THERMAL DRIVEN DESALINATION WITH ZERO WASTE DISCHARGE: A PROTOTYPE DEVELOPMENT

by

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Abstract

This Research is devoted in modifying the technology of desalination such as the multi-stage flash and the multi effect distillation. The main motive behind this research is to make these mentioned technologies use least electrical energy so that they can be integrated with renewable sources such as solar, wind etc. Secondly, use the waste discharge brine to collect salts so that we can use those salts as thermal energy storage medium. The highlight of this study is the use of wasteful discharge to make desalination zero discharge. The thesis is therefore titled as Thermal Driven Desalination with zero discharge.

As the title of this thesis suggests, this work is a combination of 3 stages of research. The first stage is the development of a program for the calculation of various mass flow rates and other parameters. The program developed mainly uses the first law of thermodynamics namely mass and energy balance. The program allows us to predict these flow rates and other parameters to design our system. The second stage of this study is the 3-D modelling and design of various assemblies like the Full separation tank, effects, heating strategy, control strategy and heat exchanger required in the system. We therefore compared the area obtained from the program and that used in the prototype and observed the changes and differences. Thirdly, this system is implemented by fabrication of a prototype. The prototype is developed to showcase the validity of the concept. The prototype would validate the simulation values as well as allow us to justify our concept behind this system. The prototype although gave a few problems during various experiment runs and hence requires more work.

NOMENCLATURE

m	Mass
Cp	Specific heat
T	Temperature
h	Enthalpy
β	Bleed fraction
X	Salinity
bf	Bleed fraction
<u>Subscripts</u>	
a	Air
hs	Heat source
FST	Full separation tank
leff	Last Effect
f	Fluid
g	Gas/vapor
s	Steam
bs	Bleed steam
amb	Ambient
out	Temperature at outlet
sw	Sea water/ feed brine
l	Latent heat
wh	Water heater
1	First effect
i	Previous effect
j	Given effect
k	Next effect
2l	Second last effect
n	Total no of effects
Csw	Cooling sea water

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1.Introduction

Water scarcity already affects every continent. Around 1.2 billion people, or almost one-fifth of the world's population, live in areas of physical scarcity, and 500 million people are approaching this situation [2]. Another 1.6 billion people, or almost one quarter of the world's population, face economic water shortage [2] (where countries lack the necessary infrastructure to take water from rivers and aquifers). Besides, there is other phenomenon like prolonged draught spells, reduced snowpack in mountains and drying up of present water bodies are adding to this crisis.

To solve this problem over the years, many desalination techniques have been developed. These techniques can be divided into 2 parts, major processes and alternate processes. The major processes are those in which significant development and research has taken place and the alternate process are those which are still not viable to be available in the market. The major process includes thermal processes and membrane process. The alternate processes include Freezing and ion exchange. Of the all major process, Reverse osmosis and multi-stage flash and Multi-effect distillation are the ones most employed around the globe. Of the alternate process the freezing process is still under development. A summary of all these is shown below in Figure 1.

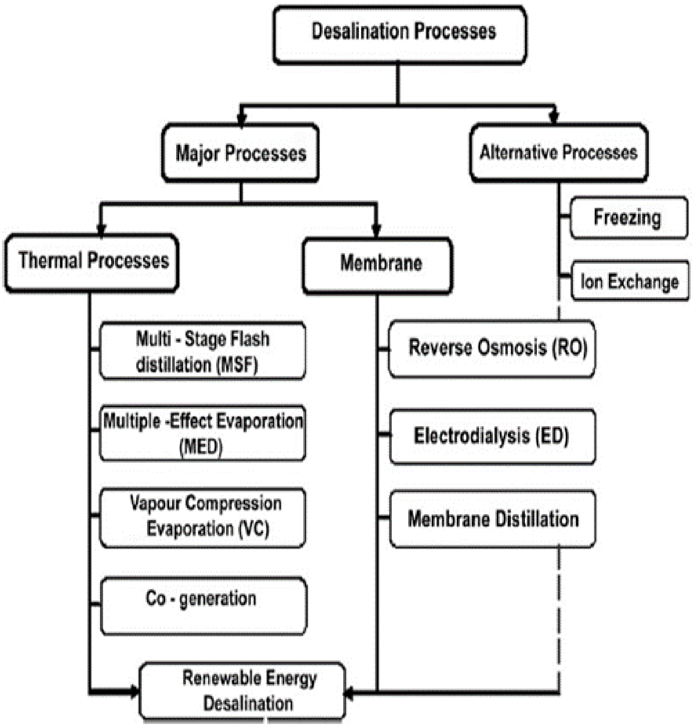


Figure 1 various desalination processes [1]

1.2 Application of various types of Desalination technologies

The cost of desalinated water taken at the outlet of a plant may vary widely from one site to the other. It depends on several factors which are: energy requirements, source, water characteristics, geographical and location constraints, product water requirements, waste disposal options, operational and maintenance issues and utilization rates. High capital, operational and maintenance costs, high energy cost, and environmental impact costs are the main challenges facing desalination plants.

