exergy of the first effect were written as following:

*Mass balance equation*

$$\dot{m}_f[1] = \dot{m}_b [1] + \dot{m}_{dv}[1] \quad (4.209)$$

$$\dot{m}_f[1] = \dot{m}_{24} \quad (4.210)$$

*Salt balance equation*

$$S_f \dot{m}_f[1] = S_b[1] \dot{m}_b [1] + S_{dv}[1] \dot{m}_{dv}[1] \quad (4.211)$$

where  $S_{dv}[1]$  is a pure vapor

$$S_{dv}[1] = 0 \quad (4.212)$$

By substituting the equation (4.212) into the equation (4.211), the mass flow rate ( $\dot{m}_b [1]$ ) of the brine exiting the first effect can be calculated from the following equation:

$$S_f \dot{m}_f[1] = S_b[1] \dot{m}_b [1] \quad (4.213)$$

where  $S_b[1]$  is the brine salinity rejected from the first effect, which can be evaluated from the following relations:

$$S_b[1] = 0.9 \times (457628.5 - 11304.11T_b [1] + 107.5781(T_b [1])^2 - 0.360747(T_b [1])^3) \quad (4.214)$$

$S_b[1]$  is in g/kg

*Energy balance equation*

The energy balance equation in the first effect due to the boiling can be written as the following:

$$\dot{m}_{19}h_{19} + \dot{m}_f[1] h_f[1] = \dot{m}_{119}h_{119} + \dot{m}_b [1] h_b[1] + \dot{m}_{dv}[1] h_{dv}[1] \quad (4.215)$$

where  $h_{19}$  (kJ/kg) represents the enthalpy of the motive hot seawater from solar system,  $h_{119}$ (kJ/kg) represents the enthalpy of the condensed motive water from solar system. This will be assumed as fully condensed seawater. It is evaluated at the condensation Temperature ( $T_{119}$ ) and the salinity at state (119);  $h_f[1]$  (kJ/kg) represents the enthalpy of the feed seawater ,  $h_b[1]$  represents the enthalpy of the remaining brine exiting the first effect and  $h_{dv}[1]$  (kj/kg) represents the enthalpy of the distillate vapor formed in the first effect.

$h_{dv}[1]$  is evaluated at the boiling temperature  $T_{dv}[1]$  of the saturated distillate vapor.

$$T_{dv}[1] = T_b[1] - \text{BPE}[1] \quad (4.216)$$

where BPE [1] is the boiling point of elevation. It can be calculated from the following equation

[35]:

$$\text{BPE}[1] = S_0 (B_1 + C_1 S_0) 10^{-3} \quad (4.217)$$

where

$$B_1 = (6.71 + 6.34 \times 10^{-2} T_b[1] + 9.74 \times 10^{-5} (T_b[1])^2) 10^{-3} \quad (4.218)$$

$$C_1 = (22.238 + 9.59 \times 10^{-3} T_b[1] + 9.42 \times 10^{-5} (T_b[1])^2) 10^{-8} \quad (4.219)$$

$S_0$  : is the salt concentration in ppm.

According to El-Dessouky [35],  $S_0$  should have the value between 20000 and 160000 ppm ;

$(T_b[1])$  shall be between 20 and 180°C; BPE is usually considered equal to 0.8°C .

$T_b[1]$  (°C): represents the boiling temperature of the brine exiting the first effect

The temperature of the feed seawater ( $T_f[1]$ ) entering the first effect can be evaluated as following:

$$T_f[1] = T_{dv}[1] - \Delta T_{MED} \quad (4.220)$$

$\Delta T_{MED}$  (°C) : is the difference in temperature between the effects

The difference of the temperature of the brine between the effects is considered to be the same and represented by the following relation:

$$\Delta T_{MED} = \frac{T_1 - T_N}{N-1} \quad (4.221)$$

where  $N$  is the total number of effect

*Entropy balance equation*

$$\dot{m}_f[1] s_{f[1]} + \dot{S}_{gen}[1] + \frac{\dot{Q}_{eff}[1]}{(T_0+273.15)} = \dot{m}_b[1] s_{b[1]} + \frac{(\dot{m}_{dv}[1] h_{dv}[1])}{T_{dv}[1]} - c_p [1] \ln \frac{T_b[1]+273.15}{T_f[1]+273.15} \quad (4.222)$$

where  $s_{19}$  (J/kg K) represents the saturated liquid entropy of the motive hot seawater from solar system,  $s_{119}$  (J/kg K) represents the saturated liquid entropy of the condensate seawater exiting the first effect,  $T_0$  (°C) represents the reference temperature and  $C_p$  (kJ/kg k) represents the specific heat capacity of feed seawater at constant pressure. It depends on seawater temperature and salinity. El-Dessouky and Shaban [36] provided the following equations:

$$C_p = (A_1 + A_2 T_1 + A_3 T_1^2 + A_4 T_1^3) \times 10^{-3} \quad (4.223)$$

where  $T_1$  (°C) is the average temperature between the feed seawater entering the effect and the brine temperature exiting the effect

$$T_1 = \frac{T_f[1] + T_b[1]}{2} \quad (4.224)$$

$$A_1 = 4206.8 - 6.6197 S_f[1] + 1.2288 \times 10^{-2} (S_f[1])^2 \quad (4.225)$$

$$A_2 = -1.1262 + 5.4178 \times 10^{-2} S_f[1] - 2.2719 \times 10^{-4} (S_f[1])^2 \quad (4.226)$$

$$A_3 = 1.2026 \times 10^{-2} - 5.3566 \times 10^{-4} S_f[1] + 1.8906 \times 10^{-6} (S_f[1])^2 \quad (4.227)$$

$$A_4 = 6.87774 \times 10^{-7} + 1.517 \times 10^{-6} S_f[1] - 4.4268 \times 10^{-9} (S_f[1])^2 \quad (4.228)$$

where  $S_f[1]$  is (g/kg)

*Exergy balance equation*

The main goal of the exergy balance equation is to calculate the exergy destruction in each effect.

$$\dot{m}_f[1] ex_{f[1]} + \dot{Q}_{eff}[1] \left(1 - \frac{T_0+273.15}{T_{dv}[1]+273.15}\right) = \dot{m}_b[1] ex_{b[1]} + \dot{m}_{dv}[1] ex_{dv}[1] - c_p [1] (T_0 + 273.15) \ln \frac{T_b[1]+273.15}{T_f[1]+273.15} + EX_d[1] \quad (4.229)$$

### Thermal load of the first effect

The most important heat transfer area is the effect area where the boiling process takes place.

This area can be calculated from the following equation:

$$A_{\text{eff}}[1] = \frac{\dot{Q}_{\text{eff}}[1]}{U_{\text{eff}}[1] \text{LMTD}_{\text{eff}}[1]} \quad (4.230)$$

where  $A_{\text{eff}}[1]$  ( $\text{m}^2$ ) is the heat transfer area

$$\dot{Q}_{\text{eff}}[1] = \dot{m}_{19} (h_{19} - h_{119}) \quad (4.231)$$

$U_{\text{eff}}[1]$  ( $\frac{\text{kW}}{\text{m}^2 \text{K}}$ ): is the overall heat transfer coefficient for the first effect. This can be calculated

from the following correlation [40]:

$$U_{\text{eff}}[1] = 1.9394 + 1.40562 \times 10^{-3} T_b[1] - 2.07525 \times 10^{-5} (T_b[1])^2 + 2.3186 \times 10^{-6} T_b[1]^3 \quad (4.232)$$

$\text{LMTD}_{\text{eff}}[1]$ : is the log mean temperature difference, in degree Celsius. It can be calculated from the following equation:

$$\text{LMTD}_{\text{eff}}[1] = \frac{(T_{19} - T_b[1]) - (T_f[1] - T_{119})}{\ln \frac{(T_{19} - T_b[1])}{(T_f[1] - T_{119})}} \quad (4.233)$$

#### ▪ Effects 2 to N

The effects 2 to N can be represented by the control volume Figure 16. This figure was developed with the assistance to the model presented by Dall [45]. This control volume undergoes two processes in the effects:

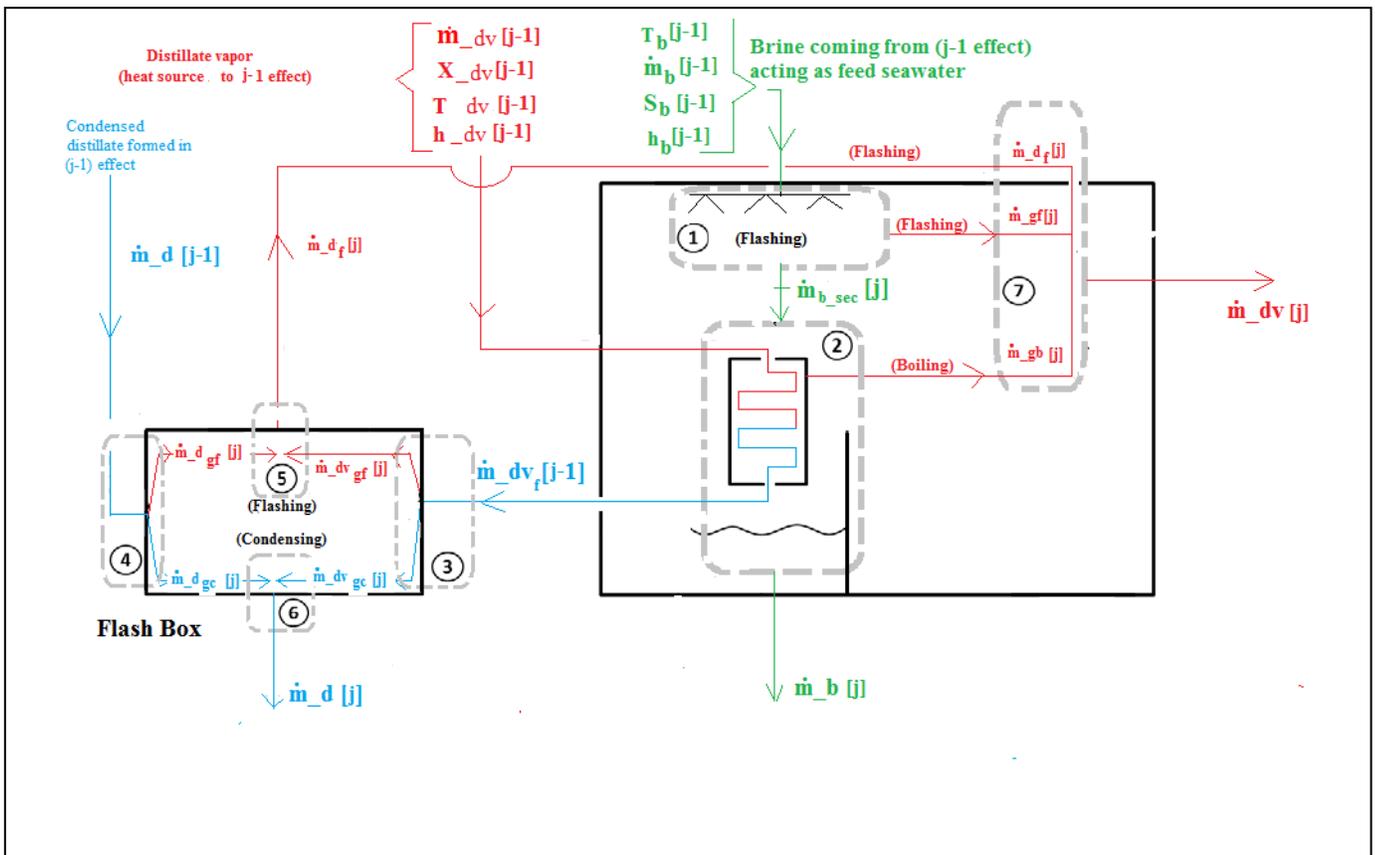
##### ○ Flashing

Brine feed seawater entering (j-1) effects undergo a flashing process through the control volume #1. This process will generate a distillate vapor with the mass flow rate ( $\dot{m}_{\text{gf}}[j]$ )

##### ○ Boiling

After flashing process in the control volume #1, the feed seawater (mass flow rate  $\dot{m}_{\text{f\_sec}}[j]$ ) will enter the control volume #2 where it is boiled by the latent heat of the distillate vapor ( $\dot{m}_{\text{dv}}[j-1]$ )

formed in the previous effect. The boiling process will generate the distillate vapor (mass flow rate  $\dot{m}_{gb} [j]$ ) that will be used as the source of heat for the next effect. After the boiling process, the remaining feed seawater called brine (mass flow rate  $\dot{m}_b [j]$ ) will exit the effect with an increase of its salinity ( $S_b[j]$ ). The particularly of the effects 2 to N is that they contained flash chambers.



**Figure 16:** Control volume for effect (2) to effect (N)

The role of flash chambers is to receive the condensate distillate water coming from the slightly superheated distillate vapor. Flash chambers will receive both the condensate distillate vapor ( $\dot{m}_{dv} [j-1]$ ) and condensate distillate water ( $\dot{m}_d [j-1]$ ) formed in the previous flash chambers. The mixture of these flow rates will allow the flash chambers to generate two processes:

- Flashing in the flash chambers: Control volume #5, generates the distillate vapor ( $\dot{m}_{df} [j]$ ) of the flash chamber
- Boiling in the flash chambers: Control volume #6, generates the distillate fresh water ( $\dot{m}_d [j]$ ) of the flash chamber. The total distillate vapor ( $\dot{m}_{dv} [j]$ ) of the effect j comes from the flashing of the seawater in the effect, the boiling the seawater in the effect and the flashing of the condensate distillate in the flash chamber. The control volume #7 described this total distillate vapor in j effect.

Four balance equations including mass, energy, entropy and exergy of the effect 2 to N were written as following:

Control Volume #1:

*Mass balance equation*

$$\dot{m}_b [j-1] = \dot{m}_{b\_sec} [j] + \dot{m}_{gf} [j] \quad (4.234)$$

*Salt balance equation*

$$\dot{m}_b [j-1] S_b[j-1] = \dot{m}_{b\_sec} [j] S_{b\_sec}[j] + \dot{m}_{gf} [j] S_{gf}[j] \quad (4.235)$$

where  $S_{gf}[j]$  is a pure vapor

$$S_{gf}[j] = 0 \quad (4.236)$$

By substituting the equation (4.236) into the equation (4.235), the following equation can be used to calculate the mass flow rate ( $\dot{m}_{b\_sec}[j]$ ) of the brine exiting the control volume #1:

$$\dot{m}_b [j-1] S_b[j-1] = \dot{m}_{b\_sec} [j] S_{b\_sec}[j] \quad (4.237)$$

where  $S_{b\_sec}[j]$  is the brine salinity rejected from the flashing control volume #1, which can be evaluated from the following relations:

$$S_{b\_sec}[j] = 0.9 \times (457628.5 - 11304.11T_b [j] + 107.5781(T_b [j])^2 - 0.360747(T_b [j])^3) \quad (4.238)$$

$S_{b\_sec}[j]$  will be in g/kg

*Energy balance equation*

$$\dot{m}_b [j-1] h_b [j - 1] = \dot{m}_{b\_sec} [j] h_{b\_sec} [j] + \dot{m}_{gf} [j] h_{gf} [j] \quad (4.239)$$

*Entropy balance equation*

$$\begin{aligned} \dot{m}_b [j-1] s_b [j - 1] + \dot{S}_{gen_{cv\#1}} [j] = \dot{m}_{b\_sec} [j] s_{b\_sec} [j] + \frac{\dot{m}_{gf} [j] h_{dv} [j]}{T_{dv} [j]} \\ - c_{p1} [j] \ln \frac{T_{b\_sec} [j] + 273.15}{T_b [j-1] + 273.15} \end{aligned} \quad (4.240)$$

where  $\dot{S}_{gen_{cv\#1}} [j]$ : is the the entropy generation in the control volume #1

*Exergy balance equation*

$$\dot{m}_b [j-1] ex [j - 1] = \dot{m}_{b\_sec} [j] ex_{b\_sec} [j] + \dot{m}_{gf} [j] ex_{gf} [j] + \dot{E}x_{d_{cv\#1}} [j] \quad (4.241)$$

where  $\dot{E}x_{d_{cv\#1}} [j]$  is the exergy destruction rate of the control volume #1

Control Volume #2:

*Mass balance equation*

$$\dot{m}_{b\_sec} [j] = + \dot{m}_{gb} [j] + \dot{m}_b [j] \quad (4.242)$$

$$\dot{m}_{dv} [j-1] = \dot{m}_{dvf} [j-1] \quad (4.243)$$

*Salt balance equation*

$$\dot{m}_{b\_sec} [j] S_{b\_sec} [j] = \dot{m}_{gb} [j] S_{gb} [j] + \dot{m}_b [j] S_b [j] \quad (4.244)$$

where  $S_{gb} [j]$  is a pure vapor

$$S_{gb} [j] = 0 \quad (4.245)$$

By substituting the equation (4.245) into the equation (4.244), the following equation can be used to calculated the mass flow rate of ( $\dot{m}_b [j]$ ):

$$\dot{m}_{b\_sec} [j] S_{b\_sec} [j] = \dot{m}_b [j] S_b [j] \quad (4.246)$$

where  $S_b [j]$  is the brine salinity rejected from the condensing control volume #2, which can be evaluated from the following relations:

$$S_b[j] = 0.9 \times (457628.5 - 11304.11T_b [j] + 107.5781(T_b [j])^2 - 0.360747(T_b [j])^3) \quad (4.247)$$

$S_b[j]$  will be in g/kg

*Energy balance equation*

$$\begin{aligned} \dot{m}_{dv} [j-1] h_{dv} [j - 1] + \dot{m}_{b\_sec} [j] h_{b\_sec} [j] &= \dot{m}_{dvf} [j-1] h_{dvf} [j - 1] \\ + \dot{m}_{gb} [j] h_{gb} [j] + \dot{m}_b [j] h_b [j] & \end{aligned} \quad (4.248)$$

where  $h_{dv}$ (kJ/kg): is the enthalpy of the distillate vapor entering the effect,  $h_{dvf}$ (kJ/kg) is the enthalpy of the condensate distillate vapor exiting the effect

*Entropy balance equation*

$$\begin{aligned} \dot{m}_{b\_sec} [j] s_{b\_sec} [j] + \dot{S}_{gen_{cv\#2}} [j] + \frac{\dot{Q}_{eff} [j]}{T_0 + 273.15} &= \dot{m}_b [j] s_b [j] + \frac{\dot{m}_{gb} [j] h_{dv} [j]}{T_{dv} [j]} \\ - c_{p2} [j] \ln \frac{T_b [j] + 273.15}{T_{dv} [j] + 273.15} & \end{aligned} \quad (4.249)$$

$s_{b\_sec} [j]$  (kJ/kg K): is the specific entropy of the brine after flashing in  $j^{th}$  effect

$s_b [j]$  (kJ/kg K): is the specific entropy of brine exiting  $j^{th}$  effect after boiling

$\dot{S}_{gen_{cv\#2}} [j]$ : is the the entropy generation in the control volume #2

*Exergy balance equation*

$$\begin{aligned} \dot{m}_{b\_sec} [j] ex_{b\_sec} [j] + \dot{Q}_{eff} [j] \left(1 - \frac{T_0 + 273.15}{T_{dv} [j] + 273.15}\right) &= \dot{m}_b [j] ex_b [j] + \dot{m}_{gb} [j] ex_{gb} [j] \\ - c_p [j] (T_0 + 273.15) \ln \frac{T_b [j] + 273.15}{T_b [j] + 273.15} \dot{E}x_{d_{cv\#2}} [j] & \end{aligned} \quad (4.250)$$

$ex_{b\_sec} [j]$  (kJ/kg): is the specific exergy of the brine after flashing in  $j^{th}$  effect

$ex_b [j]$  (kJ/kg): is the specific exergy of brine exiting  $j^{th}$  effect after boiling

$\dot{E}x_{d_{cv\#2}} [j]$ : is the exergy destruction rate of the control volume #2

Control Volume #3:

In the flash chamber, the incoming condensed distillate vapor ( $\dot{m}_{dvf}[j-1]$ ) is split into condensed distillate fresh water ( $\dot{m}_{dv_{gc}}[j]$ ) and distillate vapor generated ( $\dot{m}_{dv_{gf}}[j]$ ) through the flash chamber.

*Mass balance equation*

$$\dot{m}_{dvf}[j-1] = \dot{m}_{dv_{gc}}[j] + \dot{m}_{dv_{gf}}[j] \quad (4.251)$$

*Energy balance equation*

$$\dot{m}_{dvf}[j-1] h_{dvf}[j-1] = \dot{m}_{dv_{gc}}[j] h_{dv_{gc}}[j] + \dot{m}_{dv_{gf}}[j] h_{dv_{gf}}[j] \quad (4.252)$$

*Entropy balance equation*

$$\dot{m}_{dvf}[j-1] s_{dvf}[j-1] + \dot{S}_{gen_{cv\#3}}[j] = \dot{m}_{dv_{gc}}[j] s_{dv_{gc}}[j] + \dot{m}_{dv_{gf}}[j] s_{dv_{gf}}[j] \quad (4.253)$$

*Exergy balance equation*

$$\dot{m}_{dvf}[j-1] ex_{dvf}[j-1] = \dot{m}_{dv_{gc}}[j] ex_{dv_{gc}}[j] + \dot{m}_{dv_{gf}}[j] ex_{dv_{gf}}[j] + \dot{E}x_{d_{cv\#3}}[j] \quad (4.254)$$

Control Volume #4:

In the flash chamber, the distillate water coming from the previous flash chamber is split into condensed distillate fresh water ( $\dot{m}_{d_{gc}}[j]$ ) and distillate vapor generated ( $\dot{m}_{d_{gf}}[j]$ ) through the flash chamber.

*Mass balance equation*

$$\dot{m}_d[j-1] = \dot{m}_{d_{gc}}[j] + \dot{m}_{d_{gf}}[j] \quad (4.255)$$

*Energy balance equation*

$$\dot{m}_d[j-1] h_d[j-1] = \dot{m}_{d_{gc}}[j] h_{d_{gc}}[j] + \dot{m}_{d_{gf}}[j] h_{d_{gf}}[j] \quad (4.256)$$

*Entropy balance equation*

$$\dot{m}_d[j-1] s_d[j-1] + \dot{S}_{gen_{cv\#4}}[j] = \dot{m}_{d_{gc}}[j] s_{d_{gc}}[j] + \dot{m}_{d_{gf}}[j] s_{d_{gf}}[j] \quad (4.257)$$

*Exergy balance equation*

$$\dot{m}_d [j-1] \text{ex}_d [j - 1] = \dot{m}_{d_{gc}}[j] \text{ex}_{d_{gc}} [j] + \dot{m}_{d_{gf}}[j] \text{ex}_{d_{gf}} [j] + \dot{E}x_{d_{cv \#4}} [j] \quad (4.258)$$

Control Volume #5:

The total distillate vapor ( $\dot{m}_{d_f} [j]$ ) generated by the flash chamber is sent to the  $j^{\text{th}}$  effect and contributed to the formation of total distillate vapor release by the  $j^{\text{th}}$  effect.

*Mass balance equation*

$$\dot{m}_{d_{gf}}[j] + \dot{m}_{d_{v_{gf}}}[j] = \dot{m}_{d_f} [j] \quad (4.259)$$

*Energy balance equation*

$$\dot{m}_{d_{gf}}[j] h_{d_{gf}} [j] + \dot{m}_{d_{v_{gf}}}[j] h_{d_{v_{gf}}} [j] = \dot{m}_{d_f} [j] h_{d_f} [j] \quad (4.260)$$

*Entropy balance equation*

$$\dot{m}_{d_{gf}}[j] s_{d_{gf}} [j] + \dot{m}_{d_{v_{gf}}}[j] s_{d_{v_{gf}}} [j] + \dot{S}_{gen_{cv \#5}} [j] = \dot{m}_{d_f} [j] s_{d_f} [j] \quad (4.261)$$

*Exergy balance equation*

$$\dot{m}_{d_{gf}}[j] \text{ex}_{d_{gf}} [j] + \dot{m}_{d_{v_{gf}}}[j] \text{ex}_{d_{v_{gf}}} [j] = \dot{m}_{d_f} [j] \text{ex}_{d_f} [j] + \dot{E}x_{d_{cv \#4}} [j] \quad (4.262)$$

Control Volume #6:

The condensed distillate generated in the flash box is transferred to the next flash chamber.

*Mass balance equation*

$$\dot{m}_{d_{gc}}[j] + \dot{m}_{d_{v_{gc}}}[j] = \dot{m}_d [j] \quad (4.263)$$

*Energy balance equation*

$$\dot{m}_{d_{gc}}[j] h_{d_{gc}} [j] + \dot{m}_{d_{v_{gc}}}[j] h_{d_{v_{gc}}} [j] = \dot{m}_d [j] h_d [j] \quad (4.264)$$

*Entropy balance equation*

$$\dot{m}_{d_{gc}}[j] s_{d_{gc}} [j] + \dot{m}_{d_{v_{gc}}}[j] s_{d_{v_{gc}}} [j] + \dot{S}_{gen_{cv \#6}} [j] = \dot{m}_d [j] s_d [j] \quad (4.265)$$

*Exergy balance equation*

$$\dot{m}_{d_{gc}}[j] \text{ex}_{d_{gc}} [j] + \dot{m}_{d_{v_{gc}}}[j] \text{ex}_{d_{v_{gc}}} [j] = \dot{m}_d [j] \text{ex}_d [j] + \dot{E}x_{d_{cv \#6}} [j] \quad (4.266)$$

### Control Volume #7:

The total distillate vapor ( $\dot{m}_{dv}[j]$ ) generated in the  $j^{\text{th}}$  effect is the sum of the distillate vapor ( $\dot{m}_{gf}[j]$ ) comes from the flashing of the feed brine seawater, the boiling the feed brine ( $\dot{m}_{gb}[j]$ ) and the flashing of the condensate distillate in the flash chamber ( $\dot{m}_{df}[j]$ )

#### *Mass balance equation*

$$\dot{m}_{gf}[j] + \dot{m}_{gb}[j] + \dot{m}_{df}[j] = \dot{m}_{dv}[j] \quad (4.267)$$

#### *Energy balance equation*

$$\dot{m}_{gf}[j] h_{gf}[j] + \dot{m}_{gb}[j] h_{gb}[j] + \dot{m}_{df}[j] h_{df}[j] = \dot{m}_{dv}[j] h_{dv}[j] \quad (4.268)$$

#### *Entropy balance equation*

$$\dot{m}_{gf}[j] s_{gf}[j] + \dot{m}_{gb}[j] s_{gb}[j] + \dot{m}_{df}[j] s_{df}[j] + \dot{S}_{gen_{cv\#7}}[j] = \dot{m}_{dv}[j] s_{dv}[j] \quad (4.269)$$

#### *Exergy balance equation*

$$\dot{m}_{gf}[j] ex_{gf}[j] + \dot{m}_{gb}[j] ex_{gb}[j] + \dot{m}_{df}[j] ex_{df}[j] = \dot{m}_{dv}[j] ex_{dv}[j] + \dot{E}x_{d_{cv\#7}}[j] \quad (4.270)$$

#### *Thermal load of the $j^{\text{th}}$ effect*

Heat transfer area of  $j^{\text{th}}$  effect can be calculated from the following equation:

$$A_{eff}[j] = \frac{\dot{Q}_{eff}[j]}{U_{eff}[j] (T_{dv}[j-1] - T_b[j])} \quad (4.271)$$

where  $A_{eff}[j]$  ( $m^2$ ) is the heat transfer area

$$\dot{Q}_{eff}[j] = \dot{m}_{dv}[j-1] (h_{dv}[j-1] - h_{dvf}[j-1]) \quad (4.272)$$

$U_{eff}[j]$  ( $\frac{kW}{m^2 K}$ ): is the overall heat transfer coefficient for the  $j^{\text{th}}$  effect. This can be calculated

from the following correlation [40]:

$$U_{eff}[j] = 1.9394 + 1.40562 \times 10^{-3} T_{dv}[j-1] - 2.07525 \times 10^{-5} (T_{dv}[j-1])^2 + 2.3186 \times 10^{-6} (T_{dv}[j-1])^3 \quad (4.273)$$

#### ▪ **Last Effect Condenser**

The distillate vapor ( $\dot{m}_{dv}[N]$ ) generated in the last effect is completely condensed to the saturated vapor ( $\dot{m}_{dvf}[N]$ ) at the last condenser in Figure 17 through the control volume #8. After the condensation, the saturated vapor will combine (in control volume #9) with the distillate fresh water coming from the last flash chamber. The total distillate fresh water ( $\dot{m}_{28}$ ) produced by the system is then collected at state (28).