The RO desalination method has grown in popularity during the last decade because it has experienced noticeable developments while other desalination methods have reached a stagnation point in advancements.

Figure 2, below presents that MSF accounts for **36.5%** of the world's desalination plants, second only to RO at **47.2%**. The MSF process utilizes a process with simple mechanics making it extremely popular despite its high cost. Environmental impacts among all methods are approximately similar while energy costs of all methods are dramatically different. RO and MSF methods have the highest shares globally. Therefore, these two methods are normally associated with rejection of high saline concentration waste in addition to the thermal pollution in case of thermal processes like MSF.

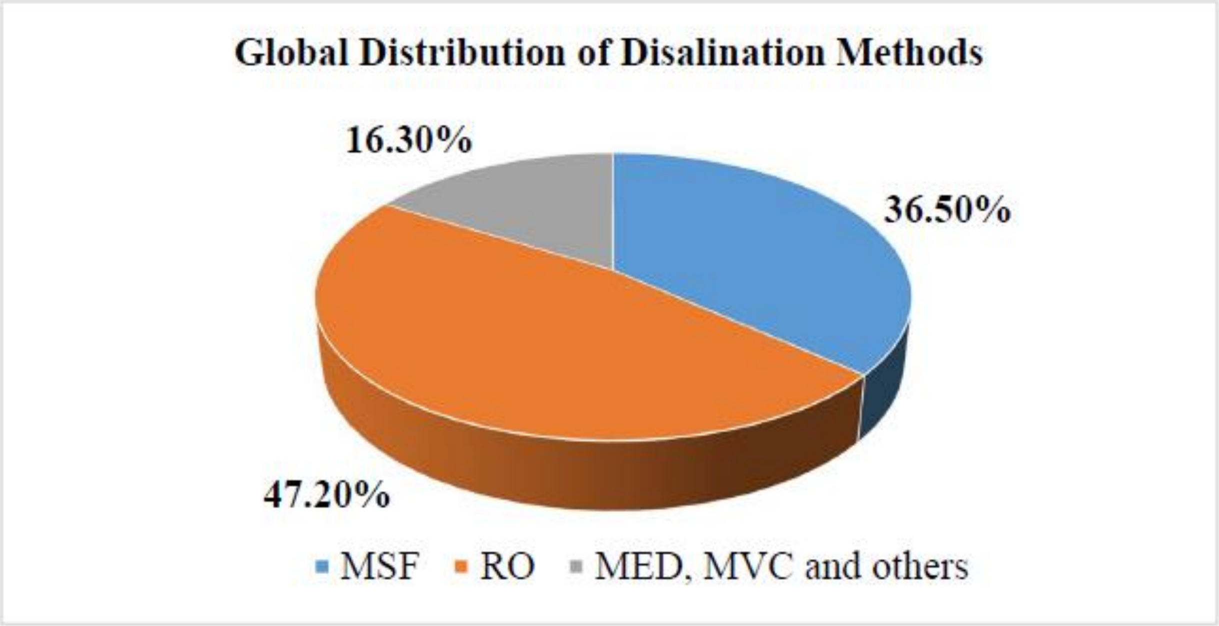


Figure 2 Distribution of desalination methods [2]

1.3 Multi Stage Flash

The multi stage flash process the second most used method globally, for desalination processes. In the flash process the water is desalinated by flashing portions of water in multiple stages. There are two ends at the extremes of the system, the cold end and the hot end respectively. The intermediate temperature stages are placed between these two extreme ends. Each stage has a different pressure that correlates to the water temperature, allowing the system to utilize the optimal boiling point for a given water temperature. Each stage contains a heat exchanger and a condensate collector. The heat exchanger condenses the steam produced and collected in the condensate collector. The condensate water is distilled and is ready to be used for consumption. Figure 3 presents a schematic of the MSF process. Multi-stage flash produce about 60% of the world's desalinated water. [2]

In general, The MSF process is considered as a reliable source to obtain fresh water from the seawater, but the process itself is a thermal energy and mechanical energy intensive process.