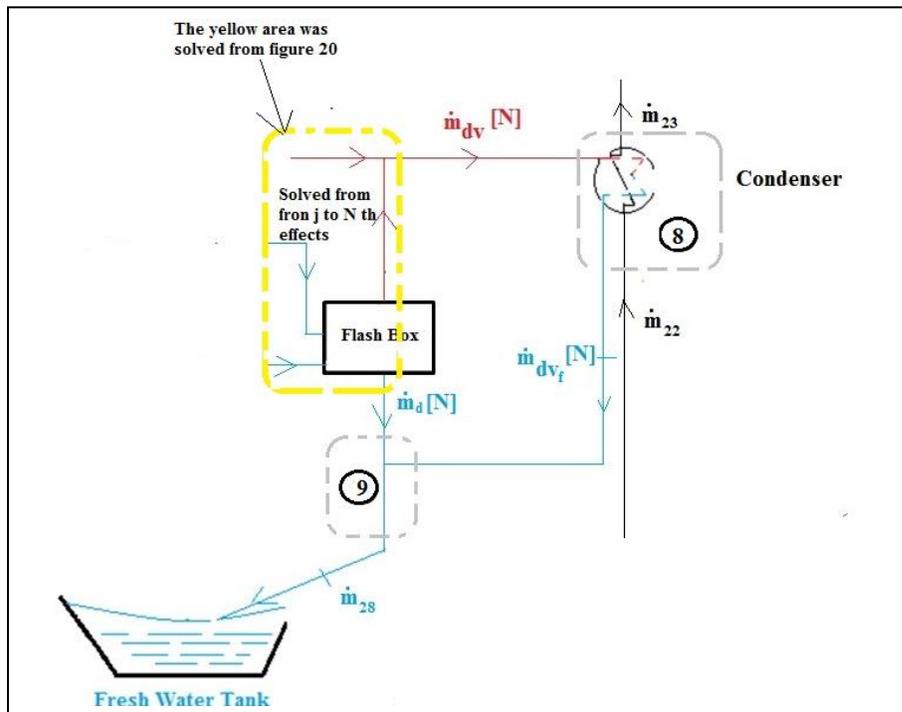
Four balance equations including mass, energy, entropy and exergy of the last condenser were written as following:

Control Volume #8

*Mass balance equation*

$$\dot{m}_{dv}[N] = \dot{m}_{dvf}[N] \tag{4.274}$$

$$\dot{m}_{22} = \dot{m}_{23} \tag{4.275}$$



**Figure 17:** Last effect condenser

*Energy balance equation*

$$\dot{m}_{dv}[N] h_{dv}[N] + \dot{m}_{22} h_{22} = \dot{m}_{dvf}[N] h_{dvf}[N] + \dot{m}_{23} h_{23} \quad (4.276)$$

*Entropy balance equation*

$$\dot{m}_{dv}[N] s_{dv}[N] + \dot{m}_{22} s_{22} + \dot{S}_{genlast\ cond} = \dot{m}_{dvf}[N] s_{dvf}[N] + \dot{m}_{23} s_{23} \quad (4.277)$$

*Exergy balance equation*

$$\dot{m}_{dv}[N] ex_{dv}[N] + \dot{m}_{22} ex_{22} = \dot{m}_{dvf}[N] ex_{dvf}[N] + \dot{m}_{23} ex_{23} + \dot{E}X_{dvlast\ cond} \quad (4.278)$$

*Thermal load of the last condenser*

Heat transfer area of the last condenser can be calculated from the following equation:

$$A_{last\ cond} = \frac{\dot{Q}_{Last\ cond}}{U_{last\ cond} LMTD_{last\ cond}} \quad (4.279)$$

where  $A_{last\ cond}$  ( $m^2$ ) is the heat transfer area

$$\dot{Q}_{Last\ cond} = \dot{m}_{22} (h_{23} - h_{22}) \quad (4.280)$$

$\dot{Q}_{Last\ cond}$ : is in kW

$U_{last\ cond}$  ( $\frac{kW}{m^2\ K}$ ): is the overall heat transfer coefficient for the last condenser. This can be

calculated from the following correlation [40]:

$$U_{last\ cond} = 1.6175 + 1.537 \times 10^{-4} T_{dv}[N] - 1.825 \times 10^{-4} (T_{dv}[N])^2 + 8.026 \times 10^{-8} (T_{dv}[N])^3 \quad (4.281)$$

$$LMTD_{last\ cond} = \frac{(T_{23} - T_{22})}{\ln\left(\frac{T_{dv}[N] - T_{22}}{T_{dv}[N] - T_{23}}\right)} \quad (4.282)$$

Control Volume #9

*Mass balance equation*

$$\dot{m}_d[N] + \dot{m}_{dvf}[N] = \dot{m}_{28} \quad (4.283)$$

*Energy balance equation*

$$\dot{m}_d[N] h_d[N] + \dot{m}_{dvf}[N] h_{dvf}[N] = \dot{m}_{28} h_{28} \quad (4.284)$$

*Entropy balance equation*

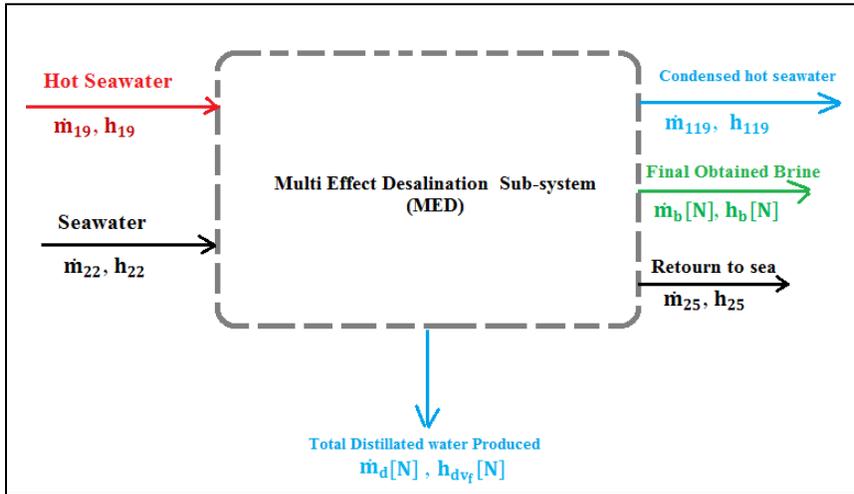
$$\dot{m}_d[N] s_d[N] + \dot{m}_{dvf}[N] s_{dvf}[N] + \dot{S}_{gen_{conv\#9}} = \dot{m}_{28} s_{28} \quad (4.285)$$

*Exergy balance equation*

$$\dot{m}_d[N] ex_d[N] + \dot{m}_{dvf}[N] ex_{dvf}[N] = \dot{m}_{28} ex_{28} + \dot{E}X_{dv_{conv\#9}} \quad (4.286)$$

- **MED total control volume**

The total control volume in Figure 18 is the representation of the mass flow rates that enter and exit the multi effect desalination subsystem at each state. The most important parameter in Figure 18 is the heating source at state (19), the feeding seawater at state (22) and the total distilled water produced by the subsystem.



**Figure 18:** MED total control volume

*Mass balance equation*

$$\dot{m}_{19} + \dot{m}_{22} = \dot{m}_d[N] + \dot{m}_{25} + \dot{m}_{119} + \dot{m}_b[N] \quad (4.287)$$

*Energy balance equation*

$$\dot{m}_{19} h_{19} + \dot{m}_{22} h_{22} = \dot{m}_d[N] h_{dvf}[N] + \dot{m}_{25} h_{25} + \dot{m}_{119} h_{119} + \dot{m}_b[N] h_b[N] \quad (4.288)$$

*Entropy balance equation*

$$\dot{m}_{19} s_{19} + \dot{m}_{22} s_{22} + \dot{S}_{gen_{MED}} = \dot{m}_d[N] s_{dvf}[N] + \dot{m}_{25} s_{25} + \dot{m}_{119} s_{119} + \dot{m}_b[N] s_b[N] \quad (4.289)$$

*Exergy balance equation*

$$\begin{aligned} \dot{m}_{19} ex_{19} + \dot{m}_{22} ex_{22} = \dot{m}_d [N] ex_{dvf}[N] + \dot{m}_{25} ex_{25} + \dot{m}_{119} ex_{119} \\ + \dot{m}_b [N] ex_b [N] + EX_{dvMED} \end{aligned} \quad (4.290)$$

▪ **Pump #4 (P4)**

*Mass balance equation*

$$\dot{m}_b [N] = \dot{m}_{26} \quad (4.291)$$

$$\dot{m}_{27} = \dot{m}_{26} \quad (4.292)$$

where  $\dot{m}_b [N]$  represent the mass flow rate of brine leaving the last effect.

*Energy balance equation*

$$\dot{m}_{26} h_{26} + \dot{W}_{P4} = \dot{m}_{27} h_{27} \quad (4.293)$$

*Entropy balance equation*

$$\dot{m}_{26} s_{26} + \dot{S}_{gen\_P4} = \dot{m}_{27} s_{27} \quad (4.294)$$

*Exergy balance equation*

$$\dot{m}_{26} ex_{26} + \dot{W}_{P4} = \dot{m}_{27} ex_{27} + \dot{E}_{xdP4} \quad (4.295)$$

where  $\dot{W}_{P4}$  (Kw) represents the work of pump (P4). This can be calculated by using the following equation:

$$\dot{W}_{P4} = \frac{\dot{m}_{26} \Delta H_{P4} g}{\eta_{P4}} \quad (4.296)$$

where  $\dot{m}_{26}$  (kg/s) is the mass flow rate of brine exiting the last effect N and return to the sea,  $\eta_{P4}$  is pump (P4) efficiency,  $\Delta H_{P4}$  (m) is the total pump head difference of the piping where the brine is returning to the sea. This can be calculated from the following equation:

$$\Delta H_{P4} = (\Delta H_{P4})_{SH} + [(\Delta H_{P4})_{SP} + (\Delta H_{P4})_M] \quad (4.297)$$

where  $(\Delta H_{P4})_{SH}$  is static head of the pump (P4). It is in (m).  $(\Delta H_{P4})_{SH}$  can be calculated from the following equation:

$$(\Delta H_{P4})_{SH} = h_{L4} - h_{L04} \quad (4.298)$$

where  $h_{L4}$  (m) is the suction level of the brine from the datum,  $h_{L04}$  (m); is the bottom discharge level of the brine from the datum,  $(\Delta H_{P4})_{SP}$  is Minors losses in straight return pipe (SP). It is in (m).  $(\Delta H_{P4})_{SP}$  can be calculated from the following equation:

$$(\Delta H_{P4})_{SP} = \sum \frac{f_{Br} L_{Br} V_{Br}^2}{ID_{Br} 2g} \quad (4.299)$$

$(\Delta H_{P4})_M$  is minor losses due to the entrance, bending, valves and exit on the brine returning pipe. It is in (m).  $(\Delta H_{P4})_M$  can be calculated from the following equation:

$$(\Delta H_{P4})_M = \sum k_{Br} \frac{V_{Br}^2}{2g} \quad (4.300)$$

**Table 7:** Total minor losses for pump (P4)

Components	Quantity	Minor losse For $25 \text{ mm} \leq ID_{Br} < 500 \text{ mm}$	Total minot losses $(\sum k_{Br})$
90° Elbow	$\alpha_4$	$0.21 (ID_{Br})^{-0.23}$	$0.21 \alpha_4 (ID_{Br})^{-0.23}$
Tee	$\beta_4$	$0.061 (ID_{Br})^{-0.46}$	$0.061 \beta_4 (ID_{Br})^{-0.46}$
Gate Valve	$\gamma_4$	$0.02 (ID_{Br})^{-1.14}$	$0.02 \gamma_4 (ID_{Br})^{-1.14}$

$$\sum k_{Br} = 0.21 \alpha_4 (ID_{Br})^{-0.23} + 0.061 \beta_4 (ID_{Br})^{-0.46} + 0.02 \gamma_4 (ID_{Br})^{-1.14} \quad (4.303)$$

Here  $f_{Br}$  is the turbulent flow friction factor coefficient for brine return piping. This can be calculated from the following equation:

$$f_{Br} = \left\{ -0.782 \ln \left[ \frac{6.9}{Re_{Br}} + \left( \frac{\varepsilon}{3.7 ID_{Br}} \right)^{1.11} \right] \right\}^{-2} \quad (4.301)$$

$L_{Br}$  (m), is the length of the return piping (m)

$V_{Br}$  is the velocity (m/s) of the return brine

$g$  is gravitational constant (9.81 m/s<sup>2</sup>)

$ID_{Br}$  is the hydraulic diameter (m) of returning brine piping

Here  $\varepsilon$  is the roughness of the pipe. For Commercial steel,  $\varepsilon = 4.572 \times 10^{-5}$  m

$Re_{Br}$  is the Reynolds Number of brine

$$Re_{Br} = \frac{\rho V_{cwr} ID_{cwr}}{\mu} = \frac{4 \dot{m}_{26}}{\mu \pi ID_{cwr}} \quad (4.302)$$

## 4.6 System performances

### 4.6.1 Steam rankine power cycle

*Energy efficiency*

This is defined as the ratio of the total net power output (in Figure 9) and the energy rate of the geothermal fluid in the reservoir.

$$\eta_{\text{energy}} = \frac{\dot{W}_{\text{HPT}} + \dot{W}_{\text{LPT}}}{\dot{m}_1 (h_1 - h_0)} \quad (4.304)$$

*Exergy efficiency*

This is defined as the ratio of the total net power output (in Figure 9) and exergy rate of the geothermal fluid at the reservoir.

$$\eta_{\text{exergy}} = \frac{\dot{W}_{\text{HPT}} + \dot{W}_{\text{LPT}}}{\dot{m}_1 ex_1} \quad (4.305)$$

### 4.6.2 Absorber chiller cooling cycle

*Energy efficiency*

This can be defined as the energetic coefficient of performance for the absorption chiller ( $COP_{en, \text{chiller}}$ )

$$COP_{\text{en, chiller}} = \frac{\dot{Q}_{\text{Evap}_1}}{\dot{Q}_{\text{Gen}} + \dot{W}_{P2}} \quad (4.306)$$

*Exergy efficiency*

The exergetic coefficient of performance for the absorption chiller ( $COP_{ex, \text{chiller}}$ )

$$\text{COP}_{\text{ex, chiller}} = \frac{\dot{Q}_{\text{Evap},1} \left(1 - \frac{T_0}{T_{\text{Evap},1}}\right)}{\dot{Q}_{\text{Gen}} \left(1 - \frac{T_0}{T_{\text{Gen}}}\right) + \dot{W}_{P2}} \quad (4.307)$$

### 4.6.3 Heating cycle

*Energy efficiency*

This can be defined as the ratio of the energy produce to the energy introduce to this space.

$$\eta_{\text{enHE}} = \frac{\dot{m}_{45} h_{45}}{\dot{m}_{46} h_{46}} \quad (4.308)$$

*Exergy efficiency*

This can be defined as the ratio of the exergy rate destroyed by this space to the exergy introduce to the space.

$$\eta_{\text{exHE}} = \frac{\dot{m}_{45} \text{ex}_{45}}{\dot{m}_{46} \text{ex}_{46} + \dot{Q}_{\text{HE}} \left(1 - \frac{T_0}{T_{\text{HR}}}\right)} \quad (4.309)$$

### 4.6.4 MED fresh water production

The performances of this subsystem are explained by Binamer [39]. These can be characterized by the following:

*Gain output ratio (GOR)*

This is defined as the ratio of the total distillate water produced ( $\dot{m}_{28}$ ) in Figure 17 to the motive hot seawater from the cylindrical parabolic solar system (Figure 11).

$$\text{GOR} = \frac{\dot{m}_{28}}{\dot{m}_{19}} \quad (4.310)$$

*Specific heat consumption (Q)*

This is defined as the thermal energy consumed by the system to produce 1 kg of distillate water.

$$Q = \frac{\dot{m}_{19} h_{19}}{\dot{m}_{28}} \quad (4.311)$$

$h_{19}$  (kJ/kg); is the motive steam latent heat

Q is the most important characteristic of thermal desalination system.

Total specific heat transfer area ( $A_t$ )

The total specific area of MED is defined by the following equation:

$$A_t = A_{eff}[1] + \sum_{j=2}^{N-1} A_{eff}[j] + A_{eff}[N] + A_{last\ cond} \quad (4.312)$$

#### 4.6.5 The overall efficiencies of the system

Overall total net power of the System

$$\dot{W}_{net,system} = (\dot{W}_{HPT} + \dot{W}_{LPT}) - [(\dot{W}_{P1} + \dot{W}_{P2} + \dot{W}_{P3} + \dot{W}_{P4})] \quad (4.313)$$

Energy efficiency of system

$$\eta_{en, system} = \frac{\dot{W}_{net,system}}{\dot{Q}_{SF}} \quad (4.314)$$

Exergy efficiency of system

$$\begin{aligned} \eta_{ex, System} = & \frac{\dot{W}_{net,rc} + \dot{Q}_{Cond,1} \left(1 - \frac{T_0}{T_{Cond,1}}\right) + \dot{Q}_{Cond,2} \left(1 - \frac{T_0}{T_{Cond,2}}\right)}{\dot{Q}_{SF} \left(1 - \frac{T_0}{T_{SF}}\right)} \\ & + \frac{\dot{Q}_{eff}[1] \left(1 - \frac{T_0}{T_b[1]}\right) + \dot{Q}_{eff}[j] \left(1 - \frac{T_0}{T_b[j]}\right) + \dot{Q}_{eff}[j-1] \left(1 - \frac{T_0}{T_b[j-1]}\right)}{\dot{Q}_{SF} \left(1 - \frac{T_0}{T_{SF}}\right)} \\ & + \frac{\dot{Q}_{eff}[N] \left(1 - \frac{T_0}{T_b[N]}\right) + \dot{Q}_{Last\ Cond} \left(1 - \frac{T_0}{T_{Last\ Cond}}\right) + \dot{Q}_E \left(1 - \frac{T_0}{T_E}\right)}{\dot{Q}_{SF} \left(1 - \frac{T_0}{T_{SF}}\right)} \end{aligned} \quad (4.315)$$

## Chapter 5: Results and Discussion

This chapter includes the data containing the parameters that were assumed and used for this project. The input data and the analyses equations in chapter 4 were processed through the engineering equation solver software.

### 5.1 Steam rankine power cycle

The data in Table 8 was used as the initial condition of the geothermal fluid and its temperature at the condenser.

**Table 8:** Input source data geothermal steam rankine power cycle

Source		Well	Fluid state	Condenser temperature
Temperature	Pressure	Flow rate	Liquid	
$T_1 = 260^\circ\text{C}$	$P_1 = 19.05 \text{ bar}$	$\dot{m}_1 = 179.1 \text{ kg/s}$	The quality at $x_1 = 0$	$T_{11} = 65^\circ\text{C}$

The temperatures, pressures and net output power of the steam rankine power cycle were assumed based on so-called “on design method”. This method gives a designer the possibility of selecting the input variables. In order to performance the analyses of the low pressure turbine, it is necessary to know the net output power of the power cycle. For the steam rankine power cycle, the net power output was assumed to be 25 MW. The enthalpy, the specific entropy and exergy at each state were calculated and the results were recorded in Table 9. By multiplying the specific exergy ( $ex$ ) with the mass flow rate ( $\dot{m}$ ), the exergy rate of the working fluid can be calculated at each state. The exergy destruction rate of each component was calculated by applying the principal of equation (4.3). As showed in Figure 19, the most exergy destruction rate happened in the condenser #1.

**Table 9:** States conditions for the power cycle

State #	Temperature T (°C)	Pressure P (kPa)	Mass flow rate $\dot{m}$ (kg/s)	Enthalpy h(kJ/kg)	Entropy s(kJ/kg-K)	Specific exergy ex (kJ/kg)
0	0	101.3		83.93	0.2962	
1	260	1905	179.16	897.5	2.884	55.03
2	198.3	1500	179.16	844.9	2.315	169.2
3	154.1	530	179.16	844.9	2.34	161.8
4	154.1	530	16.62	2751	6.802	760.2
5	98.22	95	16.62	2503	6.919	477.7
6	154.1	530	162.54	649.9	1.884	100.6
7	98.22	95	162.54	649.9	1.929	87.41
8	98.22	95	17.14	2673	7.376	513.5
9	98.22	95	33.76	2589	7.151	495.9
10	98.22	95	33.76	1971	5.486	365.6
11	65	95	33.76	411.5	0.8933	286.4
12	98.22	95	145.4	411.5	1.287	37.18
15	28	101.3	2.268	419.1	0.4088	302.1
16	30.56	101.3	2.268	419.1	0.4442	291.7

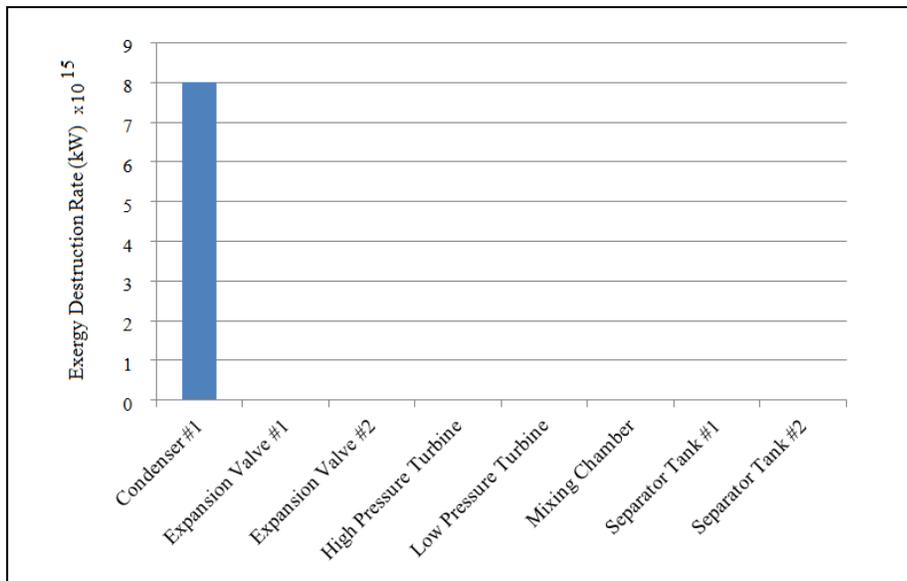
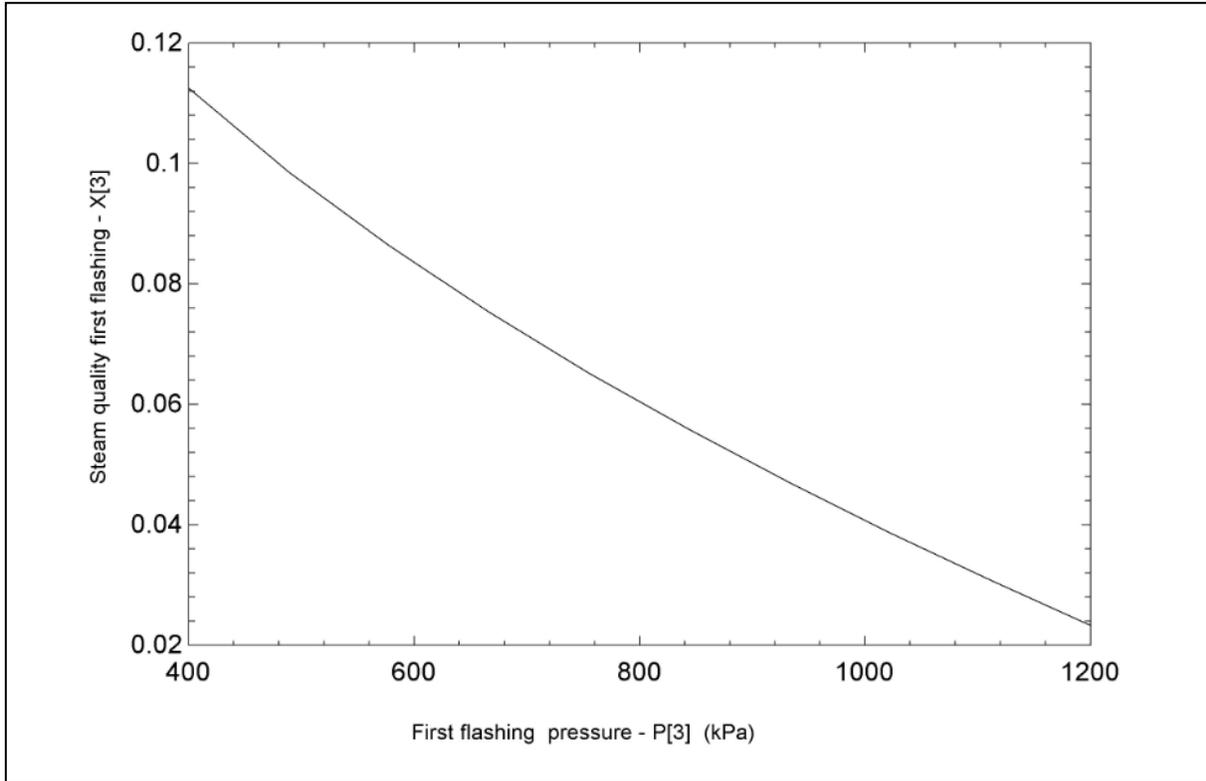
**Figure 19:** Exergy destruction rate for the components in the power cycle

Figure 20 shows the relationship between the flashing pressure and the steam quality. By decreasing the flashing pressure, the quality of the steam gained will increase. This means that more steam can be produced during the flashing. However, to avoid the scaling formation in the

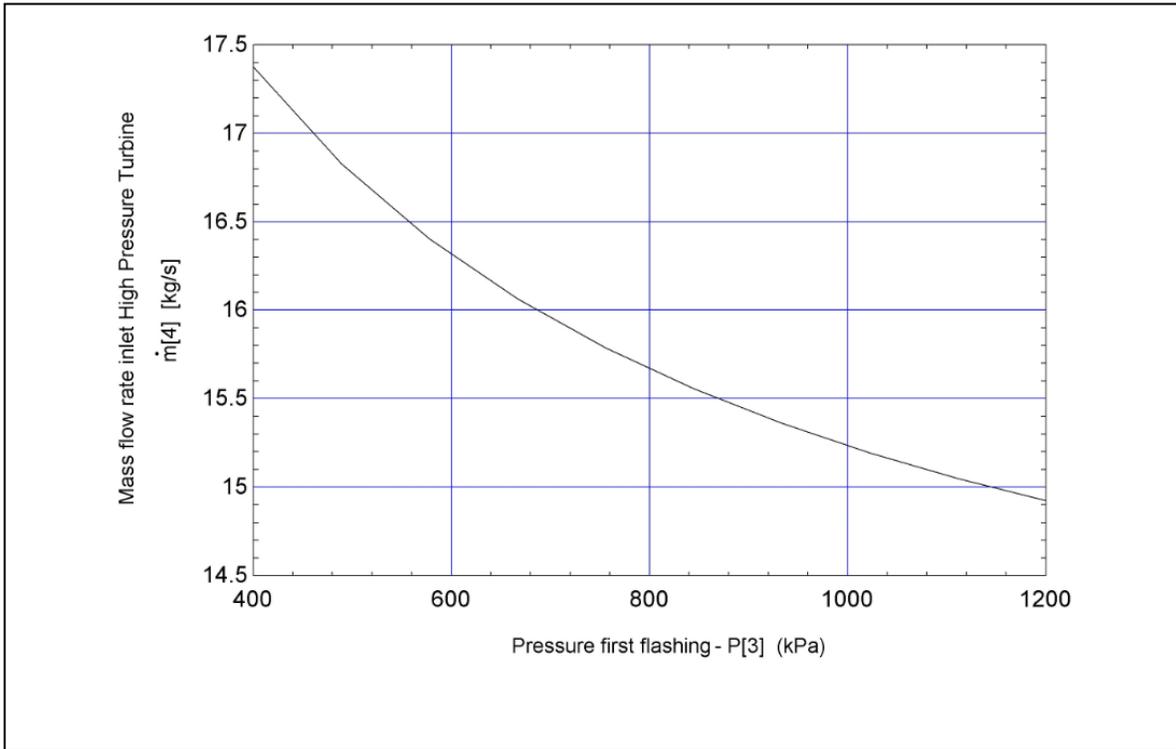
power plant due to the geothermal dissolved minerals, the flashing pressure shall not be decreased to the minimum.