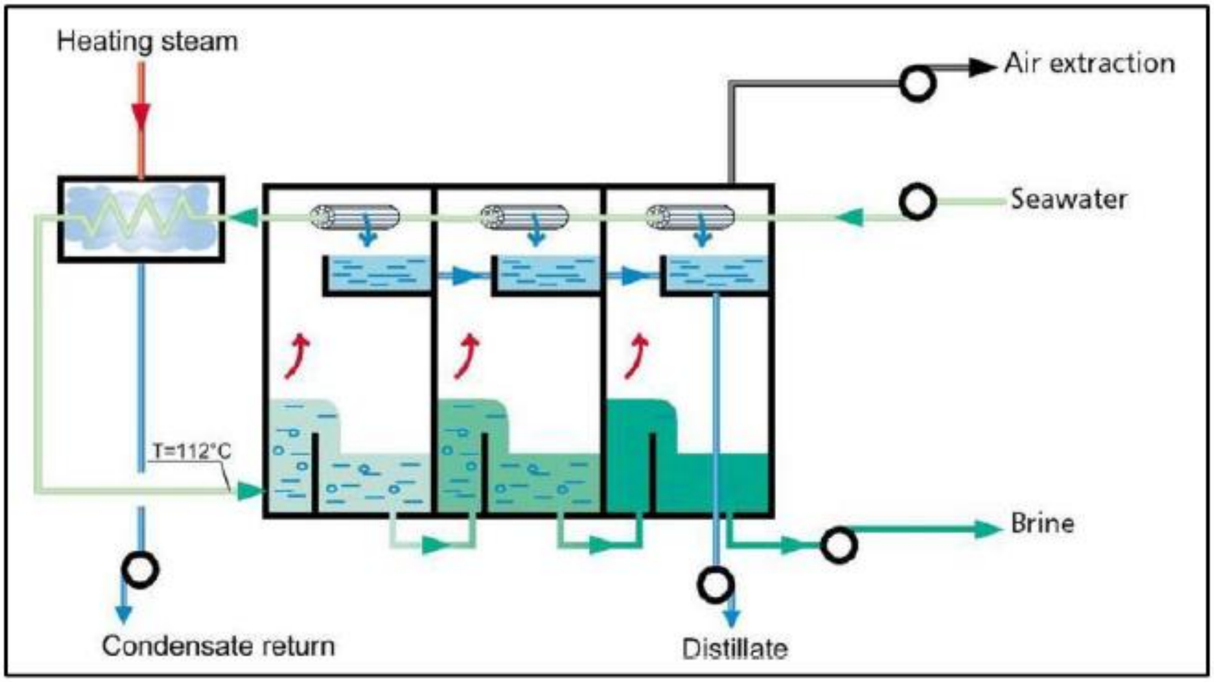


Figure 3 Multi Stage Flash Process [2]

Let us now try and analyze the Figure 4 given below step by step to understand the system better. The feed water is the saline water, and it is heated in a vessel called the brine heater until it reaches a temperature below the saturation boiling temperature. The heated sea water follows through a series of vessels, in sequence where the lower ambient pressure causes water to boil rapidly and then vaporize. This sudden introduction of the heated water into the reduced pressure chamber is called as the flashing effect, because of the water flashing into steam.

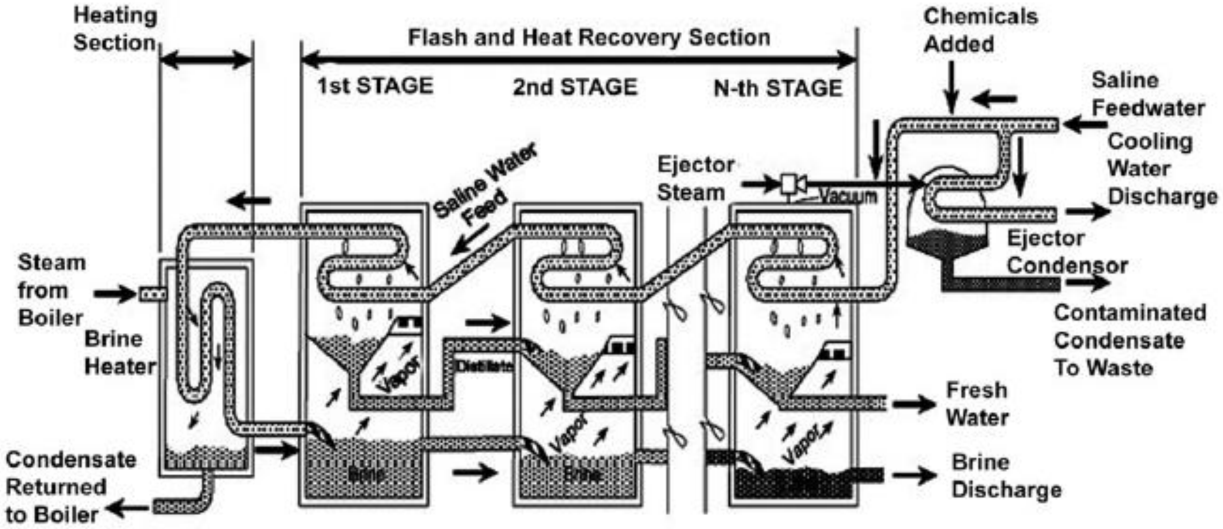


Figure 4 Schematic of Multi Stage Flash Process [3]

The pressure inside a stage of the MSF is the deciding factor of the percentage of formation of water to water-vapor, since the boiling continues until the water cools and the vaporization is stopped. This although, the formation of water vapor is small percentage.
The vapor steam as shown in Figure 4 Generated from flashing is converted to liquid on the tube-surface of the heat exchanger (condenser) that run through each stage as shown in Figure 4. the incoming feed water as shown in figure 4 goes through to the brine heater and in the process, then cools down the heat exchanging tube surfaces. This in turn heats up the feed water and then reduces the amount of thermal energy required in the brine water to raise the temperature of seawater. [3]

1.3.1 The Advantages and Disadvantages of the MSF process

- The MSF systems are relatively simple to construct and operate.
- They have no real moving parts, other than the pumps and they have only a small amount of connection tubing.
- The quality of water effluents (per [3]) contains 2-10 ppm dissolved solids, a high level of purification.

The quality of input feed water is not as important as in other membrane type processes.

- Operating the plants at higher temperatures (above 115˚C) improves their efficiency and but causes scaling problems. The salts such as calcium soleplates precipitate on the tube surface and create the issue of clogging. [3]

- It is considered as an energy intensive system and requires both thermal as well as mechanical energy.

- Adding more stages improves the efficiency and increases the water production, but it increases the capital cost and operational complexity. [3]

1.4 The multi-effect distillation process. (MED)

Figure 5 shows a typical representation of the MED process. The MED process is also known as the effects. The number of effects in this type of system depends on the engineering of the system. In this type of system each effect is maintained at a decreasing level of pressure and temperature. Each effect has a horizontal bundle of tubes acting as a heat exchangers.

As we can see from the Figure 5 the steam for the heating is pushed downwards through the bundle of tubes. Here on the surface of the tube bundles, the heating steam and the cooling seawater interact, causing the heating steam to condense. The seawater in turn trickles down vertically downwards inside the tubes and is partially evaporated due to the interaction. At the bottom end of the effect as shown in Figure 5 we are left with the higher salinity solution (brine) as compares to the input [2].

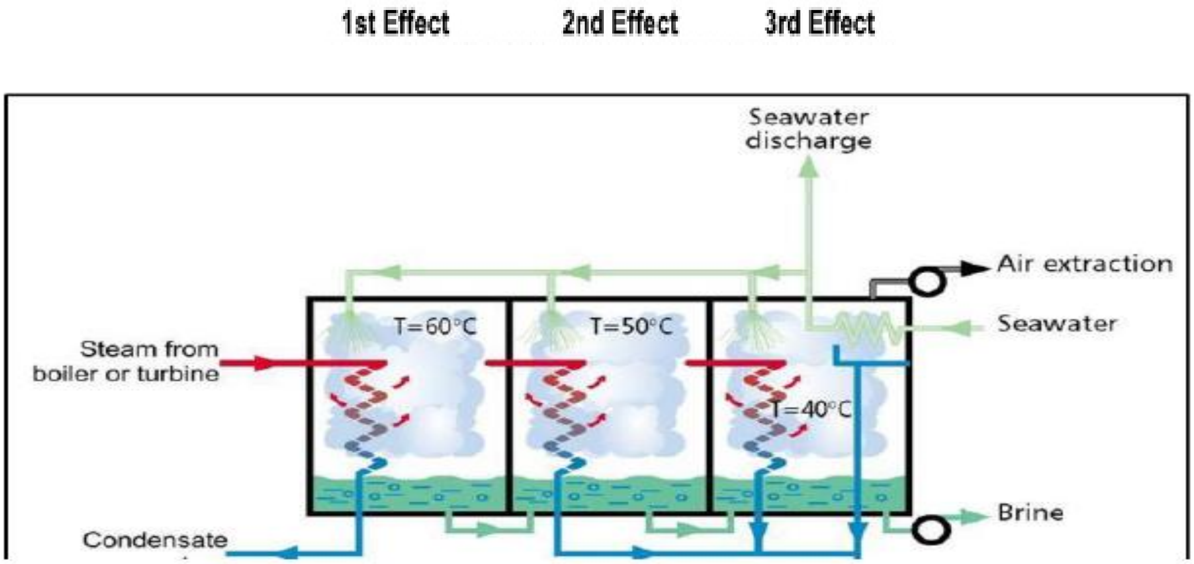


Figure 5 Multi effect Distillation [2]

Note: P1>P2>P3 P: Pressure
T1>T2>T3 T: Temperature

This effect allows the seawater to undergo multiple boiling without supplying additional heat after the first effect. As seen in the Figure 5 The first effect is supplied by heat from the boiler or a turbine which produces the steam. After the first effect the temperature of the feed seawater is raised to its boiling point after being preheated in the tubes the seawater is sprayed onto the exchanger tube bundle to promote the rapid evaporation.