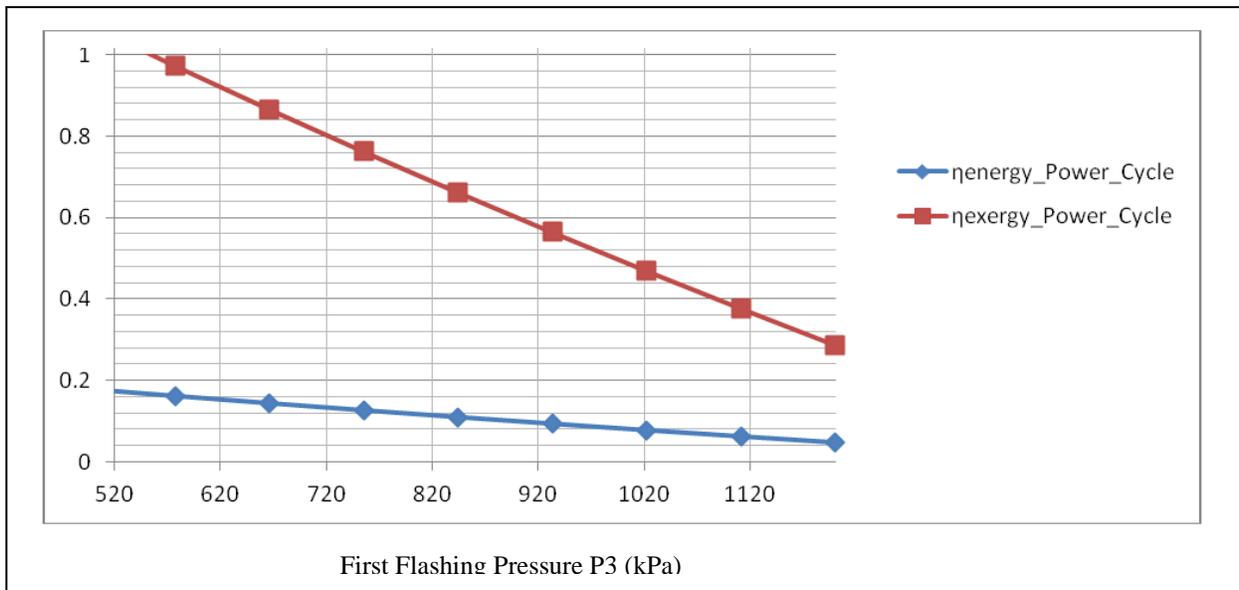
**Figure 20:** Flashing pressure vs steam quality

The relationship between the flashing pressure and the mass flow rate of the steam gained is represented in Figure 21 . The mass flow rate of the steam gained is also increasing as the flashing pressure decreased.

The relationship between the flashing pressure, the energy and exergy efficiencies of the power cycle is represented in Figure 22 . The energy and exergy efficiencies increase as the flashing pressure decreases. This means that a research of an optimum flashing pressure where the maximum energy and exergy efficiency shall be performed in order of getting the maximum net power output the cycle.



**Figure 21:** Mass Flow rate vs flashing pressure



**Figure 22:** Flashing pressure vs energy and exergy efficiencies

Figure 23 shows the relationship between the geothermal well temperature, the energy and exergy efficiencies of the power cycle. As the well temperature decreases, both energy and exergy efficiency will decrease. From this Figure 23, the higher energy efficiency of the cycle will be obtained from the well temperature of 250°C to above.

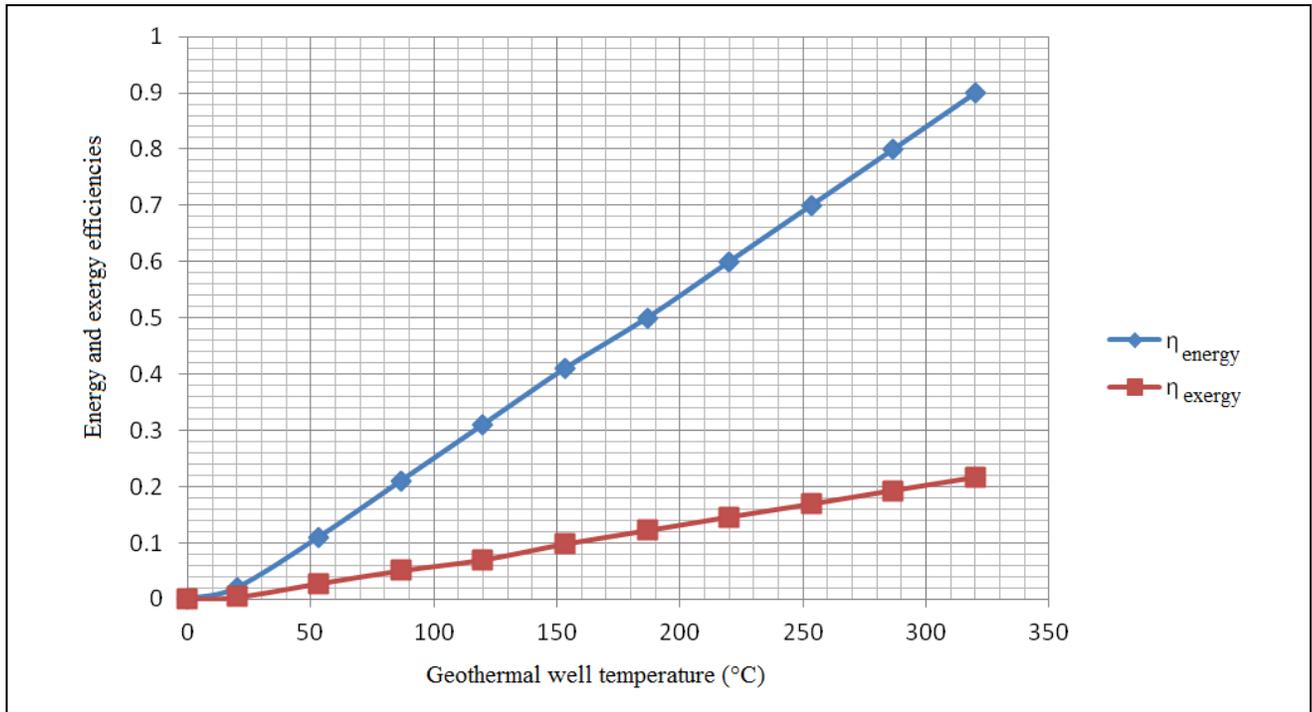


Figure 23: Geothermal well temperature vs energy and exergy efficiencies

## 5.2 Absorption chiller cooling

The Input data of LiBr/H<sub>2</sub>O is described for each state point in the following Table 10. The thermodynamics properties of the states were evaluated through the appropriated governing equations described in section 4.2 by using the Engineering Equation Solver (EES) software.

For this cooling cycle, the enthalpy, the specific entropy and exergy of each state was calculated and the results were recorded in Table 11 . By multiplying the specific exergy (ex) with the mass flow rate ( $\dot{m}$ ), the exergy rate of the working fluid can be calculated at each state.

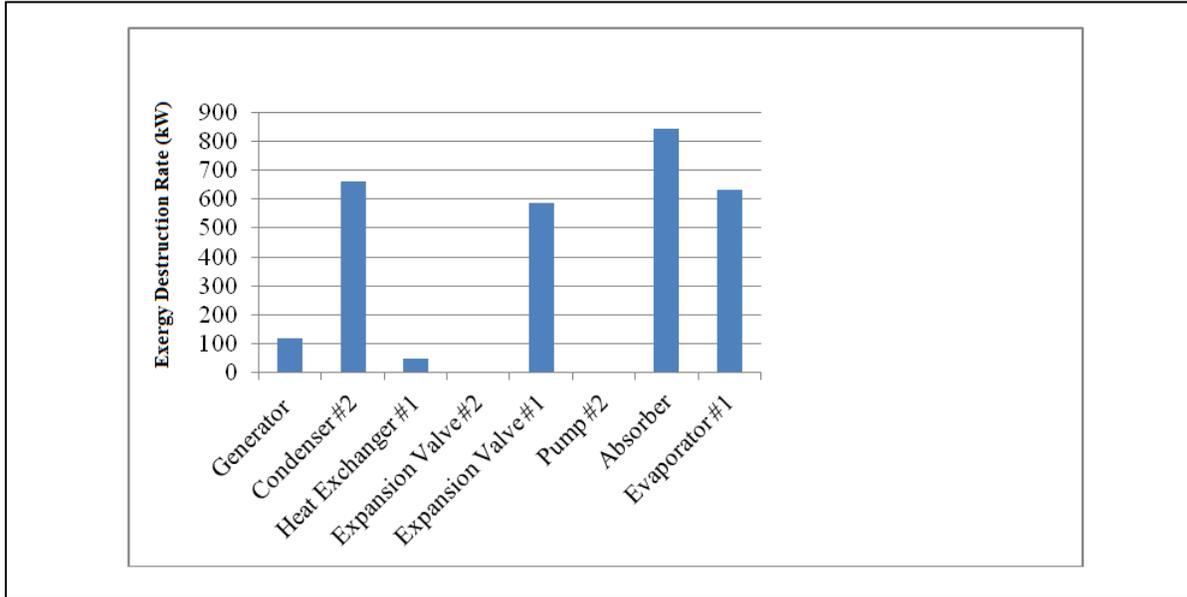
**Table 10:** Input data assumptions at each state for Figure 10

State point	Working Fluid	Temperature (°C)
13	Geothermal Warm Water	83.22
29	Saturated Cold Water	23.9
30	Saturated Warm Water	35
31	Saturated Weak Solution LiBr/H <sub>2</sub> O	40
32	Saturated Weak Solution LiBr/H <sub>2</sub> O	40
33	Saturated Weak Solution LiBr/H <sub>2</sub> O	73.97
34	Strong Solution LiBr/H <sub>2</sub> O	83.22
35	Strong Solution LiBr/H <sub>2</sub> O	40.86
36	Strong Solution LiBr/H <sub>2</sub> O	40.86
37	Superheated H <sub>2</sub> O Vapor (refrigerant)	83.22
38	Condensed Vapor water (refrigerant)	50
39	Water (refrigerant)	5
40	Water (refrigerant)	5
41	Warm Air	25
42	Cold Air	5
43	Water (refrigerant)	23.9
44	Water (refrigerant)	35

**Table 11:** States conditions for the absorber chiller cooling cycle

State #	Temperature T (°C)	Pressure P (kPa)	Mass Flow Rate $\dot{m}$ (kg/s)	Enthalpy h(kJ/kg)	Specific Entropy s(kJ/kg-K)	Specific Exergy $e_x$ (kJ/kg)
13	83.22	95	145.4	348.5	1.113	24.99
29	23.9	101.3	160.1	100.2	0.3515	0.1004
30	35	101.3	160.1	146.7	0.5050	1.543
31	40	0.872	25.64	113.9	0.4961	28.64
32	40	4.266	25.64	113.9	0.4961	28.64
33	73.97	4.266	25.64	221	0.8240	17.62
34	83.22	4.266	22.46	227.4	0.8389	15.58
35	40.86	4.266	22.46	105.1	0.4717	30.28
36	40.86	4.266	22.46	105.1	0.4717	30.28
37	83.22	4.266	3.186	2656	7.567	440.4
38	50	4.266	3.186	209.3	0.7037	5.924
39	5	0.872	3.186	209.3	0.07626	189.9
40	5	0.872	3.186	2510	9.024	132.6
41	25	101.3	16974	298.4	6.859	1709
42	5	101.3	16974	278.3	6.789	1709
43	23.9	101.3	167.9	100.2	0.3515	0.1004
44	35	101.3	167.9	146.7	0.505	1.543

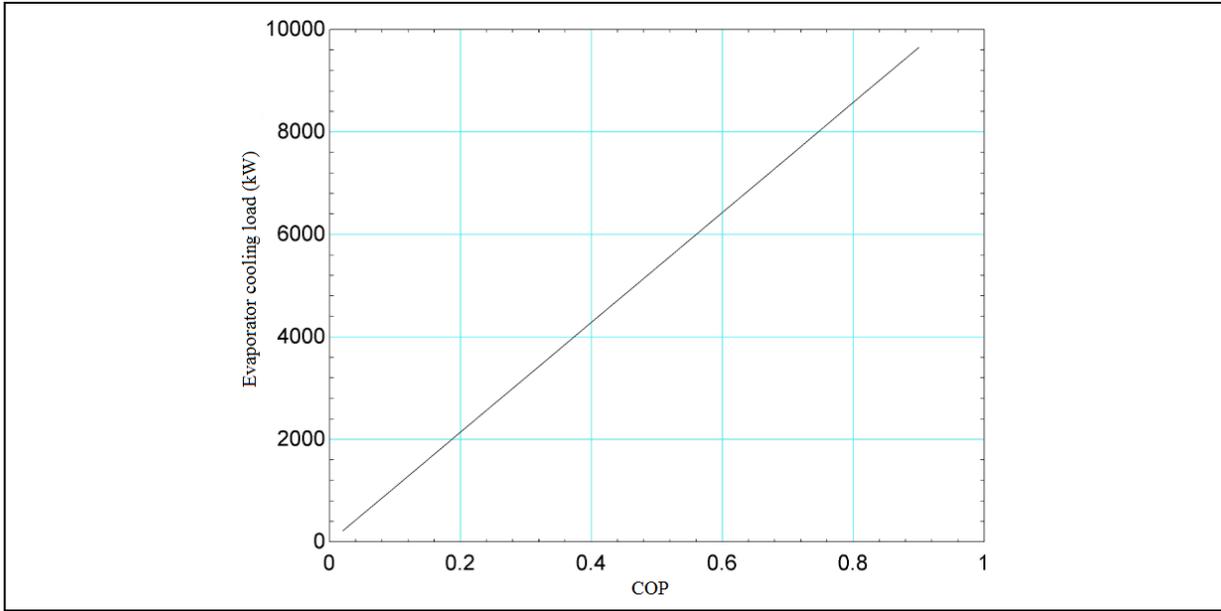
The exergy destruction rate of each component was calculated by applying the principal of equation (4.3). As showed in Figure 24, the most exergy destruction rate happened in the absorber.



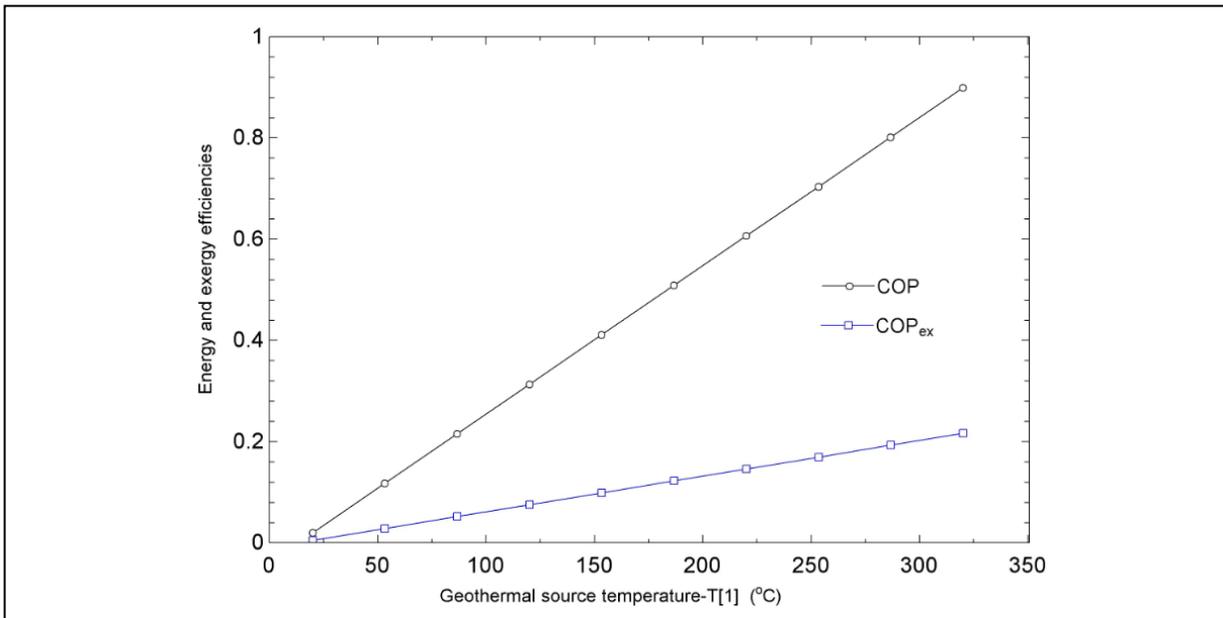
**Figure 24:** Exergy Destruction Rate for the Absorber Chiller Cooling Components

The evaporator cooling load is a function of the coefficient of performance (COP) of the cycle. Figure 25 shows the relationship between the cooling load and the COP of the cycle. As the COP decreases, the required will also decreased. This is very when sizing a cooling unit.

Figure 26 represents the relationship between the geothermal well temperature, the energy COP and the exergy COP. As the well temperature decreases, both the energy COP and exergy COP will decrease. The higher energy COP is achieved when the geothermal well temperature is greater or equal to 250°C.



**Figure 25:** COP vs Evaporator Cooling Load



**Figure 26:** Geothermal well temperature vs energy and exergy efficiencies

### 5.3 Heating space

The Input data of the heating cycle is described for each state point in the following table 12. The thermodynamics properties of the states were evaluated through the appropriated governing equations described in section 4.2 by using the Engineering Equation Solver (EES) software.

For this heating cycle, the enthalpy, the specific entropy and exergy of each state was calculated and the results were recorded in Table 13 .

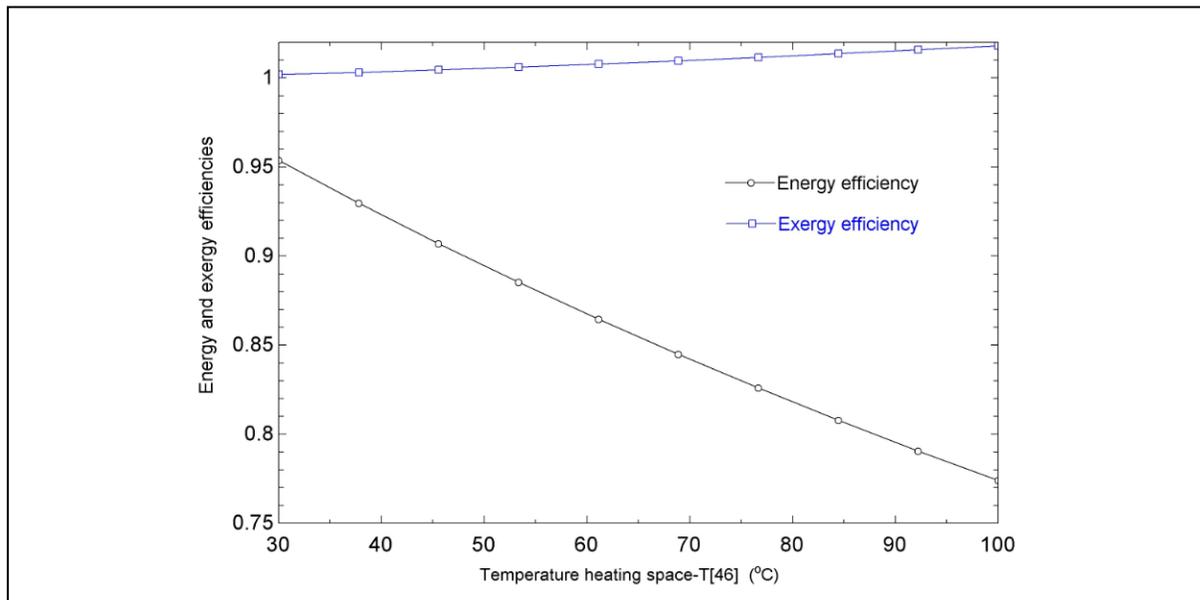
**Table 12:** Input data at each state for Figure 13

State point	Working Fluid	Temperature (°C)	Pressure (kPa)
14	Geothermal Warm Water	78.22	95
45	Cold Air	16	101.3
46	Warm Air	28	101.3

**Table 13:** States conditions for the heating cycle

State #	T (°C)	P (kPa)	$\dot{m}$ (kg/s)	h(kJ/kg)	s(kJ/kg-K)	ex (kJ/kg)
14	78.22	95	145.4	327.5	1.054	21.39
45	16	101.3	252.5	289.5	5.665	1368
46	28	101.3	252.5	301.6	5.706	1368

Figure 27 represents the relationship between heating space temperature, the energy and the exergy efficiencies. As heating space temperature decreases, the energy efficiency will increase. However, the exergy efficiency will decrease as the heating space temperature decreases



**Figure 27:** Space heating temperature vs energy and exergy efficiencies

## 5.4 Cylindrical parabolic concentrator solar field

The Input data of the cylindrical parabolic concentrator solar field is described for each state point in the Tables 14, 15 and 16. The thermodynamics properties of the states were evaluated through the appropriated governing equations described in section 4.2 by using the Engineering Equation Solver (EES) software.

- Pump#1 (P1) and Pump#4 (P4)

Table 14: Input data for pumps P1 and P4

Warm seawater & Brine level	$h_{L1} = h_{L4} = 15 \text{ m}$
Bottom warm seawater and Brine level	$h_{L01} = h_{L04} = 0$
length of the suction pipe (m) warm seawater and brine	$L_{wWS} = L_{Br} = 50 \text{ m}$
hydraulic diameter (m) of the suction pipe for warm seawater and Brine	$ID_{wWS} = ID_{Br} = 0.70 \text{ m}$
Efficiency Pumps	$\eta_{P1} = \eta_{P4} = 0.89$
Warm seawater mass flow rate at the states 17 and 21	Calculated
Number of 90° elbow	$\alpha_2 = \alpha_4 = 4$
Number of tee	$\beta_2 = \beta_4 = 1$
Number of Gate Valve	$\gamma_2 = \gamma_4 = 2$
Warm seawater temperature	$T_{17} = 22 \text{ }^\circ\text{C}$

Table 16: Input data assumptions at each state for Figure 11

State point	Working Fluid	Temperature ( $^\circ\text{C}$ )	Pressure (kPa)
17	Warm seawater	22	10
18	Warm seawater	23	12
19	Hot seawater	Calculated	12

For the SF subsystem, the enthalpy, the specific entropy and exergy of each state was calculated and the results were recorded in Table 17.

By multiplying the specific exergy ( $ex$ ) with the mass flow rate ( $\dot{m}$ ), the exergy rate of the working fluid can be calculated at each state. The exergy destruction rate of each component was calculated by applying the principal of equation (4.3). As showed in Figure 28 below, the most exergy destruction rate happened in the parabolic solar field through the concentrated collector.

Table 15: Input data for the parabolic collector

<b>Glass Cover</b>	
Absorptance of the glass envelope ( $\alpha_{gls}$ )	0.02
Emissivity of outer surface of the glass cover ( $\epsilon_{gls}$ )	0.86
Transmittivity of the glass cover ( $\tau_{gls}$ )	0.935
Glass cover interior diameter ( $D_{3gls}$ ) - m	0.075
Glass cover wall thickness ( $e_{gls}$ ) - m	0.001
Glass cover exterior diameter ( $D_{4gls}$ ) - m	$D_{3gls} + 2(e_{gls})$
Thermal conductivity of the glass ( $k_{gls}$ ) -W/m K	0.96
<b>Absorber Stainless Steel Pipe</b>	
Absorptance of the absorber pipe ( $\alpha_p$ )	0.92
Thermal conductivity of the pipe ( $k_p$ ) -W/m K	16.3
Emissivity of the absorber pipe ( $\epsilon_p$ )	$0.00032T_{p,i} - 0.065971$
Absorber pipe interior diameter ( $D_{1p}$ ) - m	0.70
Absorber pipe wall thickness ( $e_p$ ) - m	0.001
Absorber pipe exterior diameter ( $D_{2p}$ ) - m	$D_{1p} + 2(e_p)$
<b>Cylindrical Parabolic Collector Model Characteristics</b>	
Collector Opening Width ( $H_{PTC}$ ) - m	2
Collector Length ( $L_{PTC}$ ) - m	4
Area factor ( $K_{PTC}$ )	20
Incidence angle modified ( $K_\theta$ )	0.955
Optical Losses efficiency of normal solar incident irradiation ( $\eta_{opt}$ )	0.80
Solar available radiation (I) $W/m^2$	600
Sky temperature ( $T_{sky}$ ) - °C	5000
Wind velocity (t) -m/s	0.5
Stefan-Boltzmann constant ( $W/m^2-K^4$ )	$5.67 \times 10^{-9}$

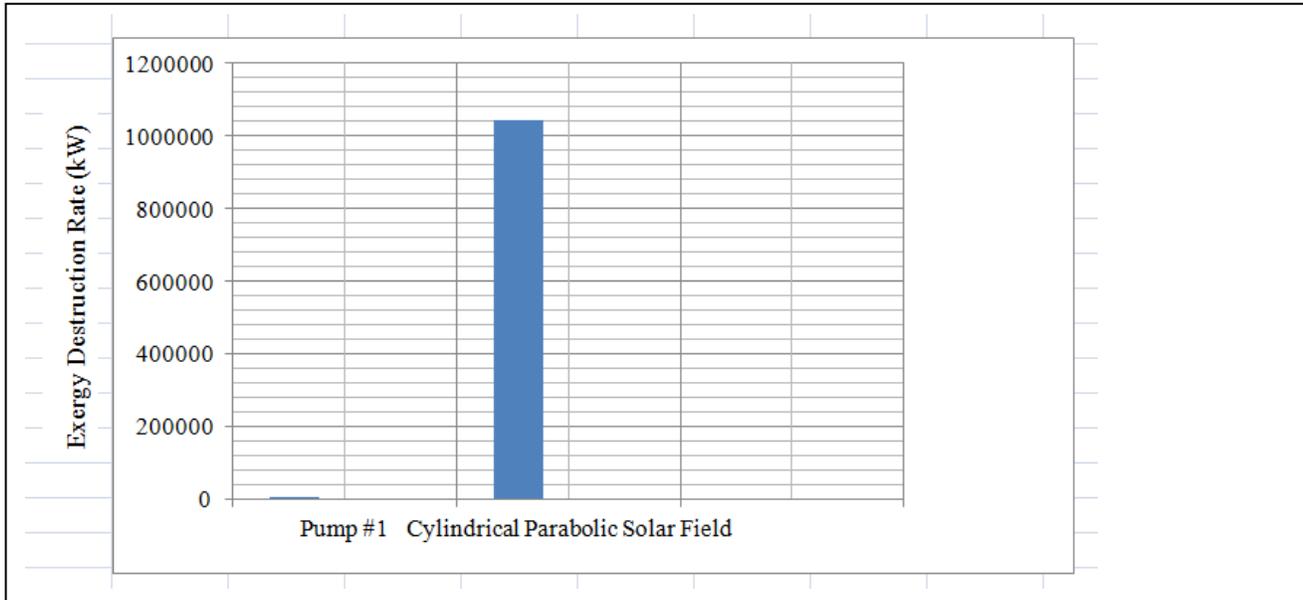
Table 17: States conditions for solar field subsystem