1.4.1 The advantages and disadvantages of the MED system.

The total number of effects is limited by the total temperature range available and the minimum allowable temperature difference between one effect and the next effect. Only a portion of the seawater applied to the tubes in the first effect is evaporated. The remaining feed water is fed to the second effect, where it is again applied to a tube bundle. These tubes are in turn heated by the vapors created in the first effect. This vapor is condensed to form the fresh water product, while giving up heat to evaporate a portion of the remaining seawater feed in the next effect.

- The MED [3] is designated to generally operate at a lower temperature of 70˚C. This tends to minimize tube corrosion and potential of scale formation.

- The pretreatment costs of the MED are low as compared to other sensitive types of systems because the quality of feed water is not as important.

- Th power consumption of the MED is low, even compared to the traditional MSF plants it is low. [3]

- The performance efficiency of the MED plants and systems is higher. The MED system is more efficient in terms of the heat transfer and fresh water production. [3]

1.5 Reverse Osmosis

In comparison to other technologies, the RO process is relatively new and is successfully commercialized in desalination since the early 1970’s.RO is a membrane separation process in which water from a pressurized saline solution is separated from solutes (dissolved material) by flowing through a membrane without need for heating or phase change. The major energy required is for heating or phase change [3].

Other definitions of reverse osmosis are that, it is a process of forcing a solvent from a region of high solute concentration through a membrane to a region of low solute concentration by applying pressure more than osmotic pressure as shown in Figure 6 Water thus flows in reverse direction to natural flow, leaving dissolved salts behind with an increase in concentration of salt.

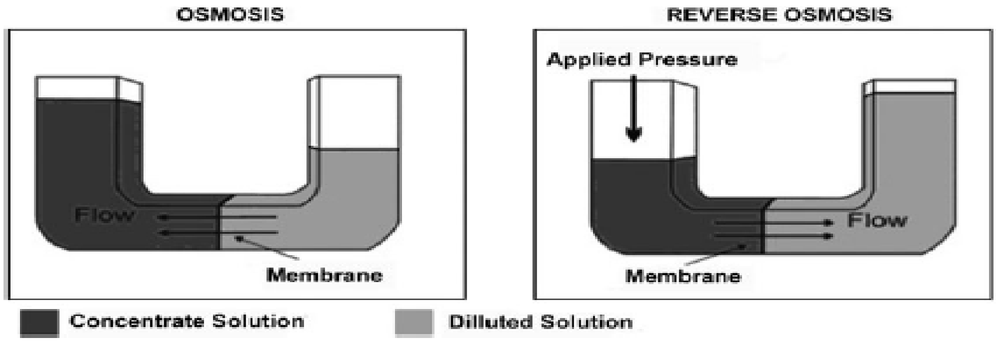


Figure 6 Reverse Osmosis [3]

A typical large saline water RO plant consists of five major components, a saline water supply system, a feed water pretreatment system, high-pressure pumping, RO modules (membrane separation) and post-treatment system.

Pretreatment: During the pretreatment process the sea water is treated against the debris and large suspended solid of size greater than 10 micrometers. The nature of pre-treatment depends on the quality of feed water characteristics, the membrane type, recovery ratio and the required product water quality. It also protects the membrane from fouling [3].

High pressure pumping: The high-pressure pump supplied the appropriate pressure needed to enable the water through the membrane where the semi-permeable membrane restricts the passage of dissolved salts. The pressure ranges from 15-25 bar for brackish and from 54-80 bar for sea water [3].

RO modules: The membrane must be strong enough for the it to withstand against the pressure drop across it. In principle, the RO membrane must be highly permeable to water and must present an impenetrable barrier to the salts. The membrane must have a large surface area to allow for maximum flow. RO membranes used commercially are generally of two types namely, spiral wound, Figure 8a and hallow fine fiber(HFF), Figure 8b.

Spiral wound membrane: This type of membrane element is most commonly manufactured as a flat sheet of either a cellulose diacetate and triacetate blend or a thin film composite usually made from polyamide, polysulphone or polyurea polymers [3].