State #	Temperature T (°C)	Pressure P (kPa)	Mass flow rate $\dot{m}$ (kg/s)	Enthalpy h(kJ/kg)	Specific entropy s(kJ/kg-K)	Specific Exergy ex (kJ/kg)
17	22	10	406.1	91.42	0.5767	13.2
18	23	12	406.1	95.5	0.289	13.67
19	373.3	12	406.1	209.9	9.44	2557

## 5.5 MED Fresh water cycle

This cycle is described by the multi effects desalination. The Input data of this cycle is recorded in the Table 18. The thermodynamics properties of the states were evaluated through the

appropriated governing equations described in section 4.5 by using the Engineering Equation Solver (EES) software. The result can be found in Table 19



**Figure 28:** Exergy destruction rate solar field subsystem

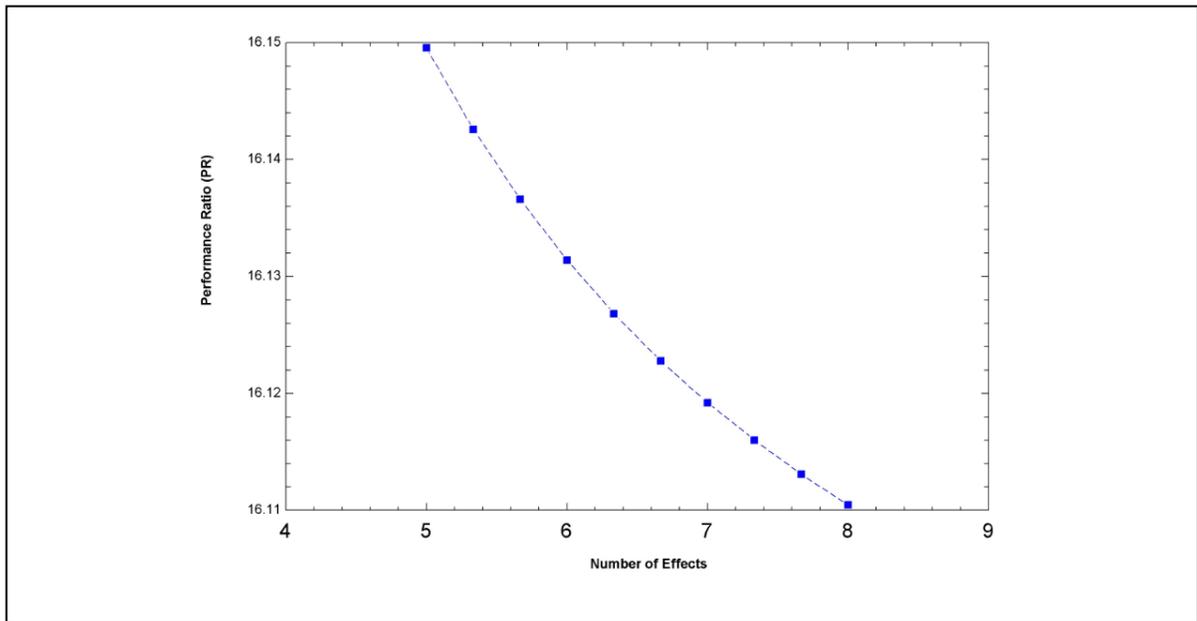
**Table 18:** Input data assumptions for figure 14

Feed seawater salinity	$X_f = 36 \text{ g/kg}$
Temperature increase in the last condenser	$\delta = 12 \text{ }^\circ\text{C}$
Heating source temperature	$T_s = 90 \text{ }^\circ\text{C}$
Temperature seawater	$T_{sw} = 25 \text{ }^\circ\text{C}$
Bottom Brine temperature (first effect)	$\text{BBT} = 56 \text{ }^\circ\text{C}$
Number of effects	$N = 8$
Saturated pressure (first effect)	$P_{e[1]} = 0.12 \text{ kPa}$
Pressure drop between effect	$\Delta p = 0.01 \text{ kPa}$
Seawater piping internal diameter	$\text{ID}_{sw} = 0.7 \text{ m}$
Design Velocity for economical pumping	$v_f = 1 \text{ m/s}$

**Table 19:** Output of MED subsystem

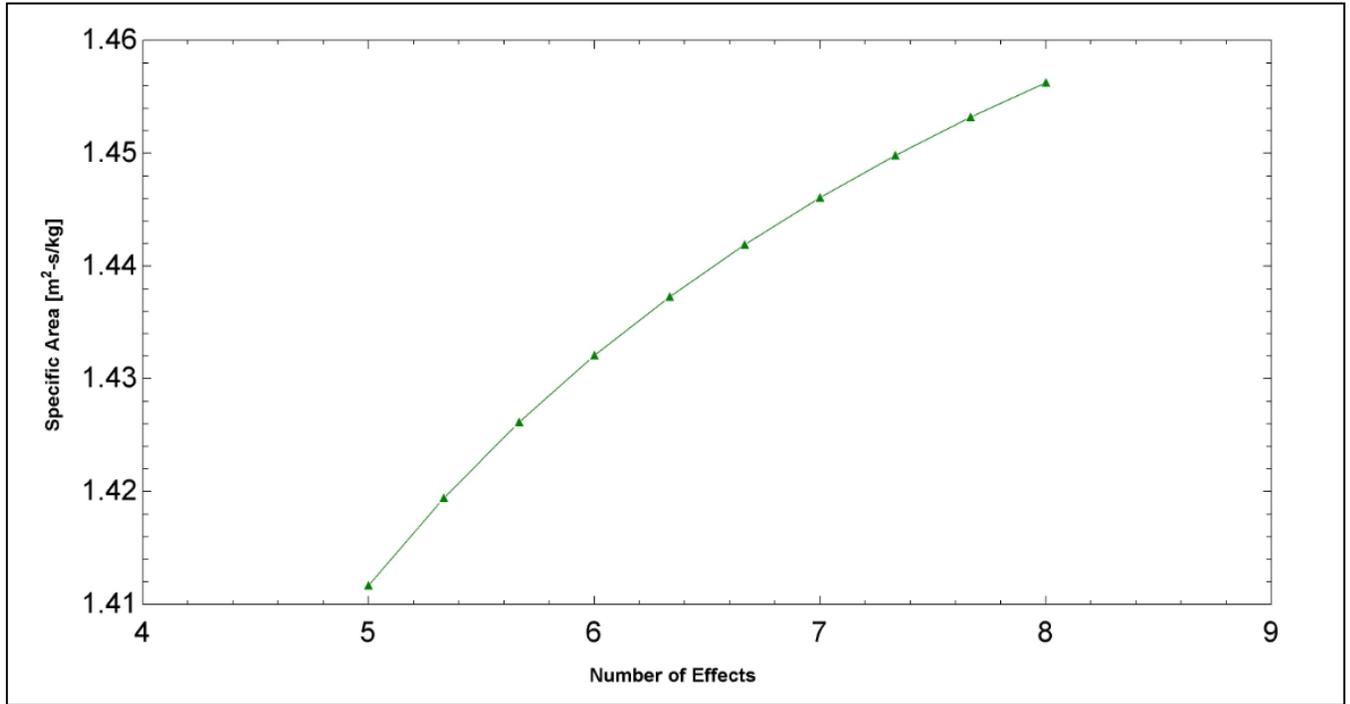
Effect[j]	$T_b[j]$ ( $^\circ\text{C}$ )	$T_{dv}[j]$ ( $^\circ\text{C}$ )	$T_{dv}[j]$ (kPa)	$Q[j]$ (kW)	$A[j]$ kW/m <sup>2</sup> K	$U$ kW/m <sup>2</sup> K	$UA$ (kW/ K)	$X_b[j]$ (g/kg)	$h_b[j]$ (kJ/kg)	$\dot{m}_f[j]$ (kg/s)	$h_f[j]$ (kJ/kg)	$h_{dv}[j]$ (kJ/kg)	$m_d[j]$ (kg/s)	Total Ex_dest[j] kW
1	56	89.41	0.12	114985	255.1	13.26	3382.63	88.75	208.4	390.5	198	2659	0	104061
2	55.14	88.55	0.12	489535	1066	13.4	14284.4	90.85	218.5	158.4	208.4	2600	24.26	141597
3	54.29	87.69	12	551645	1183	13.61	16100.6	92.96	215.6	134.2	218.5	2600	11.83	141180
4	53.43	86.83	0.9	534879	1129	13.83	15614.1	95.17	212.3	119.6	215.6	2656	10.88	140848
5	52.57	85.98	0.8	418288	869.6	14.04	12209.2	97.43	208.8	106.1	212.3	2654	9.77	140590
6	51.71	85.12	0.7	402640	824.4	14.25	11747.7	99.77	205.3	97.3	208.8	2653	8.66	140399
7	50.86	84.26	0.6	387714	781.9	14.47	11314.1	102.2	201.8	88.6	205.3	2652	8.02	140269
8	50	83.41	0.5	373472	741.9	14.69	10898.5	104.6	198.3	80.2	201.8	2650	7.85	140194
<b>Total</b>										<b>80.2</b>			<b>81.27</b>	

The performance ratio (PR) was evaluated by increasing the number of the effects (N). The relationship between **PR** and **N** is represented in Figure 29. The performance ratio is decreasing as the number of the effects increases. However, the required surface area increases with number of effects. This statement is represented by the specific area and the numbers of effect in Figure 30.

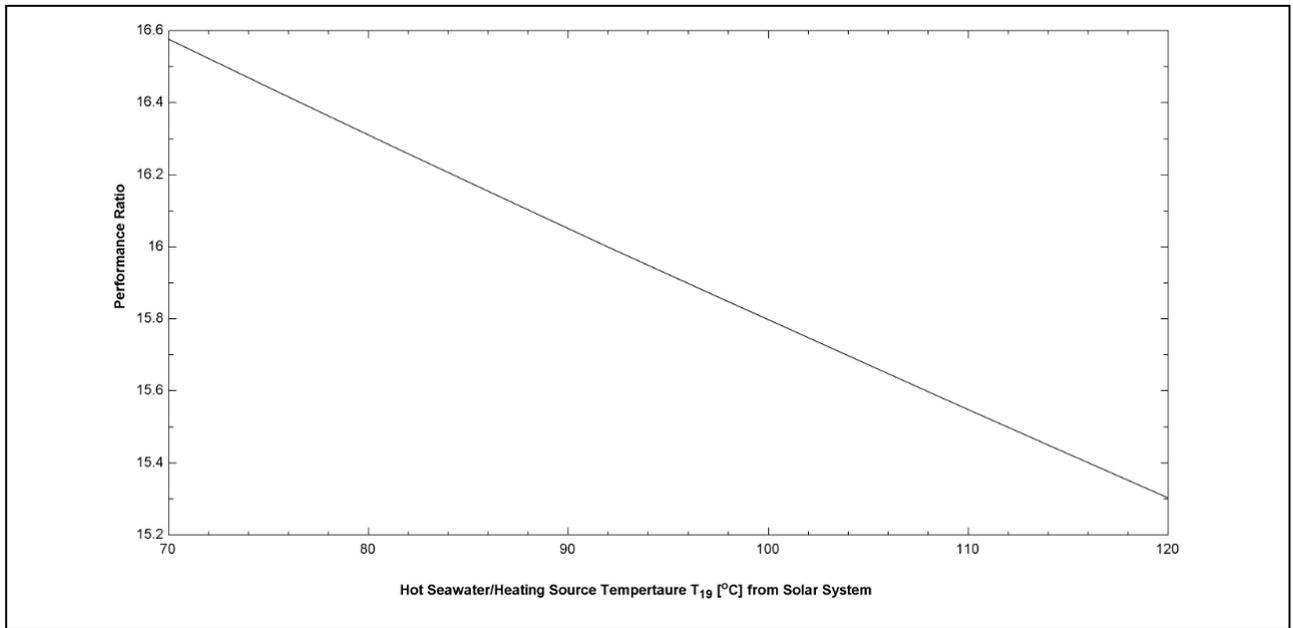


**Figure 29:** Performance ratio vs the number of effects

As the number of the effects increases, the driving temperature differences will decrease. Under this condition, an additional heat transfer area would be required in order to produce the same amount of distillate water. The temperature of hot seawater at state (19) in Figure 14 that is used as a heating source at the first effect will have an impact on PR. From Figure 31, the performance ratio is decreasing with the increase of the heating source temperature because of heat of vaporization that usually decreases with increasing temperature. Thus that, an additional vapor is needed to evaporate a certain quantity of water.



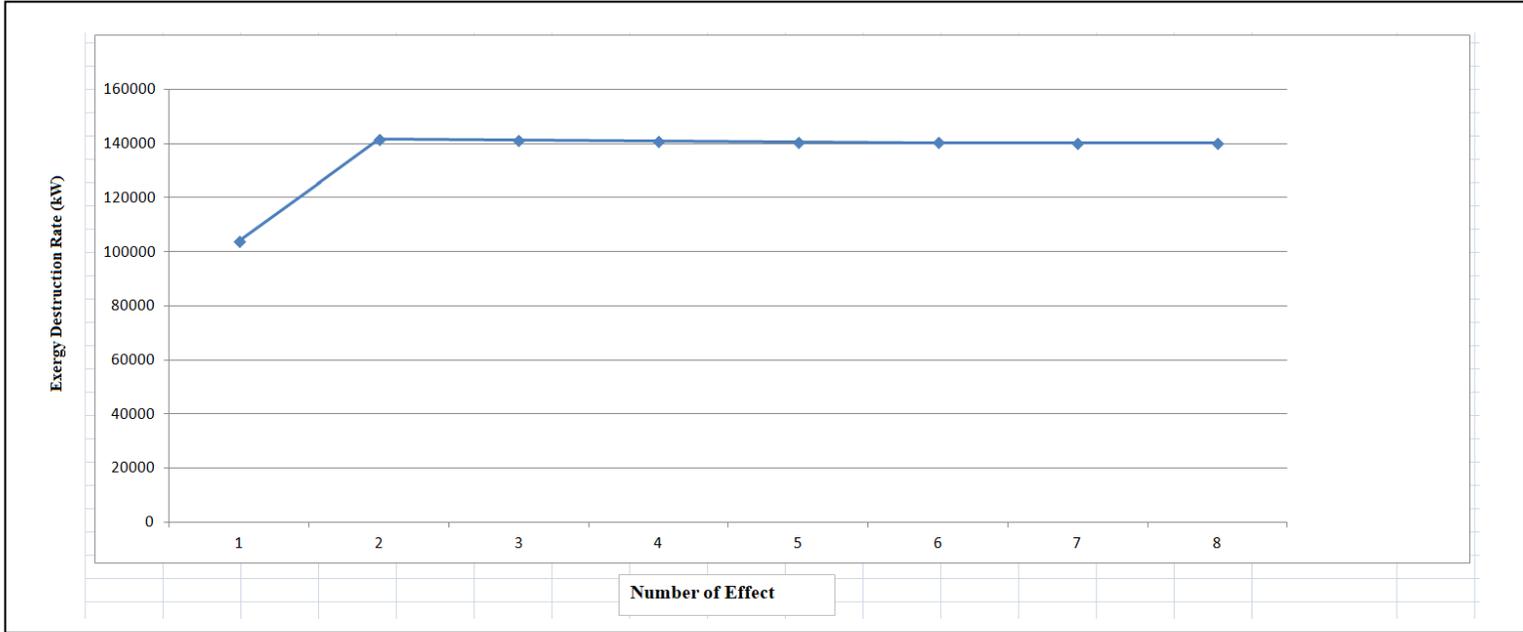
**Figure 30:** Specific area vs number of effects



**Figure 31:** Heating source temperature vs performance ratio

The exergy destruction rate is represented in Figure 32 below as function of the number of the effects. This figure shows the highest exergy losses happens between the first and second effect.

This is due to the temperature gradient between the feed seawater (brine) the heating source. As the temperature gradients become less from the second effect to N effect, the exergy losses start to decrease.



**Figure 32:** Exergy destruction rate vs number of effects

Given these results, it is necessary to obtain the quantity of fresh distillate water by using the model described in section 4.5 based on the forward feed MED configuration. However, all the results presented in Table 14 are not identical to the optimum model that was presented by El-Dessouky, H.T (2000) in reference 41. The deviation on the presented model is due to the gradient in temperatures between the feeding brine and the none consideration of the feed water heaters. Under the specified conditions in Table 18, the current model was able to produce 81.27 kg/s (7021.26 m<sup>3</sup>/day) of fresh distillate water.

## Chapter 6: Conclusions and Recommendations

### 6.1 Conclusions

The main purpose of this project was to perform the energy and exergy analyses of multigeneration systems from geothermal, solar and seawater multi effect desalination. In this project a certain parametric study was also conducted. To achieve the goal, the work performed was divided in multi stapes:

First of all, a literature review was conducted to better understand the previous studies and practical experiences that developed on the most renewable energy sources and the existing technologies about the double flashing power cycle system by using a geothermal source, the cooling system using a single effect absorber chillier, a heating space for individual and commercial activities; and the production of distillate fresh water by using a multi effect desalination process.

Then, a system was selected and divided in four (4) subsystems. A complete energy and exergy analysis was performed for each single component of a sub-system. To simplify the study, each component was considered as a control volume where the thermodynamics properties of the inputs and output can be analyzed. In order to validate the System, the inputs data were selected by using the approximated values as the one previously used in different studies.

Finally, the calculations and discussions were performed based on so-called “On design” analysis method in which the masses flow rate were calculated; the temperatures and pressures were used the inputs. The results and discussions of certain parametric study were performed under each sub-system by using Engineering Equation Solver (EES) Software.

In general, the main goal was achieved. However, the results of this study contain some deviations when comparing with certain existing similar studies. The improvement of this system can become a subject of future project study.

## 6.2 Recommendations

This report can be used for the design of the new multigeneration systems. For the future work, the designers can use this report as a guiding document that allows them to develop more energy efficient systems. Further investigations are required to improve the efficiency of the multigeneration system that was analyzed in this report. From the results obtained in this study, the following recommendations are made:

- For better comparison between the systems, further research and analyses are required to compare the results obtained from this report.
- To use advanced exergy and exergoeconomic analysis to understand the effect of the avoidable and unavoidable parts of exergy destruction in each component and optimize based on minimization of the avoidable exergy destruction in each component
- Design multigeneration energy systems by using the different renewable energy sources.

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## Appendix :

- Engineering Equation Solver Coding

```

{-----REFERENCES CONDITIONS-----}
T_0=20 [C]
P[0]=1.01325*convert(bar,kPa)
h[0]=enthalpy(Water,P=P[0],T=T_0)
s[0]=entropy(Water,P=P[0],T=T_0)
{-----POWER CYCLE SUBSYSTEM-----}
T[1]=260 [C]
X[1]=0
P[1]=19.05*convert(bar,kPa) "Assuming geothermal well is maintained at 19 bar"
h[1]=enthalpy(Water,x=X[1],P=P[1])
s[1]=entropy(Water,T=T[1],x=X[1])
v[1]=volume(Water,x=X[1],P=P[1])

T[2]=198.3
P[2]=15*convert(bar,kPa)
h[2]=enthalpy(Water,x=X[2],P=P[2])
s[2]=entropy(Water,T=T[2],x=X[2])
v[2]=volume(Water,x=X[2],P=P[2])

X[2]=X[1]
m_dot[2]=m_dot[1] "Mass balance equation"
ex[1]=(h[1]-h[0])-(T_0+273.15)*(s[1]-s[0]) "Specific exergy at state #1"
ex[2]=(h[2]-h[0])-(T_0+273.15)*(s[2]-s[0]) "Specific exergy at state #2"

"At Expansion Valve # FV1"
"Assuming that the first flash happen at state #3 respectively "

T[3]=154.1 [C]
P[3]=5.3*convert(bar,kPa)
s[3]=entropy(Water,x=X[3],T=T[3])
X[3]=(h[3]-h[6])/(h[4]-h[6])
v[3]=volume(Water,x=X[3],P=P[3])

m_dot[3]=m_dot[2] "Mass balance equation"
h[2]=h[3] "Energy balance equation"
m_dot[2]*s[2]+S_dot_gen_FV1=m_dot[3]*s[3] "Entropy balance equation"
m_dot[2]*ex[2]=m_dot[3]*ex[3]+Ex_dot_dest_FV1 "Exergy balance equation"
ex[3]=(h[3]-h[0])-(T_0+273.15)*(s[3]-s[0]) "Specific exergy at state #3"

"Separator tank #1 ST1"

T[4]=T[3]
X[4]=1
P[4]=P[3]
v[4]=volume(Water,x=X[4],P=P[4])
h[4]=enthalpy(Water,x=X[4],P=P[4])
s[4]=entropy(Water,T=T[4],x=X[4])
ex[4]=(h[4]-h[0])-(T_0+273.15)*(s[4]-s[0])

```

$T[6]=T[3]$   
 $X[6]=X[1]$   
 $P[6]=P[3]$   
 $v[6]=\text{volume}(\text{Water},x=X[6],P=P[6])$   
 $h[6]=\text{enthalpy}(\text{Water},x=X[6],P=P[6])$   
 $s[6]=\text{entropy}(\text{Water},T=T[6],x=X[6])$   
 $ex[6]=(h[6]-h[0])-(T_0+273.15)*(s[6]-s[0])$

$m\_dot[4] = X[3]*m\_dot[3]$   
 $m\_dot[3]*h[3]=m\_dot[4]*h[4]+m\_dot[6]*h[6]$  "Energy balance equation"  
 $m\_dot[3]*s[3]+S\_dot\_gen\_ST1=m\_dot[4]*s[4]+m\_dot[6]*s[6]$  "Entropy balance equation"  
 $m\_dot[3]*ex[3]=m\_dot[4]*ex[4]+m\_dot[6]*ex[6]+Ex\_dot\_dest\_ST1$  "Exergy balance equation"

"High pressure turbine HPT"

$T[5]= 98.22$  [C]  
 $P[5]=0.95*\text{convert}(\text{bar},\text{kPa})$   
 $eta\_HPT=0.85$  "high pressure turbine isentropic efficiency"  
 $s\_s[5]=s[4]$   
 $h\_s[5]=\text{enthalpy}(\text{Water},P=P[5],s=s\_s[5])$   
 $h[5]=h[4]-eta\_HPT*(h[4]-h\_s[5])$   
 $s[5]=\text{entropy}(\text{Water},P=P[5],h=h[5])$   
 $v[5]=\text{volume}(\text{Water},x=X[5],P=P[5])$   
 $x[5]=\text{quality}(\text{Water},h=h[5],P=P[5])$

//to be able to determine the enthalpy of the fluid after the mixing chamber, the flow rates of the two streams are to be determined

//assume a power output of 4.120 MW from the HPT

$W\_dot\_HPT=4120$ [kW]  
 $m\_dot[4]=W\_dot\_HPT/(h[4]-h[5])$  "Energy Balance Equation"  
 $m\_dot[4]=m\_dot[5]$  "Mass Balance Equation"  
 $m\_dot[4]*s[4]+S\_dot\_gen\_HPT=m\_dot[5]*s[5]$  "Entropy balance equation"  
 $m\_dot[4]*ex[4]=m\_dot[5]*ex[5]+W\_dot\_HPT+Ex\_dot\_dest\_HPT$  "Exergy balance equation"  
 $ex[5]=(h[5]-h[0])-(T_0+273.15)*(s[5]-s[0])$  "Specific Exergy"

"At Expansion Valve #2 FV2"

"Assuming that the first flash happen at state #7 respectively "

$T[7]=T[5]$   
 $P[7]=P[5]$   
 $s[7]=\text{entropy}(\text{Water},x=X[7],T=T[7])$   
 $v[7]=\text{volume}(\text{Water},x=X[7],P=P[7])$   
 $X[7]=(h[7]-h[12])/(h[8]-h[12])$

$m\_dot[6]=m\_dot[7]$  "Mass balance equation"  
 $h[6]=h[7]$  "Energy balance equation"  
 $m\_dot[6]*s[6]+S\_dot\_gen\_FV2=m\_dot[7]*s[7]$  "Entropy balance equation"  
 $m\_dot[6]*ex[6]=m\_dot[7]*ex[7]+Ex\_dot\_dest\_FV2$  "Exergy balance equation"  
 $ex[7]=(h[7]-h[0])-(T_0+273.15)*(s[7]-s[0])$  "Specific exergy at state #7"

### "Separator tank #2 ST2"

T[8]=T[7]  
X[8]=1  
P[8]=P[7]  
v[8]=**volume**(Water,x=X[8],P=P[8])  
h[8]=**enthalpy**(Water,x=X[8],P=P[8])  
s[8]=**entropy**(Water,T=T[8],x=X[8])  
ex[8]=(h[8]-h[0])-(T\_0+273.15)\*(s[8]-s[0])

T[12]=T[7]  
X[12]=X[1]  
P[12]=P[7]  
v[12]=**volume**(Water,x=X[12],P=P[12])  
h[12]=**enthalpy**(Water,x=X[12],P=P[12])  
s[12]=**entropy**(Water,T=T[12],x=X[12])  
ex[12]=(h[12]-h[0])-(T\_0+273.15)\*(s[12]-s[0])

m\_dot[8] =(1-X[3])\*X[7]\*m\_dot[3] "Mass balance equation"  
m\_dot[7]\*h[7]=m\_dot[8]\*h[8]+m\_dot[12]\*h[12] "Energy balance equation"  
m\_dot[7]\*s[7]+S\_dot\_gen\_ST2=m\_dot[8]\*s[8]+m\_dot[12]\*s[12] "Entropy balance equation"  
m\_dot[7]\*ex[7]=m\_dot[8]\*ex[8]+m\_dot[12]\*ex[12]+Ex\_dot\_dest\_ST2 "Exergy balance equation"

### "Mixing Chamber MC"

T[9]=T[8]  
P[9]=P[8]

s[9]=**entropy**(Water,T=T[9],x=X[9])  
v[9]=**volume**(Water,x=X[9],P=P[9])

X[9]=(h[9]-h[12])/(h[8]-h[12])  
m\_dot[5]+m\_dot[8]=m\_dot[9] "Mass balance equation"  
m\_dot[5]\*h[5]+m\_dot[8]\*h[8]=m\_dot[9]\*h[9] "Energy balance equation"  
m\_dot[5]\*s[5]+m\_dot[8]\*s[8]+S\_dot\_gen\_MC=m\_dot[9]\*s[9] "Entropy balance equation"  
m\_dot[5]\*ex[5]+m\_dot[8]\*s[8]=m\_dot[9]\*ex[9]+(Ex\_dot\_dest\_MC)\*(-1) "Exergy balance equation"  
ex[9]=(h[9]-h[0])-(T\_0+273.15)\*(s[9]-s[0]) "Specific exergy at state #9"

### "Low pressure turbine LPT"

P[10]=P[8]

//assuming 89% Turbine Isentropic Efficiency  
eta\_LPT=0.89

"Low pressure turbine isentropic efficiency"

s\_s[10]=s[9]  
h\_s[10]=**enthalpy**(Water,s=s\_s[10],P=P[10])  
h[10]=h[9]-(eta\_LPT\*(h[9]-h\_h[10]))  
s[10]=**entropy**(Water,P=P[10],h=h[10])  
v[10]=**volume**(Water,x=X[10],P=P[10])  
x[10]=**quality**(Water,h=h[10],P=P[10])

T[10]=**temperature**(Water,P=P[10],h=h[10])

//to be able to determine at the inlet of the low pressure turbine  
//assume the total net power output of 25 MW

W\_dot\_net=25000[kW]

W\_dot\_LPT=W\_dot\_net-W\_dot\_HPT

m\_dot[9]=W\_dot\_LPT/(h[9]-h[10])

"Energy Balance Equation"

m\_dot[9]=m\_dot[10]

"Mass Balance Equation"

m\_dot[9]\*s[9]+S\_dot\_gen\_LPT=m\_dot[10]\*s[10]

"Entropy balance equation"

m\_dot[9]\*ex[9]=m\_dot[10]\*ex[10]+W\_dot\_LPT+(Ex\_dot\_dest\_LPT)\*(-1)"Exergy balance equation"

ex[10]=(h[10]-h[0])-(T\_0+273.15)\*(s[10]-s[0])

"Specific Exergy"

"Condenser #1 Cond1"

"Calculation of the temperature at state 16, exiting of cold water"

cp\_cw\_Cond\_1=4180 [J/kg K]"Assuming Specific heat of cold water"

U\_Cond\_1=350 [W/m^2 K] "Overall heat transfer coefficient of Condenser #1"

"Total heat transferred. This will be calculated Q\_dot\_Cond\_1 that is function of temperature at state 16"

Q\_dot\_Cond\_1=m\_dot[15]\*\*(h[16]-h[15])

"A Counter flow"

T[15]=15 [C]

X[15]=0

P[15]=1.01325\*convert(bar,kPa)

h[15]=enthalpy(Water,x=X[15],P=P[15])

s[15]=entropy(Water,T=T[15],x=X[15])

v[15]=volume(Water,x=X[15],P=P[15])

T[16]=28[C]

X[16]=X[15]

P[16]=P[15]

h[16]=enthalpy(Water,x=X[16],P=P[16])

s[16]=entropy(Water,T=T[16],x=X[16])

v[16]=volume(Water,x=X[16],P=P[16])

T[11]=65 [C]

X[11]=0

P[11]=P[10]

h[11]=enthalpy(Water,x=X[11],P=P[11])

s[11]=entropy(Water,T=T[11],x=X[11])

v[11]=volume(Water,x=X[11],P=P[11])

m\_dot[15]=m\_dot[16]

m\_dot[11]=m\_dot[10]

"Mass Balance Equation"

m\_dot[15]\*h[15] + m\_dot[10]\*h[10]=m\_dot[11]\*h[11]+m\_dot[16]\*h[16]"Energy Balance Equation"

m\_dot[15]\*s[15] + m\_dot[10]\*s[10]+ S\_dot\_gen\_Cond\_1=m\_dot[11]\*s[11]+m\_dot[16]\*s[16]"Entropy balance equation"

```
m_dot[15]*ex[15] + m_dot[10]*ex[10]=m_dot[11]*ex[11]+m_dot[16]*ex[16]+Ex_dot_dest_Cond_1 "Exergy balance equation"
```

```
ex[11]=(h[11]-h[0])-(T_0+273.15)*(s[11]-s[0]) "Specific Exergy"  
ex[15]=(h[15]-h[0])-(T_0+273.15)*(s[15]-s[0])  
ex[16]=(h[16]-h[0])-(T_0+273.15)*(s[16]-s[0])
```

```
//energy rate of geothermal fluid in the reservoir  
Q_dot_energy_geothermal =m_dot[1]*(h[1]-h[0])
```

```
//energy efficiency power cycle  
eta_energy_Power_Cycle =W_dot_net/Q_dot_energy_geothermal
```

```
//exergy efficiency power cycle  
eta_exergy_Power_Cycle=W_dot_net/Q_dot_exergy_geothermal  
//exergy rate of geothermal fluid in the reservoir  
Q_dot_exergy_geothermal=m_dot[1]*ex[1]
```

```
{-----HEATING CYCLE-----}
```

```
//after the heat exchanger #2 HE2 for space heating  
T[14]=T[13]-5  
P[14]=P[7]
```

```
s[14]=entropy(Water,T=T[14],P=P[14])  
ex[14]=(h[14]-h[0])-(T_0+273.15)*(s[14]-s[0])  
m_dot[14]=m_dot[13]
```

```
h[14]=enthalpy(Water,T=T[14],P=P[14])  
T[45]=16[C]  
P[45]=101.325[kPa]  
T[46]=28[C]
```

```
cp=cp(Air_ha,T=22,P=P[45])  
m_dot[45]=(m_dot[13]*(h[13]-h[14]))/(Cp*(T[46]-T[45]))  
m_dot[46]=m_dot[45]
```

```
//efficiency energy heating space  
eta_energy_HE= h[45]/h[46]
```

```
h[45]=enthalpy(Air,T=T[45])  
h[46]=enthalpy(Air,T=T[46])
```

```
//efficiency Exergy efficiency heating space  
eta_exergy_HE=(m_dot[45]*ex[45])/(m_dot[45]*ex[46]+Q_dot_HE*(1-((T_0+273.15)/(T_HE+273.15))))  
ex[45]=(h[45]-h[0])-(T_0+273.15)*(s[45]-s[0])  
ex[46]=(h[46]-h[0])-(T_0+273.15)*(s[46]-s[0])
```

```
s[45]=entropy(Air,T=T[45],P=P[45])  
s[46]=entropy(Air,T=T[46],P=P[46])  
P[46]=P[45]
```

```
T_HE=T[13]  
Q_dot_HE=m_dot[13]*(h[13]-h[14])
```

{-----ABSORPTION CHILLER COOLING CYCLE-----}

//After the generator of the absorption chiller

//Send to the heat exchanger #2 HE2

P[13]=P[7]

T\_G=T[13]

T[13]=T[12]-15

h[13]=enthalpy(Water,T=T[13],P=P[13])

s[13]=entropy(Water,T=T[13],P=P[13])

ex[13]=(h[13]-h[0])-(T\_0+273.15)\*(s[13]-s[0])

m\_dot[13]=m\_dot[12]

// to Calculate the cooling load from the absorption chiller, Assume a COP of 0.8

COP=0.8

//Heat input at the Generator

Q\_dot\_Generator=m\_dot[13]\*(h[12]-h[13])

//Cooling load Q\_dot\_Evaporator1 at the Evaporator#1

COP=Q\_dot\_Evaporator1/(Q\_dot\_Generator + W\_dot\_Pump\_2)

//Assuming the refrigerant vapour at the exit of the generator (at state 37) to be in equilibrium with the strong solution leaving the generator (at state 34)

T[34]=T[13]

T[37]=T[13]

X[37]=1

h[37]=enthalpy(Water, T=T[37], P=P[37])

s[37]=entropy(Water, T=T[37], x=X[37])

P[37]=P[32]

ex[37]=(h[37]-h[0])-(T\_0+273.15)\*(s[37]-s[0])

//Heat exchanger #1 (HE1) effectiveness

epsilon\_HE\_1=(T[34]-T[35])/(T[34]-T[32])

//Assuming the effectiveness of HE1 is equal to 0.98

epsilon\_HE\_1=0.98

//Assuming the absorber temperature is equal to 40 degree celsius

T\_A=40[C]

T[32]=T\_A

T[31]=T[32]

T[36]=T[35]

//Assuming the evaporator temperature (outlet temperature at state 42) is 5 degree celcius

T\_E=5[C]

T[42]=T\_E

//The Evaporator equilibrium allows that the temperature at states 3, 4 and 42 be the same

T[39]=T[42]

T[40]=T[39]

//Assuming the pressure at the inlet of the Evaporator # 1 (at state 39) is equal to 0.872 kPa

P[39]=0.872[kPa]

//This means that the pressure at the states 31, 39 and 40 will be the same

P[31]=P[39]

P[40]=P[39]

//Assuming the mass fraction of the Weak solution of LiBr and Water is 57.8%

xi\_31=57.8/100 "mass fraction"

x[31]=molefraction\_librh2o(xi\_31)

h[31]=h\_librh2o(T[31],x[31])

s[31]=s\_librh2o(T[31],x[31])

ex[31]=(h[31]-h[0])-(T\_0+273.15)\*(s[31]-s[0])

xi\_32=xi\_31 "mass fraction"

x[32]=molefraction\_librh2o(xi\_32)

P[32]=4.266[kPa]

h[32]=h\_librh2o(T[32],x[32])

s[32]=s\_librh2o(T[32],x[32])

ex[32]=(h[32]-h[0])-(T\_0+273.15)\*(s[32]-s[0])

xi\_33=xi\_31 "mass fraction"

x[33]=molefraction\_librh2o(xi\_33)

P[33]=P[32]

(1+lamda)\*h[32]+lamda\*h[34]=(1+lamda)\*h[33]+lamda\*h[35]

h[33]=h\_librh2o(T[33],x[33])

s[33]=s\_librh2o(T[33],x[33])

ex[33]=(h[33]-h[0])-(T\_0+273.15)\*(s[33]-s[0])

//Assuming the mass fraction of the Strong solution of LiBr and Water is 66%

xi\_34=66/100 "mass fraction"

x[34]=molefraction\_librh2o(xi\_34)

P[34]=P[32]

h[34]=h\_librh2o(T[34],x[34])

s[34]=s\_librh2o(T[34],x[34])

ex[34]=(h[34]-h[0])-(T\_0+273.15)\*(s[34]-s[0])

xi\_35=xi\_34 "mass fraction"

x[35]=molefraction\_librh2o(xi\_35)

P[35]=P[32]

h[35]=h\_librh2o(T[35],x[35])

s[35]=s\_librh2o(T[35],x[35])

ex[35]=(h[35]-h[0])-(T\_0+273.15)\*(s[35]-s[0])

xi\_36=xi\_34 "mass fraction"

x[36]=molefraction\_librh2o(xi\_36)

P[36]=P[32]

h[36]=h\_librh2o(T[36],x[36])

s[36]=s\_librh2o(T[36],x[36])

ex[36]=(h[36]-h[0])-(T\_0+273.15)\*(s[36]-s[0])

//Circulation ratio

lamda=xi\_31/(xi\_36-xi\_31)

//Assuming the condenser temperature (outlet temperature at state 38) is 50 degree celcius

T\_C=50[C]

T[38] = T\_C

X[38]=0

h[38]=enthalpy(Water, T=T[38], s=s[38])

s[38]=entropy(Water, T=T[38], x=X[38])

P[38]=P[32]  
ex[38]=(h[38]-h[0])-(T\_0+273.15)\*(s[38]-s[0])

X[40]=1  
h[40]=enthalpy(Water, T=T[40], s=s[40])  
s[40]=entropy(Water, T=T[40], x=X[40])  
ex[40]=(h[40]-h[0])-(T\_0+273.15)\*(s[40]-s[0])

//Assuming the condenser temperature for cooling water (inlet temperature at state 43) is 23.9 degree celcius

T[43]=23.9[C]  
X[43]=0  
h[43]=enthalpy(Water, T=T[43], P=P[43])  
s[43]=entropy(Water, T=T[43], x=X[43])  
P[43]=P[0]  
ex[43]=(h[43]-h[0])-(T\_0+273.15)\*(s[43]-s[0])

//Assuming the condenser temperature for cooling water (outlet temperature at state 44) is 35 degree celcius

T[44]=35[C]  
X[44]=X[43]  
h[44]=enthalpy(Water, T=T[44], P=P[44])  
s[44]=entropy(Water, T=T[44], x=X[44])  
P[44]=P[0]  
ex[44]=(h[44]-h[0])-(T\_0+273.15)\*(s[44]-s[0])

//Calculation of the required mass flow rate of the refrigerant

"Evaporator #1"

m\_dot[40]=m\_dot[39] "mass balance equation"  
m\_dot[39]= Q\_dot\_Evaporator1/(h[40]-h[39]) "Energy balance Equation"  
m\_dot[39]\*s[39]+S\_dot\_gen\_Evaporator +(Q\_dot\_Evaporator1/(T\_0+273.15)) = m\_dot[40]\*s[40] "entropy balance Equation"  
m\_dot[39]\*ex[39] +Q\_dot\_Evaporator1\*(1-(T\_0+273.15)/(T\_E+273.15))=m\_dot[40]\*ex[40]+Ex\_dot\_dest\_Evaporator1 "Exergy Balance Equation"

//Evaporator air mass flow rate calculation, assuming the temperature at state 41 to be 25 degree celcius

T[41]=25[C]  
P[41]=P[0]  
P[42]=P[41]  
h[41]=enthalpy(Air\_ha, T=T[41], P=P[41])  
s[41]=entropy(Air\_ha, T=T[41], P=P[41])  
T\_av=(T[41]+T[42])/2  
cp\_1=cp(Air\_ha, T=T\_av, P=P[41])  
ex[41]=(h[41]-h[0])-(T\_0+273.15)\*(s[41]-s[0])

m\_dot[41]=(m\_dot[3]\*(h[3]-h[4]))/(cp\_1\*(T[42]-T[41]))  
m\_dot[41]=m\_dot[42]

h[42]=enthalpy(Air\_ha, T=T[42], P=P[42])  
s[42]=entropy(Air\_ha, T=T[42], P=P[42])  
ex[42]=(h[42]-h[0])-(T\_0+273.15)\*(s[42]-s[0])

"Expansion Valve #1"

```

m_dot[38]=m_dot[39] "mass balance equation"
h[39]=h[38] "Energy balance equation"
X[39]=0
s[39]=entropy(Water, T=T[39], x=X[39])
ex[39]=(h[39]-h[0])-(T_0+273.15)*(s[39]-s[0])
m_dot[38]*s[38]+S_dot_gen_Expansion_Valve_1 = m_dot[39]*s[39] "entropy balance Equation"
m_dot[38]*ex[38] =m_dot[39]*ex[39]+Ex_dot_dest_Expansion_Valve_1 "Exergy Balance Equation"

"Condenser #2"
m_dot[37]=m_dot[38] "mass balance equation"
m_dot[37]*h[37]=m_dot[38]*h[38]+Q_dot_Condenser2 "Energy balance equation"
m_dot[37]*s[37]+S_dot_gen_Condenser2 = m_dot[38]*s[38] +(Q_dot_Condenser2/(T_0+273.15)) "entropy
balance Equation"
m_dot[37]*ex[37] =m_dot[38]*ex[38]+ Q_dot_Condenser2*(1-
(T_0+273.15)/(T_C+273.15))+Ex_dot_dest_Condenser2 "Exergy Balance Equation"

//Calculation mass flow of cooling water
m_dot[43]=m_dot[44] "mass balance equation"
m_dot[43]=Q_dot_Condenser2/(h[44]-h[43])

"Heat Exchanger #1"

//From the weak solution of LiBr/H2O
m_dot[32]=m_dot[33] "mass balance equation"
m_dot[32]=(1+lamba)*m_dot[40]

//From the strong solution of LiBr/H2O
m_dot[34]=m_dot[35] "mass balance equation"
m_dot[34]=lamda*m_dot[40]
m_dot[32]*s[32]+m_dot[34]*s[34] +S_dot_gen_Heat_Exchanger1= m_dot[33]*s[33]+m_dot[35]*s[35] "entropy
balance Equation"
m_dot[32]*ex[32]+m_dot[34]*ex[34] = m_dot[33]*ex[33]+m_dot[35]*ex[35]+Ex_dot_dest_Heat_Exchanger1
"exergy balance Equation"

"Generator"
m_dot[33]*s[33]+S_dot_gen_Generator+ (Q_dot_Generator/(T_0+273.15))= m_dot[34]*s[34]+m_dot[37]*s[37]
"entropy balance Equation"
m_dot[33]*ex[33]+ Q_dot_Generator*(1-(T_0+273.15)/(T_G+273.15)) =
m_dot[34]*ex[34]+m_dot[37]*ex[37]+Ex_dot_dest_Heat_Generator "exergy balance Equation"
//Concentration ratio (CR)
CR= (1+lamba)/lamda

"Expansion Valve #2"
m_dot[35]=m_dot[36] "mass balance equation"
m_dot[35]*s[35]+S_dot_gen_Expansion_Valve_2 = m_dot[36]*s[36] "entropy balance Equation"
m_dot[35]*ex[35] =m_dot[36]*ex[36]+Ex_dot_dest_Expansion_Valve_2 "Exergy Balance Equation"

"Absorber"
m_dot[36]*h[36]+m_dot[40]*h[40]=m_dot[31]*h[31]+Q_dot_Absorber "energy balance equation"
m_dot[36]+m_dot[40]=m_dot[31] "mass balance equation"
m_dot[36]*s[36]+m_dot[40]*s[40]+S_dot_gen_Absorber= m_dot[31]*s[31]+ (Q_dot_Absorber/(T_0+273.15))
"entropy balance Equation"
m_dot[36]*ex[36]+ m_dot[40]*ex[40] = m_dot[31]*ex[31]+Q_dot_Absorber*(1-
(T_0+273.15)/(T_A+273.15))+Ex_dot_dest_Absorber "exergy balance Equation"

```

```

//Calculation mass flow of cooling water
m_dot[29]=m_dot[30] "mass balance equation"
m_dot[29]=Q_dot_Absorber/(h[30]-h[29])

//Assuming the absorber temperature for cooling water (outlet temperature at state 30) is 35 degree celcius
T[30]=35[C]
X[30]=0
h[30]=enthalpy(Water, T=T[30], P=P[30])
s[30]=entropy(Water, T=T[30], x=X[30])
P[30]=P[0]
ex[30]=(h[30]-h[0])-(T_0+273.15)*(s[30]-s[0])
//Assuming the absorber temperature for cooling water (inlet temperature at state 29) is 23.9 degree celcius
T[29]=T[43]
X[29]=X[43]
P[29]=P[30]
h[29]=h[43]
s[29]=s[43]
ex[29]=ex[43]

"Pump #2"
//The the LiBr-Water solution is assume to be incompressible and work of the electric motor is usually very small

m_dot[31]*h[31]+W_dot_Pump_2=m_dot[32]*h[32] "mass balance equation"
m_dot[31]*s[31]+S_dot_gen_Pump_2 = m_dot[32]*s[32] "entropy balance Equation"
m_dot[31]*ex[31] + W_dot_Pump_2 =m_dot[32]*ex[32]+Ex_dot_dest_Pump_2 "Exergy Balance Equation"

//Exergy efficiency COP_ex

COP_ex=((Q_dot_Evaporator1*(1-((T_0+273.15)/(T_E+273.15))))/((Q_dot_Generator*(1-
((T_0+273.15)/(T_G+273.15))))+W_dot_Pump_2))*(-1)

{-----SOLAR FIELD HEATING-----}

///Assuming temperature of warm seawater at state 17
T[17]=22[C]

//Assuming sea water salination
S=36 [g/kg]

//Assuming Pressure (kPa) of warm seawater at state 17
P[17]=0.01*convert(MPa,kPa)

//Specific enthalpy (kJ/kg) of warm seawater at state 17
h[17]=sw_enthalpy(T[17], S,P[17])/1000

//Specific entropy (kJ/kg-K) of warm seawater at state 17
s[17]=sw_entropy(T[17], S, P[17])/1000

//Prandtl Number of seawater at state 17
Pr[17]=sw_prandtl(T[17], s[17])

//Assuming warm seawater pipe inner diameter is 0.70 m
ID_wsw=0.7 [m]

```

```

//Density (kg/m^3) of warm seawater at state 17
rho[17]=sw_density(T[17], S, P[17])

//Specific volume (m^3/kg) of warm sea water
mu[17]=1/rho[17]

//Volumetric flow rate in m^3/s
V_dot[17]=m_dot[17]/rho[17]

//Renold Number
Re[17]=4*m_dot[17]/(mu[17]*pi*ID_wsw)

//Mass flow rate of warm seawater
m_dot[17]= rho[17]*v_e[17]*(Pi*(ID_wsw/2)^2)

//Assumed Design Velocity for economical pumping
v_e[17]=1[m/s]

//Assuming the isentropic efficiency of Pump #1
eta_Pump_1=0.89

//Calculation specific enthalpy at state 18
T_s[18]=22.5[C]
//Specific enthalpy (kJ/kg) of warm seawater at state 18s
h_h[18]=sw_enthalpy(T_s[18], S,P[18])/1000

h[18]=h[17]+((h_h[18]-h[17])/eta_Pump_1)

//Assuming Pressure (kPa) of warm seawater at state 17
P[18]=0.012*convert(MPa,kPa)
T[18]=T_s[18]+0.5

//Specific entropy (kJ/kg-K) of warm seawater at state 18
s[18]=sw_entropy(T[18], S, P[18])/1000

//Mass balance equation
m_dot[17] =m_dot[18]

//Energie balance equation
m_dot[17]*h[17]+W_dot_Pump_1=m_dot[18]*h[18]

//Entropy balance equation
m_dot[17]*s[17]+S_dot_gen_Pump_1=m_dot[18]*s[18]

//Exergy balance equation
m_dot[17]*ex[17]+W_dot_Pump_1=m_dot[18]*ex[18] +Ex_dot_dest_Pump_1

//Calculation specific exergy of warm seawater at states 17 and 18
ex[17]=(h[17]-h[0])-(T_0+273.15)*(s[17]-s[0])
ex[18]=(h[18]-h[0])-(T_0+273.15)*(s[18]-s[0])

```

//Parabolic Solar Field Through Collector

"Glass cover properties"

alpha\_gls=0.02 "Absorptance"

epsilon\_gls=0.86 "Emissivity"

tau\_gls= 0.935 "Transmittance"

"Absorber Stainless steel pipe properties "

alpha\_pipe=0.92 "Absorptance"

k\_pipe= 16.3 [W/m K] "Thermal conductivity of the pipe (W/m K)"

epsilon\_pipe= (0.000327\*T\_p\_i)-0.065971 "Emissivity is function of mean inside wall pipe temperature T\_p\_i"

"Parabolic Trough Collector characteristics for model Excell Sandria"

H\_PTC=2 [m] "Collector opening width"

L\_PTC=4 [m] "Collector length"

A\_PTC= K\_PTC\*L\_PTC\*H\_PTC "Collector Area"

K\_PTC=20 "Area factor"

//Calculation Effective optical efficiency (eta\_env)

K\_theta=0.955 "Incidence angle modifier"

eta\_opt=0.80 "Optical losses efficiency of normal solar incident irradiation"

D\_1\_pipe=ID\_wsw "Absorber pipe interior diameter"

e\_p=0.001 [m] "Absorber pipe wall thickness"

D\_2\_pipe=D\_1\_pipe+2\*e\_p "Absorber pipe exterior diameter"

D\_3\_glass=0.075 [m] "Tubular glass cover interior diameter"

e\_gls= e\_p "Tubular glass cover wall thickness"

D\_4\_glass=D\_3\_glass+2\*e\_gls "Tubular glass cover exterior diameter"

//Calculation Input heat rate to the tubular receiver (Q\_dot\_in\_R)

Q\_dot\_in\_R= eta\_opt\*A\_PTC\*I

I=600 [W/m^2] "Solar available radiation assuming is variable between 600 W/m^2"

//Calculation absorbed heat rate by the absorber pipe

Q\_dot\_absorbe\_pipe=tau\_gls\*alpha\_pipe\*Q\_dot\_in\_R

//Energy balance equation on the inner pipe surface

Q\_dot\_SF=Q\_dot\_conduction\_pipe

//Energy balance equation on the pipe exterior surface

Q\_dot\_absorbe\_pipe=Q\_dot\_SF+Q\_dot\_loss\_pipe\_glass

//Energy balance equation on the inner surface of the glass cover

Q\_dot\_loss\_pipe\_glass=Q\_dot\_conduction\_glass

//Energy balance equation on the outer surface of glass

Q\_dot\_conduction\_glass+Q\_dot\_absorbe\_glass=Q\_dot\_loss\_glass\_atm

//Radiation heat losses between the pipe and glass cover

Q\_dot\_loss\_pipe\_glass=pi\*D\_2\_pipe\*L\_PTC\*sigma\*((T\_p\_e+273.15)^4-(T\_gls\_i+273.15)^4)/((1/epsilon\_pipe)+(((1-epsilon\_gls)/epsilon\_gls)\*(D\_2\_pipe/D\_3\_glass)))

```

//The loss heat rate transmitted from the outer glass surface to ambient through wind convection and radiation
Q_dot_loss_glass_atm=pi*D_4_glass*L_PTC*h_wind*((T_gls_e+273.15)-
(T_atm+273.15))+pi*D_4_glass*L_PTC*epsilon_gls*sigma*((T_gls_e+273.15)^4-(T_sky+273.15)^4)

//Heat rate of conduction through the glass cover
Q_dot_conduction_glass=2*pi*L_PTC*k_gls*((T_gls_i+273.15)-(T_gls_e+273.15))/(ln(D_4_glass/D_3_glass))
k_gls=0.96[W/m K]      "Thermal conductivity of the glass-window (W/m K)"

"Conduction heat rate through the tubular pipe"
Q_dot_conduction_pipe=2*pi*L_PTC*k_pipe*(((T_p_e+273.15)-(T_p_i+273.15))/ln(D_2_pipe/D_1_pipe))

"Convection heat rate received by the seawater"
Q_dot_SF =pi*D_1_pipe*L_PTC*h_f_sw*(T_p_i-T_f)

//Heat flux absorbed by the glass cover
Q_dot_absorbe_glass=alpha_gls*Q_dot_in_R

//T_f is the mean temperature of the seawater flowing inside the absorber pipe.
//Assuming the heat transfer is developing under constant heat flux boundary condition,T_f is then consider as the
arithmetic mean temperature between the states (18) and (19)

T[19] =(2*T_f)-T[18]

//Density (kg/m^3) of warm seawater at state 18
rho[18]=sw_density(T[18], S, P[18])

//Specific volume (m^3/kg) of warn sea water at 18
mu[18]=1/rho[18]

//Prandtl Number of seawater at state 18
Pr[18]=sw_prandtl(T[18], s[18])

//Renold Number
Re[18]=4*m_dot[18]/(mu[18]*pi*ID_wsw)

//Nusselt Number at state 18
Nu[18]=0.023*(Re[18])^(0.8)*(Pr[18])^(0.4)

//Convection heat transfer coefficient h_f_sw
Nu[18]=(h_f_sw*D_1_pipe)/k[18]  "Nusselt Number"

//Thermal Conductivity of seawater (W/m K) at state 18

k[18]=sw_conductivity(T[18], S)

//Assuming there is a vacuum inside the enclose between the glass cover and the pipe. This means that heat of
convection is neglected
sigma=5.67*0.000000001[W/m^2-K^4]  "Stefann-Boltzmann constant"

//Assuming the ambient
T_atm=22[C]
//Assuming a sunny daylight around noon

```

```

T_sky=5800 [C]
//Wind convection heat transfer coefficient
h_wind=5.7+3.8*t

//Assuming wind speed t in m/s
t=0.5 [m/s]

epsilon_pipe= 0.000327 "Emissivity is function of mean inside wall pipe temperature T_p_i"

//Mass balance equation parabolic solar field through collector
" Parabolic solar field through collector"
m_dot[18]= m_dot[19] "mass balance Equation"

m_dot[18]*s[18]+S_dot_gen_Solar_Field+ ((Q_dot_SF*0.001)/(T_0+273.15))= m_dot[19]*s[19] "entropy balance
Equation"
m_dot[18]*ex[18]+ (Q_dot_SF*0.001)*(1-(T_0+273.15)/(T_sky+273.15)) =
m_dot[19]*ex[19]+Ex_dot_dest_Solar_Field "exergy balance Equation"

//Assuming only saturated hot vapor
//Calculation specific enthalpy in kJ/kg of warm seawater at state 19
h[19]=enthalpy(Water,x=0,P=P[19])

P[19]=P[18]

//Calculation specific entropy (kJ/kg-K) of warm seawater at state 19
s[19]=entropy(Water,T=T[19],P=P[19])

//Calculation specific exergy (kJ/kg) of warm seawater at state 19
ex[19]=(h[19]-h[0])-(T_0+273.15)*(s[19]-s[0])

//Assume that saturated vapor will be totally condensate at state 119
T[119]= 15[C]

//Calculation specific enthalpy in kJ/kg of condensate at state 119
h[119]=enthalpy(Water,x=0,P=P[119])
P[119]=P[19]

//Calculation specific entropy (kJ/kg-K) of condensate seawater at state 119
s[119]=entropy(Water,T=T[119],P=P[119])

//Calculation specific exergy of condensate seawater at state 119
ex[119]=(h[119]-h[0])-(T_0+273.15)*(s[119]-s[0])

//Assuming temperature of cold seawater is 4 degree celcius
T[21] =10[C]
P[21]=P[17]

//Specific enthalpy (kJ/kg) of warm seawater at state 21
h[21]=sw_enthalpy(T[21], S,P[21])/1000

//Specific entropy (kJ/kg-K) of warm seawater at state 21
s[21]=sw_entropy(T[21], S, P[21])/1000

//Assuming mass flow rate of cold seawater
m_dot[21]=m_dot[17]