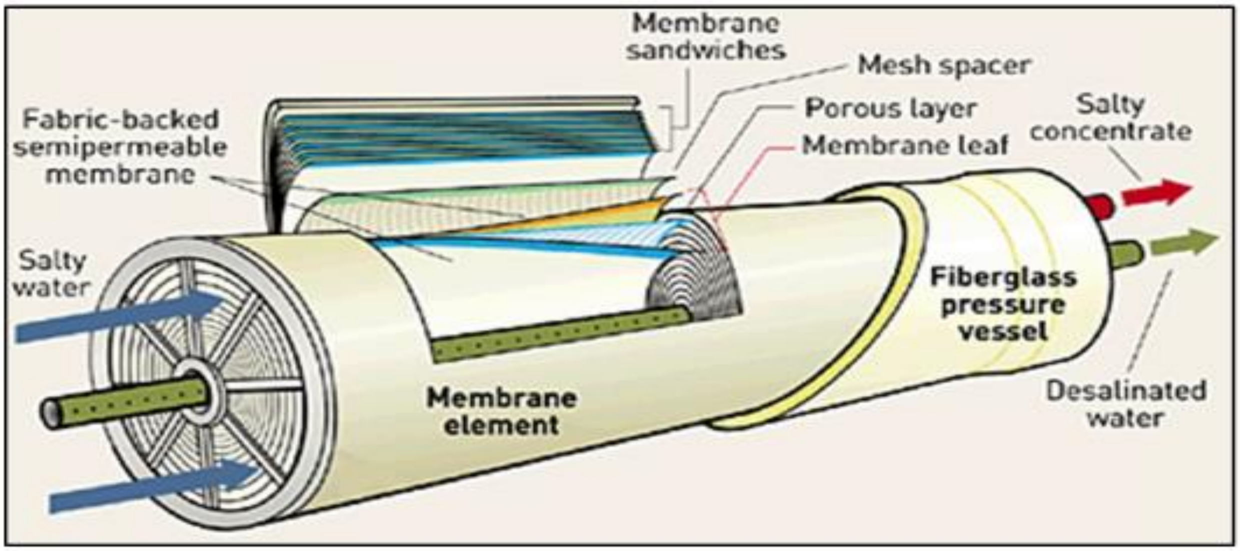


Figure 7 General Reverse Osmosis membrane structure [2]

HFF membrane: HFF is a U-shaped fiber bundle housed in a pressure vessel Figure 8b. The membrane materials are based on cellulose triacetate and polyamide and its arrangement allows the highest specific surface area of all the module configurations, resulting in compact plants [3].

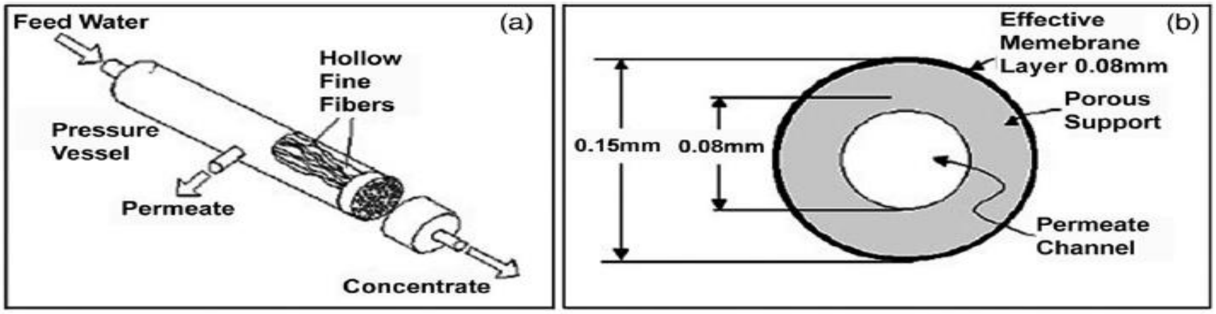


Figure 8a) spiral wound Figure 8b) HFF [3]

1.5.1 Advantages and disadvantages of RO process

The Salient points are as follows [3]:

- Material corrosion problems are significantly less compared with MSF and MED processes due to the ambient temperature conditions.

- Polymeric materials are utilized as much as possible rather than the use of metal alloys.

- RO units sold for residential water filtration require very large quantities of water since they recover only 5–15% of the feed water that enters the filter. In seawater systems, for every 5 gallons of usable water, 40–90 gallons of water are not to the wastewater system.

- Membrane scaling caused by the precipitation of salts is common problem in the RO process.

- Biological fouling can be caused by the formation of micro-organism colonies and by entrapping dead and live organisms. Colloidal fouling is caused by the settlement on membrane surfaces of colloids from an accumulation of aluminum silicate and clays and from soap detergents and organic materials.

- The concentrated brine loses only 1–4 bar relative to the applied pressure from the high-pressure pump. The devices are mechanical and generally consist of turbines or pumps that can convert a pressure difference into rotating energy that can be used to reduce energy costs.