```

```

//Assuming the isentropic efficiency of Pump #3
eta_Pump_3=eta_Pump_1

//Calculation specific enthalpy at state 22s
T_s[22]=15.5[C]
h[22]=h[21]+((h_h[22]-h[21])/eta_Pump_3)

//Specific enthalpy (kJ/kg) of warm seawater at state 22s
h_h[22]=sw_enthalpy(T_s[22], S,P[22])/1000

//Assuming pressure at state 22
P[22]=P[18]

//Assuming the temperature at state 22
T[22]=T_s[22]+0.5

//Specific entropy (kJ/kg-K) of warm seawater at state 22
s[22]=sw_entropy(T[22], S, P[22])/1000

//Pump #3

//Mass balance equation
m_dot[22] =m_dot[21]

//Energie balance equation
m_dot[21]*h[21]+W_dot_Pump_3=m_dot[22]*h[22]

//Entropy balance equation
m_dot[21]*s[21]+S_dot_gen_Pump_3=m_dot[22]*s[22]

//Exergy balance equation
m_dot[21]*ex[21]+W_dot_Pump_3=m_dot[22]*ex[22] +Ex_dot_dest_Pump_3

//Calculation specific exergy of warm seawater at states 21 and 22
ex[21]=(h[17]-h[0])-(T_0+273.15)*(s[21]-s[0])
ex[22]=(h[22]-h[0])-(T_0+273.15)*(s[22]-s[0])

T[24]=T[23]
T[25]=T[23]
P[24]=P[23]
P[25]=P[23]
P[23]=P[22]

//Cold seawater balance equation at the last condenser
m_dot[23]= m_dot[22]

//Where m_dot_23 can be calculated as following
m_dot[23]= m_dot[24]+m_dot[25]

//Assuming return cold seawater pipe inner diameter ID_rcsw is 0.25 m
ID_rcsw=0.25 [m]

```

```

//Density (kg/m^3) of cold seawater at state 25
rho[25]=sw_density(T[25], S, P[25])

//Specific volume (m^3/kg) of warm sea water
mu[25]=1/rho[25]

//Volumetric flow rate in m^3/s
V_dot[25]=m_dot[25]/rho[25]

//Renold Number
Re[25]=4*m_dot[25]/(mu[25]*pi*ID_rcsw)

//Mass flow rate of warm seawater returning to the sea
m_dot[25]= rho[25]*v_e[25]*(Pi*(ID_rcsw/2)^2)

//Economic puping velocity (m/s)
v_e[25]=v_e[17]

//Enthalpy kJ/kg of returning cold seawater at state 25
h[25]=sw_enthalpy(T[25], S,P[25])/1000

//Specific entropy (kJ/kg-K) of returning cold seawater at state 25
s[25]=sw_entropy(T[25], S, P[25])/1000

//Calculation specific exergy of return cold seawater at states 25
ex[25]=(h[25]-h[0])-(T_0+273.15)*(s[25]-s[0])

//The Overall System energy efficiency
eta_Overall_System=(W_dot_net-(W_dot_Pump_3+
W_dot_Pump_1+W_dot_Pump_4+W_dot_Pump_2))/Q_dot_SF

W_dot_Pump_4=W_dot_Pump_1

{-----MULTI EFFECT DESALINATION SYSTEM -----}
{-----}
{-----Effect 1-----}

"Effect number"

Effect[1] = 1
{-----Heating steam properties-----}

"Assuming temperature stays constant for now"
"Heating Source temperature"

T_s =90[C]

"Enthalpy of vaporization of steam entering"
h[19] = sw_enthalpy(T_s,X_f,P_e[1])/1000

"Enthalpy of vaporization of steam exiting"
h[119] = sw_enthalpy(T[119],X_f,P_e[1])/1000

"-----Temperatures-----"

```

"Top brine temperature"

$$TBT = \Delta_{Last\_Cond} + T_{sw}$$

"Last Condenser increase temperature"

$$\Delta_{Last\_Cond} = 25 \text{ [C]}$$

"Feed brine temperature"

$$T_{f[1]} = TBT$$

"Temperature of saturated distillate vapour"

$$T_{dv[1]} = T_s - BPE[1]$$

"Boiling point elevation"

$$BPE[1] = \text{sw\_bpe}(T_{dv[1]}, X_f)$$

"Bottom brine temperature"

$$BBT = 56 \text{ [C]}$$

"Number of effects"

$$N = 8$$

"Temperature difference between effects"

$$\Delta_{T\_mes} = ((TBT - BBT) / (N - 1)) * (-1)$$

"-----Pressures-----"

"Effect pressure"

$$P_e[1] = 0.12$$

"-----Enthalpy values-----"

"Enthalpy of superheated vapour"

$$h_{shv[1]} = \text{enthalpy}(\text{Water}, T = T_{f[1]}, P = P_e[1])$$

"Enthalpy of distillate vapour - sat fluid"

$$h_{dv\_f[1]} = \text{enthalpy}(\text{Water}, T = T_{dv[1]}, x = 0)$$

"Enthalpy of distillate vapour - sat steam"

$$h_{dv\_g[1]} = \text{enthalpy}(\text{Water}, T = T_{dv[1]}, x = 1)$$

"Enthalpy of feed-water "

$$h_{f[1]} = \text{sw\_enthalpy}(T_{f[1]}, X_f, P_e[1]) / 1000$$

"Enthalpy of brine entering effect"

$$h_{b\_acs[1]} = \text{sw\_enthalpy}(T_{f[1]}, X_f, P_e[1]) / 1000$$

"Enthalpy of brine generated"

$$h_b[1] = \text{sw\_enthalpy}(T_b[1], X_b[1], P_e[1])/1000$$

$$T_b[1] = \text{BBT}$$

"Mass flow rate of steam entering MES system"

//Density (kg/m<sup>3</sup>) of warm seawater at state 19 (heating source)

$$\rho[19] = \text{sw\_density}(T_s, X_f, P[19])$$

$$P[19] = 0.012 * \text{convert}(\text{MPa}, \text{kPa})$$

//Specific volume (m<sup>3</sup>/kg) of warm sea water

$$\mu[19] = 1/\rho[19]$$

//Volumetric flow rate in m<sup>3</sup>/s

$$V_{\dot{}}[19] = m_{\dot{}}_s/\rho[19]$$

//Reynold Number

$$Re[19] = 4 * m_{\dot{}}_s / (\mu[19] * \pi * ID_{sw})$$

//Mass flow rate of warm seawater (heating source)

$$m_{\dot{}}_s = \rho[19] * v_f * (\pi * (ID_{sw}/2)^2)$$

"Salt content of raw seawater"

$$X_f = 36 \text{ [g/kg]}$$

"Sea water temperature"

$$T_{sw} = 25 \text{ [C]}$$

"-----Governing equations-----"

"Mass balances"

"Brine entering effect"

//Mass flow rate of warm seawater

$$m_{\dot{}}_f[1] = \rho_f * v_f * (\pi * (ID_{sw}/2)^2)$$

$$\rho_f = \text{sw\_density}(T_f[1], X_f, P_e[1])$$

//Assumed Design Velocity for economical pumping

$$v_f = 1 \text{ [m/s]}$$

"Seawater piping internal diameter"

$$ID_{sw} = 0.7 \text{ [m]}$$

"Brine entering after flashing"

$$m_{\dot{}}_f[1] = m_{\dot{}}_b_{acs}[1] + m_{\dot{}}_gf[1]$$

"No flashing in 1st effect"

m\_dot\_gf[1] = 0

"Boiling of brine"

m\_dot\_b\_acs[1] = m\_dot\_gb[1] + m\_dot\_b[1]

"Distillate vapour formed in effect"

m\_dot\_dv[1] = m\_dot\_gf[1] + m\_dot\_gb[1] + m\_dot\_df[1]

"-----Entropy-----"

//Specific entropy (kJ/kg-K) of hot seawater heating source at state 19

s[19]=sw\_entropy(T\_s , X\_f, P\_e[1])/1000

//Specific entropy (kJ/kg-K) of feed brine

s\_f[1]=sw\_entropy(T\_f[1] , X\_f, P\_e[1])/1000

//Calculation specific entropy (kJ/kg-K) of condensate seawater at state 119

s[119]=sw\_entropy(T[119] , X\_f, P\_e[1])/1000

T[119]=15[C]

//Calculation specific entropy (kJ/kg-K) of vapor formed

s\_dv[1]=entropy(Water,T=T\_dv[1],P=P\_e[1])

//Calculation specific entropy (kJ/kg-K) of brine exiting the first effect

s\_b[1]=sw\_entropy(T\_b[1] , X\_b[1], P\_e[1])/1000

"-----Specific Exergy-----"

T\_0=20 [C]

P[0]=1.01325\*convert(bar,kPa)

h[0]=enthalpy(Water,P=P[0],T=T\_0)

s[0]=entropy(Water,P=P[0],T=T\_0)

//Calculation specific exergy (kJ/kg) of hot seawater heating source

ex[19]=(h[19]-h[0])-(T\_0+273.15)\*(s[19]-s[0])

//Calculation specific exergy (kJ/kg) of condensate seawater at state 119

ex[119]=(h[119]-h[0])-(T\_0+273.15)\*(s[119]-s[0])

//Calculation specific exergy (kJ/kg) of brine exiting the first effect

ex\_b[1]=(h\_b[1]-h[0])-(T\_0+273.15)\*(s\_b[1]-s[0])

//Calculation specific exergy (kJ/kg) of vapor formed

ex\_dv[1]=(h\_dv\_g[1]-h[0])-(T\_0+273.15)\*(s\_dv[1]-s[0])

//Specific exergy (kJ/kg) of feed brine

ex\_f[1]=(h\_f[1]-h[0])-(T\_0+273.15)\*(s\_f[1]-s[0])

"-----Entropy balance Equation-----"

m\_dot\_f[1]\*s\_f[1]+S\_dot\_gen[1] + (Q\_dot\_eff[1]/(T\_0+273.15))=

m\_dot\_b[1]\*s\_b[1]+((m\_dot\_dv[1]\*h\_dv\_g[1])/(T\_dv[1]+273.15))-c\_p[1]\*(ln((T\_b[1]+273.15)/(T\_f[1]+273.15)))

c\_p[1]=(sw\_spheat(T\_b[1], X\_b[1], P\_e[1]))/1000

```

"-----Exergy balance Equation-----"
m_dot_f[1]*ex_f[1]+Q_dot_eff[1]*(1-
((T_0+273.15)/(T_dv[1]+273.15)))=m_dot_b[1]*ex_b[1]+m_dot_dv[1]*ex_dv[1]+EX_dot_dest_eff[1]-
c_p[1]*(T_0+273.15)*(ln((T_b[1]+273.15)/(T_f[1]+273.15)))

"-----Flash chamber-----"

"Flash box - 1st effect has no flash chamber"

"Distillate generated by flashing"

m_dot_df[1] = 0

"Distillate condensed"

m_dot_d[1] = 0

"Salt balance flashing "
X_f*m_dot_f[1] = X_b_acs[1]*m_dot_b_acs[1]

"Salt balance boiling"
X_b_acs[1]*m_dot_b_acs[1] = X_b[1]*m_dot_b[1]
X_b[1]=0.9*0.001*(457628.5-11304.11*(T_b[1])+107.5781*(T_b[1])^2-0.360747*(T_b[1])^3)

"Energy balances"
"Heat transfer area"
Q_dot_eff[1]= A_effect[1]*U_effect[1]*(T_s - T_b[1])

"Heat transfer"
Q_dot_eff[1] = m_dot_s*(h[19]-h[119])

"Overall heat transfer coefficient"
U_effect[1] = (10^(-3))*(1939.1 + 1.40562*(T_s-273.15) - 0.0207525*(T_s-273.15)^2 + 0.0023186*(T_s-
273.15)^3))

{ -----Effect 2 ----- }

"Effect number"
Effect[2] = 2

"-----Temperatures-----"

"Top feed brine temperature"

T_f[2] = T_b[1]

"Bottom brine temperature exiting effect 2"
T_b[2]= T_b[1]-Delta_T_mes

"Temperature of saturated distillate vapour at effect 2"
T_dv[2] = T_dv[1] - Delta_T_mes

"-----Pressures-----"

```

"Effect pressure"

$$P_e[2] = 0.11$$

"-----Enthalpy values-----"

"Enthalpy of superheated vapour"

$$h_{shv}[2] = \text{enthalpy}(\text{Water}, T=T_f[2], P=P_e[2])$$

"Enthalpy of distillate vapour - sat fluid"

$$h_{dv_f}[2] = \text{enthalpy}(\text{Water}, T=T_{dv}[2], x=0)$$

"Enthalpy of distillate vapour - sat steam"

$$h_{dv_g}[2] = \text{enthalpy}(\text{Water}, T=T_{dv}[2], x=1)$$

"Enthalpy of feed-water "

$$h_f[2] = h_b[1]$$

"Enthalpy of brine after flashing process"

$$h_{b\_acs}[2] = \text{sw\_enthalpy}(T_f[2], X_f, P_e[2])/1000$$

"Enthalpy of brine generated after boiling process"

$$h_b[2] = \text{sw\_enthalpy}(T_b[2], X_b[2], P_e[2])/1000$$

//Calculation specific entropy (kJ/kg-K) of condensate vapor exiting effect 2 and entering the first flash chamber

//Assumed condensed vapor temperature is 20 degree celcius

$$T_{dv_f}[2] = 20[\text{C}]$$

"-----Entropy Control volume #1-----"

//Specific entropy (kJ/kg-K) of heating source at effect 2

$$s_{b\_acs}[2] = \text{sw\_entropy}(T_b[2], X_f[2], P_e[2])/1000$$

//Specific entropy (kJ/kg-K) of vapor generated after flashing in effect2

$$s_{gf}[2] = \text{entropy}(\text{Water}, T=T_{dv}[2], P=P_e[2])$$

//Entropy balance equation control volume #1

$$m_{dot\_b}[1] * s_b[1] +$$

$$S_{dot\_gen\_control\_volume\_1}[2] = m_{dot\_b\_acs}[2] * s_{b\_acs}[2] + ((m_{dot\_gf}[2] * h_{dv\_g}[2]) / T_{dv}[2]) -$$

$$c_p[2] * (\ln((T_{b\_acs}[2] + 273.15) / (T_b[2] + 273.15)))$$

$$c_p[2] = (\text{sw\_spheat}(T_b[2], X_f, P_e[2])) / 1000$$

//Assuming flashing happens at the temperature  $T_b[1]$

$$T_{b\_acs}[2] = T_b[1]$$

"-----Entropy Control volume #2-----"

//Specific entropy (kJ/kg-K) of brine exiting effect 2

$$s_b[2] = \text{sw\_entropy}(T_b[2], X_b[2], P_e[2])/1000$$

//Entropy balance equation control volume #2

$$m_{dot\_b\_acs}[2] * s_{b\_acs}[2] + S_{dot\_gen\_control\_volume\_2}[2]$$

$$+ (Q_{dot\_eff}[2] / (T_0 + 273.15)) = m_{dot\_b}[2] * s_b[2] + ((m_{dot\_gb}[2] * h_{dv\_g}[2]) / T_{dv}[2]) -$$

$$c_p[2] * (\ln((T_b[2] + 273.15) / (T_{b\_acs}[2] + 273.15)))$$

//Calculation specific exergy (kJ/kg) of brine exiting effect 2

$$\text{ex\_b}[2]=(\text{h\_b}[2]-\text{h}[0])-(\text{T}_0+273.15)*(\text{s\_b}[2]-\text{s}[0])$$

$$\text{s\_dv}[2]=\text{entropy}(\text{Water}, \text{T}=\text{T\_dv}[2], \text{P}=\text{P\_e}[2])$$

"-----Exergy balance Equation Control Volume #1 -----"

$$\text{m\_dot\_b}[1]*\text{ex\_b}[1]=\text{m\_dot\_b\_acs}[2]*\text{ex\_b\_acs}[2]+\text{m\_dot\_gf}[2]*\text{ex\_gf}[2]+\text{EX\_dot\_dest\_ctrl\_vol\_1}[2]$$

$$\text{ex\_b\_acs}[2]=(\text{h\_b\_acs}[2]-\text{h}[0])-(\text{T}_0+273.15)*(\text{s\_b\_acs}[2]-\text{s}[0])$$

$$\text{ex\_gf}[2]=(\text{h\_dv\_g}[2]-\text{h}[0])-(\text{T}_0+273.15)*(\text{s\_dv}[2]-\text{s}[0])$$

"-----Exergy balance Equation Control Volume #2 -----"

$$\text{m\_dot\_f}* \text{ex\_f}[1]+ \text{Q\_dot\_eff}[2]*(1-((\text{T}_0+273.15)/(\text{T\_dv}[1]+273.15)))=\text{m\_dot\_b}[2]*\text{ex\_b}[2]+\text{m\_dot\_gb}[2]*\text{ex\_gb}[2]+\text{EX\_dot\_dest\_Ctrl\_Vol}[2]-\text{c\_p}[2]*(\text{T}_0+273.15)*(\ln((\text{T\_b}[2]+273.15)/(\text{T\_b}[1]+273.15)))$$

$$\text{ex\_gb}[2]=(\text{h\_dv\_g}[2]-\text{h}[0])-(\text{T}_0+273.15)*(\text{s\_gb}[2]-\text{s}[0])$$

//Specific entropy (kJ/kg-K) of vapor generated after boiling in effect2

$$\text{s\_gb}[2]=\text{entropy}(\text{Water}, \text{T}=\text{T\_dv}[2], \text{P}=\text{P\_e}[2])$$

//Total Exergy destruction by effect 2

$$\text{EX\_dot\_dest\_eff}[2]=\text{EX\_dot\_dest\_ctrl\_vol\_1}[2] + \text{EX\_dot\_dest\_Ctrl\_Vol}[2]$$

"-----Governing equations-----"

"Mass balances"

"Brine entering after flashing"

$$\text{m\_dot\_b}[2] = \text{m\_dot\_b\_acs}[2] + \text{m\_dot\_gf}[2]$$

$$\text{m\_dot\_f}[2]=\text{m\_dot\_b}[1]$$

"Boiling of brine"

$$\text{m\_dot\_b\_acs}[2] = \text{m\_dot\_gb}[2] + \text{m\_dot\_b}[2]$$

"Distillate vapour formed in effect"

$$\text{m\_dot\_dv}[2] = \text{m\_dot\_gf}[2] + \text{m\_dot\_gb}[2] + \text{m\_dot\_df}[2]$$

"Salt balance"

"Flashing of brine"

$$\text{X\_b}[2]*\text{m\_dot\_f}[1] = \text{X\_b\_acs}[2]*\text{m\_dot\_b\_acs}[2]$$

$$\text{X\_f}[2]=\text{X\_b}[1]$$

"Boiling over tubes"

$$\text{X\_b\_acs}[2]*\text{m\_dot\_b\_acs}[2] = \text{X\_b}[2]*\text{m\_dot\_b}[2]$$

$$\text{X\_b\_acs}[2]=0.9*0.001*(457628.5-11304.11*\text{T\_b}[1]+107.5781*(\text{T\_b}[1])^2-0.360747*(\text{T\_b}[1])^3)$$

"Energy balances"

"Flashing of brine"

$$\text{m\_dot\_f}[2]*\text{h\_f}[2] = \text{m\_dot\_b\_acs}[2]*\text{h\_b\_acs}[2] + \text{m\_dot\_gf}[2]*\text{h\_shv}[2]$$

"Distillate vapour formed in effect"

$$\text{m\_dot\_dv}[2]*\text{h\_dv\_g\_in}[2] = \text{m\_dot\_gf}[2]*\text{h\_shv}[2] + \text{m\_dot\_gb}[2]*\text{h\_shv}[2] + \text{m\_dot\_df}[2]*\text{h\_dv\_g}[2]$$

"Effect heat source"

$$\text{m\_dot\_dv}[1]*\text{h\_dv\_g}[2] + \text{m\_dot\_b\_acs}[2]*\text{h\_b\_acs}[2] = \text{m\_dot\_dv}[1]*\text{h\_dv\_f}[2] + \text{m\_dot\_gb}[2]*\text{h\_shv}[2] + \text{m\_dot\_b}[2]*\text{h\_b}[2]$$

"Effect Heat transfer area"

$$Q_{\text{dot\_eff}}[2] = A_{\text{effect}}[2] * U_{\text{effect}}[2] * (T_{\text{dv}}[1] - T_{\text{b}}[2])$$

"Overall heat transfer coefficient"

$$U_{\text{effect}}[2] = (10^{(-3)} * (1939.1 + 1.40562 * (T_{\text{dv}}[1] - 273.15)) - 0.0207525 * (T_{\text{dv}}[1] - 273.15)^2 + 0.0023186 * (T_{\text{dv}}[1] - 273.15)^3)$$

"Heat transfer"

$$Q_{\text{dot\_eff}}[2] = m_{\text{dot\_dv}}[1] * (h_{\text{dv\_g}}[2] - h_{\text{dv\_f}}[2])$$

"-----Flash chamber-----"

"Mass balances"

"Mass flow into flash chamber"

"Flashing of previous flash chamber distillate"

$$m_{\text{dot\_d}}[1] = m_{\text{dot\_d\_gf}}[2] + m_{\text{dot\_d\_gc}}[2]$$

"Flashing of condensed distillate vapour heat source"

$$m_{\text{dot\_dv}}[1] = m_{\text{dot\_dv\_gf}}[2] + m_{\text{dot\_dv\_gc}}[2]$$

"Mass flow out of flash chamber "

"Distillate generated by flashing"

$$m_{\text{dot\_df}}[2] = m_{\text{dot\_d\_gf}}[2] + m_{\text{dot\_dv\_gf}}[2]$$

"Distillate generated by condensation"

$$m_{\text{dot\_d}}[2] = m_{\text{dot\_d\_gc}}[2] + m_{\text{dot\_dv\_gc}}[2]$$

"Energy balances"

"Flashing of distillate from previous flash chamber"

$$m_{\text{dot\_d}}[1] * h_{\text{dv\_f}}[1] = m_{\text{dot\_d\_gf}}[2] * h_{\text{dv\_g}}[2] + m_{\text{dot\_d\_gc}}[2] * h_{\text{dv\_f}}[2]$$

"Flashing of condensed distillate vapour heat source"

$$m_{\text{dot\_dv}}[1] * h_{\text{dv\_f}}[1] = m_{\text{dot\_dv\_gf}}[2] * h_{\text{dv\_g}}[2] + m_{\text{dot\_dv\_gc}}[2] * h_{\text{dv\_f}}[2]$$

{ -----Effect 3 ----- }

"Effect number"

$$\text{Effect}[3] = 3$$

"-----Temperatures-----"

"Top feed brine temperature"

$$T_{\text{f}}[3] = T_{\text{b}}[2]$$

"Bottom brine temperature exiting effect 3"

$$T_{\text{b}}[3] = T_{\text{b}}[2] - \Delta T_{\text{mes}}$$

"Temperature of saturated distillate vapour at effect 3"

$$T_{\text{dv}}[3] = T_{\text{dv}}[2] - \Delta T_{\text{mes}}$$

"-----Pressures-----"

"Effect pressure"

P\_e[3]=0.10

"-----Enthalpy values-----"

"Enthalpy of superheated vapour"

h\_shv[3] = **enthalpy**(Water,T=T\_f[3],P=P\_e[3])

"Enthalpy of distillate vapour - sat fluid"

h\_dv\_f[3] = **enthalpy**(Water,T=T\_dv[3],x=0)

"Enthalpy of distillate vapour - sat steam"

h\_dv\_g[3] = **enthalpy**(Water,T=T\_dv[3],x=1)

"Enthalpy of feed-water "

h\_f[3] = h\_b[2]

"Enthalpy of brine after flashing process"

h\_b\_acs[3] = **sw\_enthalpy**(T\_f[3],X\_b[2],P\_e[3])/1000

"Enthalpy of brine generated after boiling process"

h\_b[3] = **sw\_enthalpy**(T\_b[3],X\_b[3],P\_e[3])/1000

//Calculation specific entropy (kJ/kg-K) of condensate vapor exiting effect 3 and entering the first flash chamber

//Assumed condensed vapor temperature is 20 degree celcius

T\_dv\_f[3]=20[C]

"-----Entropy Control volume #1-----"

//Specific entropy (kJ/kg-K) of heating source at effect 3

s\_b\_acs[3]=**sw\_entropy**(T\_b[3] , X\_b[2], P\_e[3])/1000

//Specific entropy (kJ/kg-K) of vapor generated after flashing in effect 3

s\_gf[3]=**entropy**(Water,T=T\_dv[3],P=P\_e[3])

//Entropy balance equation control volume #1

m\_dot\_b[2]\*s\_b[2]+

S\_dot\_gen\_control\_volume\_1[3]=m\_dot\_b\_acs[3]\*s\_b\_acs[3]+((m\_dot\_gf[3]\*h\_dv\_g[3])/T\_dv[3])-

c\_p[3]\*(ln((T\_b\_acs[3]+273.15)/(T\_b[3]+273.15)))

c\_p[3]=(**sw\_spheat**(T\_b[3], X\_f, P\_e[3]))/1000

//Assuming flashing happens at the temperature T\_b[2]

T\_b\_acs[3]=T\_b[2]

"-----Entropy Control volume #2-----"

//Specific entropy (kJ/kg-K) of brine exiting effect 3

s\_b[3]=**sw\_entropy**(T\_b[3] , X\_b[3], P\_e[3])/1000

//Entropy balance equation control volume #2

$m_{\text{dot}_b\text{acs}[3]} * s_{\text{b\_acs}[3]} + S_{\text{dot\_gen\_control\_volume\_2}[3]} + (Q_{\text{dot\_eff}[3]} / (T_0 + 273.15)) = m_{\text{dot}_b[3]} * s_{\text{b}[3]} + ((m_{\text{dot\_gb}[3]} * h_{\text{dv\_g}[3]}) / T_{\text{dv}[3]}) - c_{\text{p}[3]} * (\ln((T_{\text{b}[3]} + 273.15) / (T_{\text{b\_acs}[3]} + 273.15)))$

//Calculation specific exergy (kJ/kg) of brine exiting effect 3

$ex_{\text{b}[3]} = (h_{\text{b}[3]} - h[0]) - (T_0 + 273.15) * (s_{\text{b}[3]} - s[0])$

$s_{\text{dv}[3]} = \text{entropy}(\text{Water}, T = T_{\text{dv}[3]}, P = P_{\text{e}[3]})$

"-----Exergy balance Equation Control Volume #1 -----"

$m_{\text{dot}_b[2]} * ex_{\text{b}[2]} = m_{\text{dot}_b\text{acs}[3]} * ex_{\text{b\_acs}[3]} + m_{\text{dot\_gf}[3]} * ex_{\text{gf}[3]} + EX_{\text{dot\_dest\_ctrl\_vol\_1}[3]}$

$ex_{\text{b\_acs}[3]} = (h_{\text{b\_acs}[3]} - h[0]) - (T_0 + 273.15) * (s_{\text{b\_acs}[3]} - s[0])$

$ex_{\text{gf}[3]} = (h_{\text{dv\_g}[3]} - h[0]) - (T_0 + 273.15) * (s_{\text{dv}[3]} - s[0])$

"-----Exergy balance Equation Control Volume #2 -----"

$m_{\text{dot}_b\text{acs}[3]} * ex_{\text{b\_acs}[3]} + Q_{\text{dot\_eff}[3]} * (1 - ((T_0 + 273.15) / (T_{\text{dv}[3]} + 273.15))) = m_{\text{dot}_b[3]} * ex_{\text{b}[3]} + m_{\text{dot\_gb}[3]} * ex_{\text{gb}[3]} + EX_{\text{dot\_dest\_Ctrl\_Vol}[3]} - c_{\text{p}[3]} * (T_0 + 273.15) * (\ln((T_{\text{b}[3]} + 273.15) / (T_{\text{b}[2]} + 273.15)))$

$ex_{\text{gb}[3]} = (h_{\text{dv\_g}[3]} - h[0]) - (T_0 + 273.15) * (s_{\text{gb}[3]} - s[0])$