1.6 Electro-Dialysis Process

In the electro-dialysis process, there is an application of an electric field across the pair of an ion selective membranes, causing various ion salts to move through the membranes into a concentrated solution which ultimately leaves behind a dilute solution. The feed water though must be free of any suspended salts and non-ionic contaminants. The Figure 9 shows that the ions in the feedwater are separated through the membranes as the driving force (electric potential) is applied on the feed. The ions of the salts get attracted to their opposite ends, thus causing separation. [3]

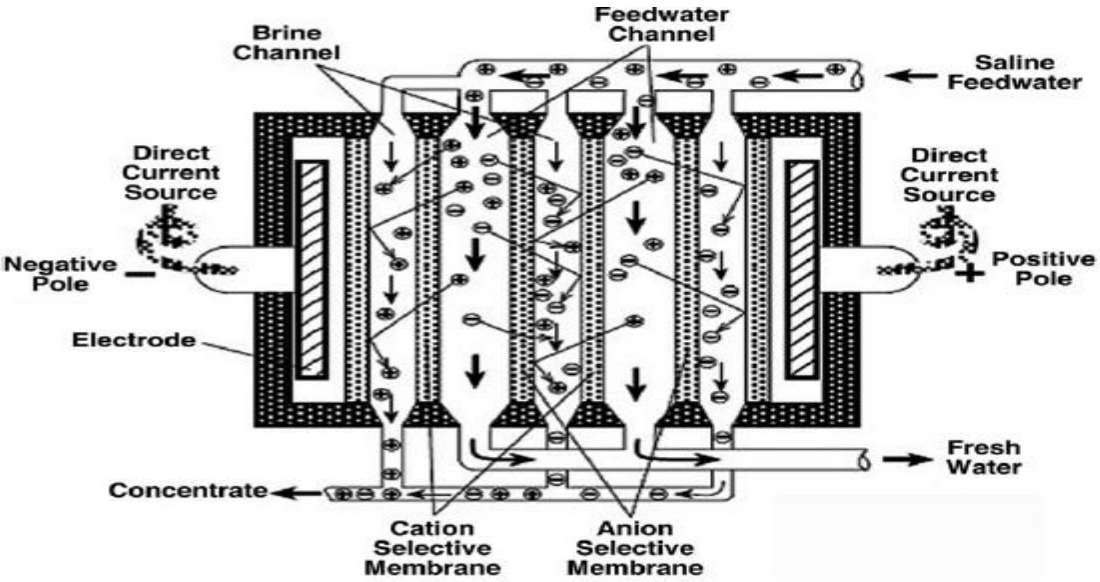


Figure 9 Electro Dialysis process [3]

1.6.1 Advantages and disadvantages

The salient points are as follows [3]:

- It has the capability of high recovery in terms of more fresh water product and less brine.

- ED is feasible for brackish water with a salinity of 0.6 g/l of dissolved solids, but not suitable for water with dissolved. solids of ,0.4 g/l.
- The desalination of water with concentrations of dissolved solids higher than 30 g/l, like seawater, is possible, but it is not economically viable.
- The major energy requirement is the direct current to separate the ionic substances in the membrane. And energy usage is proportional to the salts removed.
- It can treat feed water with a higher level of suspended solids than RO.

1.7 Freezing process

The basic principles of freezing desalination are simple. During the process of freezing, dissolved salts are excluded during the formation of ice crystals. Seawater can be desalinated by cooling the water to form crystals under controlled conditions. Before the entire mass of water has been frozen, the mixture is usually washed and rinsed to remove the salts in the remaining water or adhering to the ice crystals. The ice is then melted to produce fresh water. The main heat transfer processes, that is freezing and melting, are regenerative, resulting in very high energy efficiency. [3]

The ice crystals in this process is the pure water and the remaining salts are trapped in the boundaries of the solid cubes of ice. The polycrystalline ice must be removed from the remaining brine solution. Heat is removed by evaporation of refrigerant in direct contact with the brine, refrigerant may be water itself or an immiscible refrigerant with water called as secondary. The heat required for melting is obtained from condensation of the refrigerant and thus both refrigerant and water are obtained as products. The process carried out under vacuum freezing vapor and power required is estimated to be 0.1kWh/m^3. This process is still being developed and not yet commercialized because of delicate handling of the crystals.

1.7.1 Advantages and Disadvantages

The salient points are as follows [3]:

- The advantages include a lower theoretical energy requirement, minimal potential for corrosion and little scaling or salt precipitation.
- It can produce very pure potable water, and it has special advantages to produce water for irrigation.
- The disadvantage is that it involves handling ice and water.

- mixtures that are mechanically complicated to move and process.

2. Economics of various systems Cost Surveys, and Project Objectives

There are various cost considerations that must be looked at to justify that we are we interested in the thermal systems. The prototype and model developed in this research is a combination of the MED and the MSF systems. The Table 1 is the cost analysis for the portable water produced in various desalination processes. From the data of this table we are clearly able to understand that for any plant taking a desalination process on a large scale the difference between the costs of the membrane technology, reverse osmosis multi stage flash process in very minute and of the order of **0.01-0.08$/ m^3**. Hence this point of the cost makes one reason for using the multi stage flash processes and other thermal processes.