//Specific entropy (kJ/kg-K) of vapor generated after boiling in effect 3

$s_{\text{gb}[3]} = \text{entropy}(\text{Water}, T = T_{\text{dv}[3]}, P = P_{\text{e}[3]})$

//Total Exergy destruction by effect 2

$EX_{\text{dot\_dest\_eff}[3]} = EX_{\text{dot\_dest\_ctrl\_vol\_1}[3]} + EX_{\text{dot\_dest\_Ctrl\_Vol}[3]}$

"-----Governing equations-----"

"Mass balances"

"Brine entering after flashing"

$m_{\text{dot}_f[3]} = m_{\text{dot}_b\text{acs}[3]} + m_{\text{dot\_gf}[3]}$

$m_{\text{dot}_f[3]} = m_{\text{dot}_b[2]}$

"Boiling of brine"

$m_{\text{dot}_b\text{acs}[3]} = m_{\text{dot\_gb}[3]} + m_{\text{dot}_b[3]}$

"Distillate vapour formed in effect"

$m_{\text{dot}_\text{dv}[3]} = m_{\text{dot\_gf}[3]} + m_{\text{dot\_gb}[3]} + m_{\text{dot}_\text{df}[3]}$

"Salt balance"

"Flashing of brine"

$X_{\text{f}[3]} * m_{\text{f}[3]} = X_{\text{b\_acs}[3]} * m_{\text{dot}_b\text{acs}[3]}$

$X_{\text{f}[3]} = X_{\text{b}[2]}$

"Boiling over tubes"

$X_{\text{b\_acs}[3]} * m_{\text{dot}_b\text{acs}[3]} = X_{\text{b}[3]} * m_{\text{dot}_b[3]}$

$X_{\text{b}[3]} = (0.9 * 0.001 * (457628.5 - 11304.11 * T_{\text{b}[3]} + 107.5781 * (T_{\text{b}[3]})^2 - 0.360747 * (T_{\text{b}[3]})^3))$

"Energy balances"

"Flashing of brine"

$m_{\text{dot}_f[3]} * h_{\text{f}[3]} = m_{\text{dot}_b\text{acs}[3]} * h_{\text{b\_acs}[3]} + m_{\text{dot\_gf}[3]} * h_{\text{shv}[3]}$

"Distillate vapour formed in effect"

$$m_{\text{dot\_dv}}[3]*h_{\text{dv\_g\_in}}[3] = m_{\text{dot\_gf}}[3]*h_{\text{shv}}[3] + m_{\text{dot\_gb}}[3]*h_{\text{shv}}[3] + m_{\text{dot\_df}}[3]*h_{\text{dv\_g}}[3]$$

"Effect heat source"

$$m_{\text{dot\_dv}}[2]*h_{\text{dv\_g}}[3] + m_{\text{dot\_b\_acs}}[3]*h_{\text{b\_acs}}[3] = m_{\text{dot\_dv}}[2]*h_{\text{dv\_f}}[3] + m_{\text{dot\_gb}}[3]*h_{\text{shv}}[3] + m_{\text{dot\_b}}[3]*h_{\text{b}}[3]$$

"Effect Heat transfer area"

"

$$Q_{\text{dot\_eff}}[3] = A_{\text{effect}}[3]*U_{\text{effect}}[3]*(T_{\text{dv}}[2] - T_{\text{b}}[3])$$

"Overall heat transfer coefficient"

$$U_{\text{effect}}[3] = (10^{-3})*(1939.1 + 1.40562*(T_{\text{dv}}[2]-273.15) - 0.0207525*(T_{\text{dv}}[2]-273.15)^2 + 0.0023186*(T_{\text{dv}}[2]-273.15)^3)$$

"Heat transfer"

$$Q_{\text{dot\_eff}}[3] = m_{\text{dot\_dv}}[2]*(h_{\text{dv\_g}}[3]-h_{\text{dv\_f}}[3])$$

"-----Flash chamber-----"

"Mass balances"

"Mass flow into flash chamber"

"Flashing of previous flash chamber distillate"

$$m_{\text{dot\_d}}[2] = m_{\text{dot\_d\_gf}}[3] + m_{\text{dot\_d\_gc}}[3]$$

"Flashing of condensed distillate vapour heat source"

$$m_{\text{dot\_dv}}[2] = m_{\text{dot\_dv\_gf}}[3] + m_{\text{dot\_dv\_gc}}[3]$$

"Mass flow out of flash chamber"

"Distillate generated by flashing"

$$m_{\text{dot\_df}}[3] = m_{\text{dot\_d\_gf}}[3] + m_{\text{dot\_dv\_gf}}[3]$$

"Distillate generated by condensation"

$$m_{\text{dot\_d}}[3] = m_{\text{dot\_d\_gc}}[3] + m_{\text{dot\_dv\_gc}}[3]$$

"Energy balances"

"Flashing of distillate from previous flash chamber"

$$m_{\text{dot\_d}}[2]*h_{\text{dv\_f}}[2] = m_{\text{dot\_d\_gf}}[3]*h_{\text{dv\_g}}[3] + m_{\text{dot\_d\_gc}}[3]*h_{\text{dv\_f}}[3]$$

"Flashing of condensed distillate vapour heat source"

$$m_{\text{dot\_dv}}[2]*h_{\text{dv\_f}}[2] = m_{\text{dot\_dv\_gf}}[3]*h_{\text{dv\_g}}[3] + m_{\text{dot\_dv\_gc}}[3]*h_{\text{dv\_f}}[3]$$

{-----Effect 4-----}

"Effect number"

$$\text{Effect}[4] = 4$$

"-----Temperatures-----"

"Top feed brine temperature"

$$T_{f[4]} = T_{b[3]}$$

"Bottom brine temperature exiting effect 4"

$$T_{b[4]} = T_{b[3]} - \Delta T_{mes}$$

"Temperature of saturated distillate vapour at effect 4"

$$T_{dv[4]} = T_{dv[3]} - \Delta T_{mes}$$

"-----Pressures-----"

"Effect pressure"

$$P_{e[4]} = 0.9$$

"-----Enthalpy values-----"

"Enthalpy of superheated vapour"

$$h_{shv[4]} = \text{enthalpy}(\text{Water}, T=T_{f[4]}, P=P_{e[4]})$$

"Enthalpy of distillate vapour - sat fluid"

$$h_{dv_f[4]} = \text{enthalpy}(\text{Water}, T=T_{dv[4]}, x=0)$$

"Enthalpy of distillate vapour - sat steam"

$$h_{dv_g[4]} = \text{enthalpy}(\text{Water}, T=T_{dv[4]}, x=1)$$

"Enthalpy of feed-water "

$$h_{f[4]} = h_{b[3]}$$

"Enthalpy of brine after flashing process"

$$h_{b\_acs[4]} = \text{sw\_enthalpy}(T_{f[4]}, X_{f[4]}, P_{e[4]})/1000$$

"Enthalpy of brine generated after boiling process"

$$h_{b[4]} = \text{sw\_enthalpy}(T_{b[4]}, X_{b[4]}, P_{e[4]})/1000$$

//Calculation specific entropy (kJ/kg-K) of condensate vapor exiting effect 4 and entering the first flash chamber

//Assumed condensed vapor temperature is 20 degree celcius

$$T_{dv_f[4]} = 20[\text{C}]$$

"-----Entropy Control volume #1-----"

//Specific entropy (kJ/kg-K) of heating source at effect 4

$$s_{b\_acs[4]} = \text{sw\_entropy}(T_{b[4]}, X_{f[4]}, P_{e[4]})/1000$$

//Specific entropy (kJ/kg-K) of vapor generated after flashing in effect4

$$s_{gf[4]} = \text{entropy}(\text{Water}, T=T_{dv[4]}, P=P_{e[4]})$$

//Entropy balance equation control volume #1

```

m_dot_b[3]*s_b[3]+
S_dot_gen_control_volume_1[4]=m_dot_b_acs[4]*s_b_acs[4]+((m_dot_gf[4]*h_dv_g[4])/T_dv[4])-
c_p[4]*(ln((T_b_acs[4]+273.15)/(T_b[4]+273.15)))
c_p[4]=(sw_spcheat(T_b[4], X_b[4], P_e[4]))/1000

//Assuming flashing happens at the temperature T_b[3]
T_b_acs[4]=T_b[3]

"-----Entropy Control volume #2-----"

//Specific entropy (kJ/kg-K) of brine exiting effect 4
s_b[4]=sw_entropy(T_b[4], X_b[4], P_e[4])/1000

//Entropy balance equation control volume #2
m_dot_b_acs[4]*s_b_acs[4]+ S_dot_gen_control_volume_2[4]
+(Q_dot_eff[4]/(T_0+273.15))=m_dot_b[4]*s_b[4]+((m_dot_gb[4]*h_dv_g[4])/T_dv[4])-
c_p[4]*(ln((T_b[4]+273.15)/(T_b_acs[4]+273.15)))

//Calculation specific exergy (kJ/kg) of brine exiting effect 4
ex_b[4]=(h_b[4]-h[0])-(T_0+273.15)*(s_b[4]-s[0])

s_dv[4]=entropy(Water,T=T_dv[4],P=P_e[4])

"-----Exergy balance Equation Control Volume #1 -----"
m_dot_b[3]*ex_b[3]=m_dot_b_acs[4]*ex_b_acs[4]+m_dot_gf[4]*ex_gf[4]+EX_dot_dest_ctrl_vol_1[4]
ex_b_acs[4]=(h_b_acs[4]-h[0])-(T_0+273.15)*(s_b_acs[4]-s[0])
ex_gf[4]=(h_dv_g[4]-h[0])-(T_0+273.15)*(s_dv[4]-s[0])

"-----Exergy balance Equation Control Volume #2 -----"
m_dot_b_acs[4]*ex_b_acs[4]+Q_dot_eff[4]*(1-
((T_0+273.15)/(T_dv[4]+273.15)))=m_dot_b[4]*ex_b[4]+m_dot_gb[4]*ex_gb[4]+EX_dot_dest_Ctrl_Vol[4]-
c_p[4]*(T_0+273.15)*(ln((T_b[4]+273.15)/(T_b[3]+273.15)))

ex_gb[4]=(h_dv_g[4]-h[0])-(T_0+273.15)*(s_gb[4]-s[0])
//Specific entropy (kJ/kg-K) of vapor generated after boiling in effect 4
s_gb[4]=entropy(Water,T=T_dv[4],P=P_e[4])

//Total Exergy destruction by effect 4
EX_dot_dest_eff[4]=EX_dot_dest_ctrl_vol_1[4] + EX_dot_dest_Ctrl_Vol[4]

"-----Governing equations-----"

"Mass balances"
"Brine entering after flashing"
m_dot_f[4] = m_dot_b_acs[4] +m_dot_gf[4]
m_dot_f[4]=m_dot_b[3]

"Boiling of brine"
m_dot_b_acs[4] = m_dot_gb[4] + m_dot_b[4]

"Distillate vapour formed in effect"
m_dot_dv[4] = m_dot_gf[4] + m_dot_gb[4] + m_dot_df[4]

```

"Salt balance"

"Flashing of brine"

$$X_f[4]*m_f[4] = X_{b\_acs}[4]*m_{dot\_b\_acs}[4]$$
$$X_f[4]=X_b[3]$$

"Boiling over tubes"

$$X_{b\_acs}[4]*m_{dot\_b\_acs}[4] = X_b[4]*m_{dot\_b}[4]$$
$$X_b[4]=0.9*0.001*(457628.5-11304.11*T_b[4]+107.5781*(T_b[4])^2-0.360747*(T_b[4])^3)$$

"Energy balances"

"Flashing of brine"

$$m_{dot\_f}[4]*h_f[4] = m_{dot\_b\_acs}[4]*h_{b\_acs}[4] + m_{dot\_gf}[4]*h_{shv}[4]$$

"Distillate vapour formed in effect"

$$m_{dot\_dv}[4]*h_{dv\_g\_in}[4] = m_{dot\_gf}[4]*h_{shv}[4] + m_{dot\_gb}[4]*h_{shv}[4] + m_{dot\_df}[4]*h_{dv\_g}[4]$$

"Effect heat source"

$$m_{dot\_dv}[3]*h_{dv\_g}[4] + m_{dot\_b\_acs}[4]*h_{b\_acs}[4] = m_{dot\_dv}[3]*h_{dv\_f}[4] + m_{dot\_gb}[4]*h_{shv}[4] + m_{dot\_b}[4]*h_b[4]$$

"Effect Heat transfer area"

"

$$Q_{dot\_eff}[4] = A_{effect}[4]*U_{effect}[4]*(T_{dv}[3] - T_b[4])$$

"Overall heat transfer coefficient"

$$U_{effect}[4] = ((10^{(-3)}*(1939.1 + 1.40562*(T_{dv}[3]-273.15) - 0.0207525*(T_{dv}[3]-273.15)^2 + 0.0023186*(T_{dv}[3]-273.15)^3)))*(-1)$$

"Heat transfer"

$$Q_{dot\_eff}[4] = m_{dot\_dv}[3]*(h_{dv\_g}[4]-h_{dv\_f}[4])$$

"-----Flash chamber-----"

"Mass balances"

"Mass flow into flash chamber"

"Flashing of previous flash chamber distillate"

$$m_{dot\_d}[3] = m_{dot\_d\_gf}[4] + m_{dot\_d\_gc}[4]$$

"Flashing of condensed distillate vapour heat source"

$$m_{dot\_dv}[3] = m_{dot\_dv\_gf}[4] + m_{dot\_dv\_gc}[4]$$

"Mass flow out of flash chamber"

"Distillate generated by flashing"

$$m_{dot\_df}[4] = m_{dot\_d\_gf}[4] + m_{dot\_dv\_gf}[4]$$

"Distillate generated by condensation"

$$m_{dot\_d}[4] = m_{dot\_d\_gc}[4] + m_{dot\_dv\_gc}[4]$$

"Energy balances"

"Flashing of distillate from previous flash chamber"

$$m\_dot\_d[3]*h\_dv\_f[3] = m\_dot\_d\_gf[4]*h\_dv\_g[4] + m\_dot\_d\_gc[4]*h\_dv\_f[4]$$

"Flashing of condensed distillate vapour heat source"

$$m\_dot\_dv[3]*h\_dv\_f[3] = m\_dot\_dv\_gf[4]*h\_dv\_g[4] + m\_dot\_dv\_gc[4]*h\_dv\_f[4]$$

{-----Effect 5-----}

"Effect number"

$$\text{Effect}[5] = 5$$

"-----Temperatures-----"

"Top feed brine temperature"

$$T\_f[5] = T\_b[4]$$

"Bottom brine temperature exiting effect 5"

$$T\_b[5] = T\_b[4] - \Delta T\_mes$$

"Temperature of saturated distillate vapour at effect 5"

$$T\_dv[5] = T\_dv[4] - \Delta T\_mes$$

"-----Pressures-----"

"Effect pressure"

$$P\_e[5] = 0.8$$

"-----Enthalpy values-----"

"Enthalpy of superheated vapour"

$$h\_shv[5] = \text{enthalpy}(\text{Water}, T=T\_f[5], P=P\_e[5])$$

"Enthalpy of distillate vapour - sat fluid"

$$h\_dv\_f[5] = \text{enthalpy}(\text{Water}, T=T\_dv[5], x=0)$$

"Enthalpy of distillate vapour - sat steam"

$$h\_dv\_g[5] = \text{enthalpy}(\text{Water}, T=T\_dv[5], x=1)$$

"Enthalpy of feed-water "

$$h\_f[5] = h\_b[4]$$

"Enthalpy of brine after flashing process"

$$h\_b\_acs[5] = \text{sw\_enthalpy}(T\_f[5], X\_f, P\_e[5])/1000$$

"Enthalpy of brine generated after boiling process"

$$h\_b[5] = \text{sw\_enthalpy}(T\_b[5], X\_f, P\_e[5])/1000$$

//Calculation specific entropy (kJ/kg-K) of condensate vapor exiting effect 5 and entering the first flash chamber

//Assumed condensed vapor temperature is 20 degree celcius

T\_dv\_f[5]=20[C]

"-----Entropy Control volume #1-----"

//Specific entropy (kJ/kg-K) of heating source at effect 5

s\_b\_acs[5]=sw\_entropy(T\_b[5], X\_f[5], P\_e[5])/1000

//Specific entropy (kJ/kg-K) of vapor generated after flashing in effect 5

s\_gf[5]=entropy(Water,T=T\_dv[5],P=P\_e[5])

//Entropy balance equation control volume #1

m\_dot\_b[4]\*s\_b[4]+

S\_dot\_gen\_control\_volume\_1[5]=m\_dot\_b\_acs[5]\*s\_b\_acs[5]+((m\_dot\_gf[5]\*h\_dv\_g[5])/T\_dv[4])-

c\_p[5]\*(ln((T\_b\_acs[5]+273.15)/(T\_b[5]+273.15)))

c\_p[5]=(sw\_spheat(T\_b[5], X\_b[5], P\_e[5])/1000

//Assuming flashing happens at the temperature T\_b[4]

T\_b\_acs[5]=T\_b[4]

"-----Entropy Control volume #2-----"

//Specific entropy (kJ/kg-K) of brine exiting effect 5

s\_b[5]=sw\_entropy(T\_b[5], X\_b[5], P\_e[5])/1000

//Entropy balance equation control volume #2

m\_dot\_b\_acs[5]\*s\_b\_acs[5]+ S\_dot\_gen\_control\_volume\_2[5]

+(Q\_dot\_eff[5]/(T\_0+273.15))=m\_dot\_b[5]\*s\_b[5]+((m\_dot\_gb[5]\*h\_dv\_g[5])/T\_dv[5])-

c\_p[5]\*(ln((T\_b[5]+273.15)/(T\_b\_acs[5]+273.15)))

//Calculation specific exergy (kJ/kg) of brine exiting effect 5

ex\_b[5]=(h\_b[5]-h[0])-(T\_0+273.15)\*(s\_b[5]-s[0])

s\_dv[5]=entropy(Water,T=T\_dv[5],P=P\_e[5])

"-----Exergy balance Equation Control Volume #1 -----"

m\_dot\_b[4]\*ex\_b[4]=m\_dot\_b\_acs[5]\*ex\_b\_acs[5]+m\_dot\_gf[5]\*ex\_gf[5]+EX\_dot\_dest\_ctrl\_vol\_1[5]

ex\_b\_acs[5]=(h\_b\_acs[5]-h[0])-(T\_0+273.15)\*(s\_b\_acs[5]-s[0])

ex\_gf[5]=(h\_dv\_g[5]-h[0])-(T\_0+273.15)\*(s\_dv[5]-s[0])

"-----Exergy balance Equation Control Volume #2 -----"

m\_dot\_b\_acs[5]\*ex\_b\_acs[5]+Q\_dot\_eff[5]\*(1-

((T\_0+273.15)/(T\_dv[5]+273.15)))=m\_dot\_b[5]\*ex\_b[5]+m\_dot\_gb[5]\*ex\_gb[5]+EX\_dot\_dest\_Ctrl\_Vol[5]-

c\_p[5]\*(T\_0+273.15)\*(ln((T\_b[5]+273.15)/(T\_b[4]+273.15)))

ex\_gb[5]=(h\_dv\_g[5]-h[0])-(T\_0+273.15)\*(s\_gb[5]-s[0])

//Specific entropy (kJ/kg-K) of vapor generated after boiling in effect 5

s\_gb[5]=entropy(Water,T=T\_dv[5],P=P\_e[5])

//Total Exergy destruction by effect 5

EX\_dot\_dest\_eff[5]=EX\_dot\_dest\_ctrl\_vol\_1[5] + EX\_dot\_dest\_Ctrl\_Vol[5]

"-----Governing equations-----"

"Mass balances"

"Brine entering after flashing"

m\_dot\_f[5] = m\_dot\_b\_acs[5] +m\_dot\_gf[5]

$$m\_dot\_f[5]=m\_dot\_b[4]$$

"Boiling of brine"

$$m\_dot\_b\_acs[5] = m\_dot\_gb[5] + m\_dot\_b[5]$$

"Distillate vapour formed in effect"

$$m\_dot\_dv[5] = m\_dot\_gf[5] + m\_dot\_gb[5] + m\_dot\_df[5]$$

"Salt balance"

"Flashing of brine"

$$X\_f[5]*m\_f[5] = X\_b\_acs[5]*m\_dot\_b\_acs[5]$$

$$X\_f[5]=X\_b[4]$$

"Boiling over tubes"

$$X\_b\_acs[5]*m\_dot\_b\_acs[5] = X\_b[5]*m\_dot\_b[5]$$

$$X\_b[5]=0.9*0.001*(457628.5-11304.11*T\_b[5]+107.5781*(T\_b[5])^2-0.360747*(T\_b[5])^3)$$

"Energy balances"

"Flashing of brine"

$$m\_dot\_f[5]*h\_f[5] = m\_dot\_b\_acs[5]*h\_b\_acs[5] + m\_dot\_gf[5]*h\_shv[5]$$

"Distillate vapour formed in effect"

$$m\_dot\_dv[5]*h\_dv\_g\_in[5] = m\_dot\_gf[5]*h\_shv[5] + m\_dot\_gb[5]*h\_shv[5] + m\_dot\_df[5]*h\_dv\_g[5]$$

"Effect heat source"

$$m\_dot\_dv[4]*h\_dv\_g[5] + m\_dot\_b\_acs[5]*h\_b\_acs[5] = m\_dot\_dv[4]*h\_dv\_f[5] + m\_dot\_gb[5]*h\_shv[5] + m\_dot\_b[5]*h\_b[5]$$

"Effect Heat transfer area"

"

$$Q\_dot\_eff[5] = A\_effect[5]*U\_effect[5]*(T\_dv[4] - T\_b[5])$$

"Overall heat transfer coefficient"

$$U\_effect[5] = ((10^{(-3)}*(1939.1 + 1.40562*(T\_dv[4]-273.15) - 0.0207525*(T\_dv[4]-273.15)^2 + 0.0023186*(T\_dv[4]-273.15)^3)))*(-1)$$

"Heat transfer"

$$Q\_dot\_eff[5] = m\_dot\_dv[4]*(h\_dv\_g[5]-h\_dv\_f[5])$$

"-----Flash chamber-----"

"Mass balances"

"Mass flow into flash chamber"

"Flashing of previous flash chamber distillate"

$$m\_dot\_d[4] = m\_dot\_d\_gf[5] + m\_dot\_d\_gc[5]$$

"Flashing of condensed distillate vapour heat source"

$$m\_dot\_dv[4] = m\_dot\_dv\_gf[5] + m\_dot\_dv\_gc[5]$$

"Mass flow out of flash chamber"

"Distillate generated by flashing"

$$m\_dot\_df[5] = m\_dot\_d\_gf[5] + m\_dot\_dv\_gf[5]$$

"Distillate generated by condensation"

$$m\_dot\_d[5] = m\_dot\_d\_gc[5] + m\_dot\_dv\_gc[5]$$

"Energy balances"

"Flashing of distillate from previous flash chamber"

$$m\_dot\_d[4]*h\_dv\_f[4] = m\_dot\_d\_gf[5]*h\_dv\_g[5] + m\_dot\_d\_gc[5]*h\_dv\_f[5]$$

"Flashing of condensed distillate vapour heat source"

$$m\_dot\_dv[4]*h\_dv\_f[4] = m\_dot\_dv\_gf[5]*h\_dv\_g[5] + m\_dot\_dv\_gc[5]*h\_dv\_f[5]$$

{-----Effect 6 -----}

"Effect number"

$$\text{Effect}[6] = 6$$

"-----Temperatures-----"

"Top feed brine temperature"

$$T\_f[6] = T\_b[5]$$

"Bottom brine temperature exiting effect 6"

$$T\_b[6] = T\_b[5] - \Delta T\_mes$$

"Temperature of saturated distillate vapour at effect 6"

$$T\_dv[6] = T\_dv[5] - \Delta T\_mes$$

"-----Pressures-----"

"Effect pressure"

$$P\_e[6] = 0.7$$

"-----Enthalpy values-----"

"Enthalpy of superheated vapour"

$$h\_shv[6] = \text{enthalpy}(\text{Water}, T=T\_f[6], P=P\_e[6])$$

"Enthalpy of distillate vapour - sat fluid"

$$h\_dv\_f[6] = \text{enthalpy}(\text{Water}, T=T\_dv[6], x=0)$$

"Enthalpy of distillate vapour - sat steam"

$$h\_dv\_g[6] = \text{enthalpy}(\text{Water}, T=T\_dv[5], x=1)$$

"Enthalpy of feed-water "

$$h\_f[6] = h\_b[5]$$

"Enthalpy of brine after flashing process"

$h_{b\_acs}[6] = \text{sw\_enthalpy}(T\_f[6], X\_f[6], P\_e[6])/1000$

"Enthalpy of brine generated after boiling process"

$h_b[6] = \text{sw\_enthalpy}(T_b[6], X_b[6], P_e[6])/1000$

//Calculation specific entropy (kJ/kg-K) of condensate vapor exiting effect 6 and entering the first flash chamber

//Assumed condensed vapor temperature is 20 degree celcius

$T_{dv\_f}[6]=20[C]$

"-----Entropy Control volume #1-----"

//Specific entropy (kJ/kg-K) of heating source at effect 6

$s_{b\_acs}[6]=\text{sw\_entropy}(T_b[6], X_f[6], P_e[6])/1000$

//Specific entropy (kJ/kg-K) of vapor generated after flashing in effect 6

$s_{gf}[6]=\text{entropy}(\text{Water}, T=T_{dv}[6], P=P_e[6])$

//Entropy balance equation control volume #1

$m_{dot\_b}[5]*s_b[5]+$

$S_{dot\_gen\_control\_volume\_1}[6]=m_{dot\_b\_acs}[6]*s_{b\_acs}[6]+((m_{dot\_gf}[6]*h_{dv\_g}[6])/T_{dv}[5])-$

$c_p[6]*(\ln((T_{b\_acs}[6]+273.15)/(T_b[6]+273.15)))$

$c_p[6]=\text{(sw\_spcheat}(T_b[6], X_b[6], P_e[6])/1000$

//Assuming flashing happens at the temperature  $T_b[5]$

$T_{b\_acs}[6]=T_b[5]$

"-----Entropy Control volume #2-----"

//Specific entropy (kJ/kg-K) of brine exiting effect 6

$s_b[6]=\text{sw\_entropy}(T_b[6], X_b[6], P_e[6])/1000$

//Entropy balance equation control volume #2

$m_{dot\_b\_acs}[6]*s_{b\_acs}[6]+ S_{dot\_gen\_control\_volume\_2}[6]$

$+ (Q_{dot\_eff}[6]/(T_0+273.15))=m_{dot\_b}[6]*s_b[6]+((m_{dot\_gb}[6]*h_{dv\_g}[6])/T_{dv}[6])-$

$c_p[6]*(\ln((T_b[6]+273.15)/(T_{b\_acs}[6]+273.15)))$

//Calculation specific exergy (kJ/kg) of brine exiting the 6 effect

$ex_b[6]=(h_b[6]-h[0])-(T_0+273.15)*(s_b[6]-s[0])$

$s_{dv}[6]=\text{entropy}(\text{Water}, T=T_{dv}[6], P=P_e[6])$

"-----Exergy balance Equation Control Volume #1 -----"

$m_{dot\_b}[5]*ex_b[5]=m_{dot\_b\_acs}[6]*ex_{b\_acs}[6]+m_{dot\_gf}[6]*ex_{gf}[6]+EX_{dot\_dest\_ctrl\_vol\_1}[6]$

$ex_{b\_acs}[6]=(h_{b\_acs}[6]-h[0])-(T_0+273.15)*(s_{b\_acs}[6]-s[0])$

$ex_{gf}[6]=(h_{dv\_g}[6]-h[0])-(T_0+273.15)*(s_{dv}[6]-s[0])$

"-----Exergy balance Equation Control Volume #2 -----"

$m_{dot\_b\_acs}[6]*ex_{b\_acs}[6]+Q_{dot\_eff}[6]*(1-$

$((T_0+273.15)/(T_{dv}[6]+273.15)))=m_{dot\_b}[6]*ex_b[6]+m_{dot\_gb}[6]*ex_{gb}[6]+EX_{dot\_dest\_Ctrl\_Vol}[6]-$

$c_p[6]*(T_0+273.15)*(\ln((T_b[6]+273.15)/(T_b[6]+273.15)))$

$ex_{gb}[6]=(h_{dv\_g}[6]-h[0])-(T_0+273.15)*(s_{gb}[6]-s[0])$

//Specific entropy (kJ/kg-K) of vapor generated after boiling in effect 6

s\_gb[6]=entropy(Water,T=T\_dv[6],P=P\_e[6])

//Total Exergy destruction by effect 6

EX\_dot\_dest\_eff[6]=EX\_dot\_dest\_ctrl\_vol\_1[6] + EX\_dot\_dest\_Ctrl\_Vol[6]

"-----Governing equations-----"

"Mass balances"

"Brine entering after flashing"

m\_dot\_f[6] = m\_dot\_b\_acs[6] + m\_dot\_gf[6]

m\_dot\_f[6]=m\_dot\_b[5]

"Boiling of brine"

m\_dot\_b\_acs[6] = m\_dot\_gb[6] + m\_dot\_b[6]

"Distillate vapour formed in effect"

m\_dot\_dv[6] = m\_dot\_gf[6] + m\_dot\_gb[6] + m\_dot\_df[6]

"Salt balance"

"Flashing of brine"

X\_f[6]\*m\_f[6] = X\_b\_acs[6]\*m\_dot\_b\_acs[6]

X\_f[6]=X\_b[5]

"Boiling over tubes"

X\_b\_acs[6]\*m\_dot\_b\_acs[6] = X\_b[6]\*m\_dot\_b[6]

X\_b[6]=0.9\*0.001\*(457628.5-11304.11\*T\_b[6]+107.5781\*(T\_b[6])^2-0.360747\*(T\_b[6])^3)

"Energy balances"

"Flashing of brine"

m\_dot\_f[6]\*h\_f[6] = m\_dot\_b\_acs[6]\*h\_b\_acs[6] + m\_dot\_gf[6]\*h\_shv[6]

"Distillate vapour formed in effect"

m\_dot\_dv[6]\*h\_dv\_g\_in[6] = m\_dot\_gf[6]\*h\_shv[6] + m\_dot\_gb[6]\*h\_shv[6] + m\_dot\_df[6]\*h\_dv\_g[6]

"Effect heat source"

m\_dot\_dv[5]\*h\_dv\_g[6] + m\_dot\_b\_acs[6]\*h\_b\_acs[6] = m\_dot\_dv[5]\*h\_dv\_f[6] + m\_dot\_gb[6]\*h\_shv[6] + m\_dot\_b[6]\*h\_b[6]

"Effect Heat transfer area"

"

Q\_dot\_eff[6] = A\_effect[6]\*U\_effect[6]\*(T\_dv[5] - T\_b[6])

"Overall heat transfer coefficient"

U\_effect[6] = ((10^(-3))\*(1939.1 + 1.40562\*(T\_dv[5]-273.15) - 0.0207525\*(T\_dv[5]-273.15)^2 + 0.0023186\*(T\_dv[5]-273.15)^3)))\*(-1)

"Heat transfer"

Q\_dot\_eff[6] = m\_dot\_dv[5]\*(h\_dv\_g[6]-h\_dv\_f[6])

"-----Flash chamber-----"

"Mass balances"

"Mass flow into flash chamber"

"Flashing of previous flash chamber distillate"

$$m_{\text{dot}_d[5]} = m_{\text{dot}_d\_gf[6]} + m_{\text{dot}_d\_gc[6]}$$

"Flashing of condensed distillate vapour heat source"

$$m_{\text{dot}_{dv}[5]} = m_{\text{dot}_{dv}\_gf[6]} + m_{\text{dot}_{dv}\_gc[6]}$$

"Mass flow out of flash chamber"

"Distillate generated by flashing"

$$m_{\text{dot}_{df}[6]} = m_{\text{dot}_d\_gf[6]} + m_{\text{dot}_{dv}\_gf[6]}$$

"Distillate generated by condensation"

$$m_{\text{dot}_d[6]} = m_{\text{dot}_d\_gc[6]} + m_{\text{dot}_{dv}\_gc[6]}$$

"Energy balances"

"Flashing of distillate from previous flash chamber"

$$m_{\text{dot}_d[5]}*h_{dv\_f[5]} = m_{\text{dot}_d\_gf[6]}*h_{dv\_g[6]} + m_{\text{dot}_d\_gc[6]}*h_{dv\_f[6]}$$

"Flashing of condensed distillate vapour heat source"

$$m_{\text{dot}_{dv}[5]}*h_{dv\_f[5]} = m_{\text{dot}_{dv}\_gf[6]}*h_{dv\_g[6]} + m_{\text{dot}_{dv}\_gc[6]}*h_{dv\_f[6]}$$

{-----Effect 7 -----}

"Effect number"

$$\text{Effect}[7] = 7$$

"-----Temperatures-----"

"Top feed brine temperature"

$$T\_f[7] = T\_b[6]$$

"Bottom brine temperature exiting effect 7"

$$T\_b[7] = T\_b[6] - \Delta T\_mes$$

"Temperature of saturated distillate vapour at effect 7"

$$T\_dv[7] = T\_dv[6] - \Delta T\_mes$$

"-----Pressures-----"

"Effect pressure"

$$P\_e[7] = 0.6$$

"-----Enthalpy values-----"

"Enthalpy of superheated vapour"

$$h\_shv[7] = \text{enthalpy}(\text{Water}, T=T\_f[7], P=P\_e[7])$$

"Enthalpy of distillate vapour - sat fluid"

$$h\_dv\_f[7] = \text{enthalpy}(\text{Water}, T=T\_dv[7], x=0)$$

"Enthalpy of distillate vapour - sat steam"

$$h_{dv\_g}[7] = \text{enthalpy}(\text{Water}, T=T_{dv}[6], x=1)$$

"Enthalpy of feed-water "

$$h_f[7] = h_b[6]$$

"Enthalpy of brine after flashing process"

$$h_{b\_acs}[7] = \text{sw\_enthalpy}(T_f[7], X_f, P_e[7])/1000$$

"Enthalpy of brine generated after boiling process"

$$h_b[7] = \text{sw\_enthalpy}(T_b[7], X_f, P_e[7])/1000$$

//Calculation specific entropy (kJ/kg-K) of condensate vapor exiting effect 7 and entering the first flash chamber

//Assumed condensed vapor temperature is 20 degree celcius

$$T_{dv\_f}[7]=20[C]$$

"-----Entropy Control volume #1-----"

//Specific entropy (kJ/kg-K) of heating source at effect 7

$$s_{b\_acs}[7]=\text{sw\_entropy}(T_b[7], X_f[7], P_e[7])/1000$$

//Specific entropy (kJ/kg-K) of vapor generated after flashing in effect 7

$$s_{gf}[7]=\text{entropy}(\text{Water}, T=T_{dv}[7], P=P_e[7])$$

//Entropy balance equation control volume #1

$$\begin{aligned} m_{dot\_b}[6]*s_b[6]+S_{dot\_gen\_control\_volume\_1}[7]&=m_{dot\_b\_acs}[7]*s_{b\_acs}[7] \\ &+((m_{dot\_gf}[7]*h_{dv\_g}[7])/T_{dv}[6])-c_p[7]*(\ln((T_{b\_acs}[7]+273.15)/(T_b[7]+273.15))) \\ c_p[7]&=(\text{sw\_spheat}(T_b[7], X_b[7], P_e[7])/1000 \end{aligned}$$

//Assuming flashing happens at the temperature  $T_b[6]$

$$T_{b\_acs}[7]=T_b[6]$$

"-----Entropy Control volume #2-----"

//Specific entropy (kJ/kg-K) of brine exiting effect 7

$$s_b[7]=\text{sw\_entropy}(T_b[7], X_b[7], P_e[7])/1000$$

//Entropy balance equation control volume #2

$$\begin{aligned} m_{dot\_b\_acs}[7]*s_{b\_acs}[7]+S_{dot\_gen\_control\_volume\_2}[7] \\ &+(Q_{dot\_eff}[7]/(T_0+273.15))=m_{dot\_b}[7]*s_b[7]+((m_{dot\_gb}[7]*h_{dv\_g}[7])/T_{dv}[7]) \\ &-c_p[7]*(\ln((T_b[7]+273.15)/(T_{b\_acs}[7]+273.15))) \end{aligned}$$

//Calculation specific exergy (kJ/kg) of brine exiting the 7 effect

$$ex_b[7]=(h_b[7]-h[0])-(T_0+273.15)*(s_b[7]-s[0])$$

$$s_{dv}[7]=\text{entropy}(\text{Water}, T=T_{dv}[7], P=P_e[7])$$

"-----Exergy balance Equation Control Volume #1 -----"

$m_{\text{dot}_b[6]} \cdot \text{ex}_b[6] = m_{\text{dot}_b\_acs[7]} \cdot \text{ex}_b\_acs[7] + m_{\text{dot}_g[7]} \cdot \text{ex}_g[7] + \text{EX\_dot\_dest\_ctrl\_vol}_1[7]$   
 $\text{ex}_b\_acs[7] = (h_b\_acs[7] - h[0]) - (T_0 + 273.15) \cdot (s_b\_acs[7] - s[0])$   
 $\text{ex}_g[7] = (h_{\text{dv}_g[7]} - h[0]) - (T_0 + 273.15) \cdot (s_{\text{dv}[7]} - s[0])$

"-----Exergy balance Equation Control Volume #2 -----"

$m_{\text{dot}_b\_acs[7]} \cdot \text{ex}_b\_acs[7] + Q_{\text{dot\_eff}[7]} \cdot (1 - ((T_0 + 273.15) / (T_{\text{dv}[7]} + 273.15))) = m_{\text{dot}_b[7]} \cdot \text{ex}_b[7] + m_{\text{dot}_g[7]} \cdot \text{ex}_g[7] + \text{EX\_dot\_dest\_Ctrl\_Vol}[7] - c_p[7] \cdot (T_0 + 273.15) \cdot (\ln((T_b[7] + 273.15) / (T_b[7] + 273.15)))$

$\text{ex}_g[7] = (h_{\text{dv}_g[7]} - h[0]) - (T_0 + 273.15) \cdot (s_{\text{gb}[7]} - s[0])$   
//Specific entropy (kJ/kg-K) of vapor generated after boiling in effect 7  
 $s_{\text{gb}[7]} = \text{entropy}(\text{Water}, T = T_{\text{dv}[7]}, P = P_e[7])$

//Total Exergy destruction by effect 7

$\text{EX\_dot\_dest\_eff}[7] = \text{EX\_dot\_dest\_ctrl\_vol}_1[7] + \text{EX\_dot\_dest\_Ctrl\_Vol}[7]$

"-----Governing equations-----"

"Mass balances"

"Brine entering after flashing"

$m_{\text{dot}_f[7]} = m_{\text{dot}_b\_acs[7]} + m_{\text{dot}_g[7]}$   
 $m_{\text{dot}_f[7]} = m_{\text{dot}_b[6]}$

"Boiling of brine"

$m_{\text{dot}_b\_acs[7]} = m_{\text{dot}_g[7]} + m_{\text{dot}_b[7]}$

"Distillate vapour formed in effect"

$m_{\text{dot}_d[7]} = m_{\text{dot}_g[7]} + m_{\text{dot}_b[7]} + m_{\text{dot}_f[7]}$

"Salt balance"

"Flashing of brine"

$X_f[7] \cdot m_f[7] = X_b\_acs[7] \cdot m_{\text{dot}_b\_acs[7]}$   
 $X_f[7] = X_b[6]$

"Boiling over tubes"

$X_b\_acs[7] \cdot m_{\text{dot}_b\_acs[7]} = X_b[7] \cdot m_{\text{dot}_b[7]}$   
 $X_b[7] = 0.9 \cdot 0.001 \cdot (457628.5 - 11304.11 \cdot T_b[7] + 107.5781 \cdot (T_b[7])^2 - 0.360747 \cdot (T_b[7])^3)$

"Energy balances"

"Flashing of brine"

$m_{\text{dot}_f[7]} \cdot h_f[7] = m_{\text{dot}_b\_acs[7]} \cdot h_b\_acs[7] + m_{\text{dot}_g[7]} \cdot h_{\text{shv}[7]}$

"Distillate vapour formed in effect"

$m_{\text{dot}_d[7]} \cdot h_{\text{dv}_g[7]} = m_{\text{dot}_g[7]} \cdot h_{\text{shv}[7]} + m_{\text{dot}_b[7]} \cdot h_{\text{shv}[7]} + m_{\text{dot}_f[7]} \cdot h_{\text{dv}_g[7]}$

"Effect heat source"

$m_{\text{dot}_d[6]} \cdot h_{\text{dv}_g[6]} + m_{\text{dot}_b\_acs[7]} \cdot h_b\_acs[7] = m_{\text{dot}_d[6]} \cdot h_{\text{dv}_f[6]} + m_{\text{dot}_g[7]} \cdot h_{\text{shv}[7]} + m_{\text{dot}_b[7]} \cdot h_b[7]$

"Effect Heat transfer area"

$Q_{\text{dot\_eff}[7]} = A_{\text{effect}[7]} \cdot U_{\text{effect}[7]} \cdot (T_{\text{dv}[6]} - T_b[7])$

"Overall heat transfer coefficient"

$$U\_effect[7] = ((10^{(-3)} * (1939.1 + 1.40562 * (T\_dv[6] - 273.15) - 0.0207525 * (T\_dv[6] - 273.15)^2 + 0.0023186 * (T\_dv[6] - 273.15)^3))) * (-1)$$

"Heat transfer"

$$Q\_dot\_eff[7] = m\_dot\_dv[6] * (h\_dv\_g[7] - h\_dv\_f[7])$$

"-----Flash chamber-----"

"Mass balances"

"Mass flow into flash chamber"

"Flashing of previous flash chamber distillate"

$$m\_dot\_d[6] = m\_dot\_d\_gf[7] + m\_dot\_d\_gc[7]$$

"Flashing of condensed distillate vapour heat source"

$$m\_dot\_dv[6] = m\_dot\_dv\_gf[7] + m\_dot\_dv\_gc[7]$$

"Mass flow out of flash chamber"

"Distillate generated by flashing"

$$m\_dot\_df[7] = m\_dot\_d\_gf[7] + m\_dot\_dv\_gf[7]$$

"Distillate generated by condensation"

$$m\_dot\_d[7] = m\_dot\_d\_gc[7] + m\_dot\_dv\_gc[7]$$

"Energy balances"

"Flashing of distillate from previous flash chamber "

$$m\_dot\_d[6] * h\_dv\_f[6] = m\_dot\_d\_gf[7] * h\_dv\_g[7] + m\_dot\_d\_gc[7] * h\_dv\_f[7]$$

"Flashing of condensed distillate vapour heat source"

$$m\_dot\_dv[6] * h\_dv\_f[6] = m\_dot\_dv\_gf[7] * h\_dv\_g[7] + m\_dot\_dv\_gc[7] * h\_dv\_f[7]$$

{-----Effect 8 -----}

"Effect number"

$$Effect[8] = 8$$

"-----Temperatures-----"

"Top feed brine temperature"

$$T\_f[8] = T\_b[7]$$

"Bottom brine temperature exiting effect 8"

$$T\_b[8] = T\_b[7] - \Delta T\_mes$$

"Temperature of saturated distillate vapour at effect 8"

$$T\_dv[8] = T\_dv[7] - \Delta T\_mes$$

"-----Pressures-----"

"Effect pressure"

P\_e[8]=0.5

"-----Enthalpy values-----"

"Enthalpy of superheated vapour"

h\_shv[8] = **enthalpy**(Water,T=T\_f[8],P=P\_e[8])

"Enthalpy of distillate vapour - sat fluid"

h\_dv\_f[8] = **enthalpy**(Water,T=T\_dv[8],x=0)

"Enthalpy of distillate vapour - sat steam"

h\_dv\_g[8] = **enthalpy**(Water,T=T\_dv[7],x=1)

"Enthalpy of feed-water "

h\_f[8] = h\_b[7]

"Enthalpy of brine after flashing process"

h\_b\_acs[8] = **sw\_enthalpy**(T\_f[8],X\_f,P\_e[8])/1000

"Enthalpy of brine generated after boiling process"

h\_b[8] = **sw\_enthalpy**(T\_b[8],X\_f,P\_e[8])/1000

//Calculation specific entropy (kJ/kg-K) of condensate vapor exiting effect 8 and entering the first flash chamber

//Assumed condensed vapor temperature is 20 degree celcius

T\_dv\_f[8]=20[C]

"-----Entropy Control volume #1-----"

//Specific entropy (kJ/kg-K) of heating source at effect 8

s\_b\_acs[8]=**sw\_entropy**(T\_b[8], X\_f[8], P\_e[8])/1000

//Specific entropy (kJ/kg-K) of vapor generated after flashing in effect 8

s\_gf[8]=**entropy**(Water,T=T\_dv[8],P=P\_e[8])

//Entropy balance equation control volume #1

m\_dot\_b[7]\*s\_b[7]+

S\_dot\_gen\_control\_volume\_1[8]=m\_dot\_b\_acs[8]\*s\_b\_acs[8]+((m\_dot\_gf[8]\*h\_dv\_g[8])/T\_dv[7])-  
c\_p[8]\*(ln((T\_b\_acs[8]+273.15)/(T\_b[8]+273.15)))

c\_p[8]=(**sw\_spheat**(T\_b[8], X\_b[8], P\_e[8])/1000

//Assuming flashing happens at the temperature T\_b[7]

T\_b\_acs[8]=T\_b[7]

"-----Entropy Control volume #2-----"

//Specific entropy (kJ/kg-K) of brine exiting effect 8

s\_b[8]=**sw\_entropy**(T\_b[8], X\_b[8], P\_e[8])/1000

//Entropy balance equation control volume #2

$m_{\dot{b}}[8] * s_{\dot{b}}[8] + S_{\dot{gen}}[8] + S_{\dot{gen}}[8] + S_{\dot{gen}}[8]$   
 $+ (Q_{\dot{eff}}[8] / (T_0 + 273.15)) = m_{\dot{b}}[8] * s_{\dot{b}}[8] + ((m_{\dot{gb}}[8] * h_{\dot{dv}}[8]) / T_{\dot{dv}}[8]) -$   
 $c_p[8] * (\ln((T_b[8] + 273.15) / (T_{\dot{b}}[8] + 273.15)))$

//Calculation specific exergy (kJ/kg) of brine exiting the 8 effect

$ex_b[8] = (h_b[8] - h[0]) - (T_0 + 273.15) * (s_b[8] - s[0])$

$s_{\dot{dv}}[8] = \text{entropy}(\text{Water}, T = T_{\dot{dv}}[8], P = P_e[8])$

"-----Exergy balance Equation Control Volume #1 -----"

$m_{\dot{b}}[7] * ex_b[7] = m_{\dot{b}}[8] * ex_b[8] + m_{\dot{gf}}[8] * ex_{gf}[8] + EX_{\dot{dest}}[8] + EX_{\dot{dest}}[8]$   
 $ex_b[8] = (h_b[8] - h[0]) - (T_0 + 273.15) * (s_b[8] - s[0])$   
 $ex_{gf}[8] = (h_{\dot{dv}}[8] - h[0]) - (T_0 + 273.15) * (s_{\dot{dv}}[8] - s[0])$

"-----Exergy balance Equation Control Volume #2 -----"

$m_{\dot{b}}[8] * ex_b[8] + Q_{\dot{eff}}[8] * (1 - ((T_0 + 273.15) / (T_{\dot{dv}}[8] + 273.15))) = m_{\dot{b}}[8] * ex_b[8] + m_{\dot{gb}}[8] * ex_{gb}[8] + EX_{\dot{dest}}[8] + EX_{\dot{dest}}[8]$   
 $c_p[8] * (T_0 + 273.15) * (\ln((T_b[8] + 273.15) / (T_b[8] + 273.15)))$

$ex_{gb}[8] = (h_{\dot{dv}}[8] - h[0]) - (T_0 + 273.15) * (s_{\dot{gb}}[8] - s[0])$

//Specific entropy (kJ/kg-K) of vapor generated after boiling in effect 8

$s_{\dot{gb}}[8] = \text{entropy}(\text{Water}, T = T_{\dot{dv}}[8], P = P_e[8])$

//Total Exergy destruction by effect 8

$EX_{\dot{dest}}[8] = EX_{\dot{dest}}[8] + EX_{\dot{dest}}[8] + EX_{\dot{dest}}[8]$

"-----Governing equations-----"

"Mass balances"

"Brine entering after flashing"

$m_{\dot{f}}[8] = m_{\dot{b}}[8] + m_{\dot{gf}}[8]$   
 $m_{\dot{f}}[8] = m_{\dot{b}}[7]$

"Boiling of brine"

$m_{\dot{b}}[8] = m_{\dot{gb}}[8] + m_{\dot{b}}[8]$

"Distillate vapour formed in effect"

$m_{\dot{dv}}[8] = m_{\dot{gf}}[8] + m_{\dot{gb}}[8] + m_{\dot{df}}[8]$

"Salt balance"

"Flashing of brine"

$X_f[8] * m_f[8] = X_b[8] * m_b[8]$   
 $X_f[8] = X_b[7]$

"Boiling over tubes"

$X_b[8] * m_b[8] = X_b[8] * m_b[8]$   
 $X_b[8] = 0.9 * 0.001 * (457628.5 - 11304.11 * T_b[8] + 107.5781 * (T_b[8])^2 - 0.360747 * (T_b[8])^3)$

"Energy balances"

"Flashing of brine"

$m_{\dot{f}}[8] * h_f[8] = m_{\dot{b}}[8] * h_b[8] + m_{\dot{gf}}[8] * h_{shv}[8]$

"Distillate vapour formed in effect"

$$m_{\text{dot\_dv}}[8]*h_{\text{dv\_g\_in}}[8] = m_{\text{dot\_gf}}[8]*h_{\text{shv}}[8] + m_{\text{dot\_gb}}[8]*h_{\text{shv}}[8] + m_{\text{dot\_df}}[8]*h_{\text{dv\_g}}[8]$$

"Effect heat source"

$$m_{\text{dot\_dv}}[7]*h_{\text{dv\_g}}[8] + m_{\text{dot\_b\_acs}}[8]*h_{\text{b\_acs}}[8] = m_{\text{dot\_dv}}[7]*h_{\text{dv\_f}}[8] + m_{\text{dot\_gb}}[8]*h_{\text{shv}}[8] + m_{\text{dot\_b}}[8]*h_{\text{b}}[8]$$

"Effect Heat transfer area"

"

$$Q_{\text{dot\_eff}}[8] = A_{\text{effect}}[8]*U_{\text{effect}}[8]*(T_{\text{dv}}[7] - T_{\text{b}}[8])$$

"Overall heat transfer coefficient"

$$U_{\text{effect}}[8] = ((10^{(-3)}*(1939.1 + 1.40562*(T_{\text{dv}}[7]-273.15) - 0.0207525*(T_{\text{dv}}[7]-273.15)^2 + 0.0023186*(T_{\text{dv}}[7]-273.15)^3))^{(-1)}$$

"Heat transfer"

$$Q_{\text{dot\_eff}}[8] = m_{\text{dot\_dv}}[7]*(h_{\text{dv\_g}}[8]-h_{\text{dv\_f}}[8])$$

"-----Flash chamber-----"

"Mass balances"

"Mass flow into flash chamber"

"Flashing of previous flash chamber distillate"

$$m_{\text{dot\_d}}[7] = m_{\text{dot\_d\_gf}}[8] + m_{\text{dot\_d\_gc}}[8]$$

"Flashing of condensed distillate vapour heat source"

$$m_{\text{dot\_dv}}[7] = m_{\text{dot\_dv\_gf}}[8] + m_{\text{dot\_dv\_gc}}[8]$$

"Mass flow out of flash chamber"

"Distillate generated by flashing"

$$m_{\text{dot\_df}}[8] = m_{\text{dot\_d\_gf}}[8] + m_{\text{dot\_dv\_gf}}[8]$$

"Distillate generated by condensation"

$$m_{\text{dot\_d}}[8] = m_{\text{dot\_d\_gc}}[8] + m_{\text{dot\_dv\_gc}}[8]$$

"Energy balances"

"Flashing of distillate from previous flash chamber"

$$m_{\text{dot\_d}}[7]*h_{\text{dv\_f}}[7] = m_{\text{dot\_d\_gf}}[8]*h_{\text{dv\_g}}[8] + m_{\text{dot\_d\_gc}}[8]*h_{\text{dv\_f}}[8]$$

"Flashing of condensed distillate vapour heat source"

$$m_{\text{dot\_dv}}[7]*h_{\text{dv\_f}}[7] = m_{\text{dot\_dv\_gf}}[8]*h_{\text{dv\_g}}[8] + m_{\text{dot\_dv\_gc}}[8]*h_{\text{dv\_f}}[8]$$

{-----Condenser-----}

//Cold seawater balance equation at the last condenser

$$m_{\text{dot}}[23] = m_{\text{dot}}[22]$$

//Where m\_dot\_23 can be calculated as following

$$m_{\text{dot}}[23] = m_{\text{dot}}[24] + m_{\text{dot}}[25]$$

$$m_{\text{dot}}[24] = m_{\text{dot\_f}}$$

```

//Assuming return cold seawater pipe inner diameter ID_rcsw is 0.25 m
ID_rcsw=0.25 [m]

//Density (kg/m^3) o seawater at state 25
rho[25]=sw_density(T[25], X_f, P[25])
T[25]=T_f[1]
P[25]=P_e[1]
//Specific volume (m^3/kg) of warm sea water
mu[25]=1/rho[25]

//Volumetric flow rate in m^3/s
V_dot[25]=m_dot[25]/rho[25]

//Renold Number
Re[25]=4*m_dot[25]/(mu[25]*pi*ID_rcsw)

//Mass flow rate of warm seawater returning to the sea
m_dot[25]= rho[25]*v_f*(Pi*(ID_rcsw/2)^2)

"Motat Distillate water Produce"
m_dot[28]= (m_dot_d[2]+m_dot_d[3]+m_dot_d[4]+m_dot_d[5]+m_dot_d[6]
+m_dot_d[7]+m_dot_d[8])+m_dot_dv[8]

"Overall heat transfer coefficient"
U_condenser =10^(-3)* (1617.5 + 0.1537*(T_dv[8]-273.17) + 0.1825*(T_dv[8]-273.15)^2 -
0.00008026*(T_dv[8]-273.15)^3)

"Log mean temperature difference"
LMTD_condenser = (T_f[1]-T_sw)/(ln((T_dv[8]-T_sw)/(T_dv[8]-T_f[1])))

"Heat transfer area"
Q_dot_Last_Condenser=m_dot[22]*(h_sw_out-h_sw_in)

m_dot[22]*(h_sw_out-h_sw_in) = A_condenser*U_condenser*LMTD_condenser

h_sw_out=sw_enthalpy(T_f[1], X_f, P_e[1])/1000
h_sw_in=sw_enthalpy(T_sw, X_f, P_atm)/1000
P_atm=0.103

"-----Performance ratio-----"
PR = m_dot[28]/ m_dot_s

"-----Recovery ratio-----"
RR = m_dot[28]/m_dot_f

"-----Gained output ratio GOR-----"
GOR= m_dot_f/m_dot[28]

"-----Specific area-----"

"Effects total area"

```

$A_{\text{effects\_tot}} = A_{\text{effect}[1]} + A_{\text{effect}[2]} + A_{\text{effect}[3]} + A_{\text{effect}[4]} + A_{\text{effect}[5]} + A_{\text{effect}[6]} + A_{\text{effect}[7]} + A_{\text{effect}[8]}$

"Total heat transfer area"

$A_{\text{MES\_tot}} = A_{\text{condenser}} + A_{\text{effects\_tot}}$

"Specific area"

$SA = (A_{\text{MES\_tot}}) / m_{\text{dot}[28]}$