Desalination process	Estimated costs per cubic meter of portable water($)
Electro dialysis-Multi Stage Flash (EDMSF)	**0.44**
Membrane Technology (MT)	**0.53**
Multi Stage Flash (MSF)	**0.52**
Vertical tube Evaporation (VTE)	**0.45**
Reverse Osmosis (RE)	**0.45**
Vapor compression Evaporation (VCE)	**0.39**
Secondary referigeration Freezing (SRF)	**0.35**

Table1: Estimated cost of portable water per cubic meter from various processes [4]

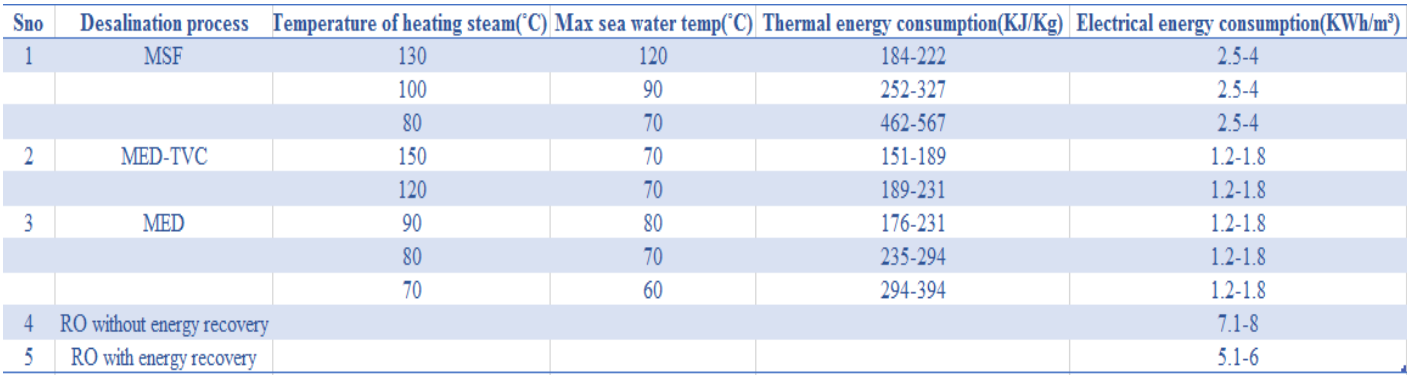
From another set of data in the Table 2 we can see the advantages and disadvantages of various sets of plants using different technologies. All the technologies are highly intensive in terms of capital but the high-pressure pump cost, which is the most crucial factor is high for the RO process. Although the plant utilities are low in comparison to the thermal processes but ultimately the overall operational costs become high due to such large costs for the pumps (crucial element in any desalination procedure).

Desalination Process	Capital intensive	plant utlities	High Pressuree Pump costs
Multi Stage Flash Distillation	high	high	low
Multi effect Desalination	high	high	low
Vertical tube evaporator	high	medium	medium
Vapor compression Evaporator	high	high	high
Reverse Osmosis with membrane modules	high	low	high
Vaccum Freezing vapor compression	medium	medium	high

Table2: Various types costs involved and their effects in technology selection [4]

Let us now summarize these costs and try and understand the project objective for this research. In effect, we want to desalinate brackish type of water or sea water which is most commonly available. We are not only looking at the desalination of water but also we are looking at collection of salts. Salts are an important medium for storage and collection of thermal energy. A lot of the salts have been identified in the lab in other experimental studies for storage of thermal energy. The objective of this research is also to experiment with solutions other than water and then observe the behavior of the system for other solutions as well. This unique approach which will be introduced in the following chapter will aim at utilizing the benefits of both the MSF and the MED systems. This will help in taking advantage of the flashing water at varying pressures at their respective temperatures by using the variable water flow systems. As a future aspect, we want to use renewable sources of energy for this project and hence it is very important to look at the energy consumption of each of these technologies. The data from Table 3 given below shows that the electrical energy requirement for the MSF and MED is much less than that of the RO system. From a futuristic perspective, this is beneficial to us because the lesser the amount of electrical energy requirement the easier it will be for the system to be integrated with solar and other renewable sources. This higher requirement of the electrical energy in the RO process can be attributed to the high pump costs mentioned earlier. RO pump pressure is around **6.4-7.6 MPa**, which is much higher than **30-35 kPa** of a MED plant for a capacity of **24000 m^3/day**, hence the electrical energy requirement for the pump is more.

It is therefore justified to use a combination of thermal desalination techniques to desalinate water. The thermal energy requirements as seen from the Table 3 are low compared to any other technique, hence we use the combinations of MSF and MED. In future, the research proposes to integrate the system with solar parabolic trough collectors to provide cheap energy to power electrical equipment in the system.



Sno	Desalination process	Temperature of heating steam(°C)	Max sea water temp(°C)	Thermal energy consumption(KJ/Kg)	Electrical energy consumption(KWh/m^3)
1	MSF	130	120	184-222	2.5-4
		100	90	252-327	2.5-4
		80	70	462-567	2.5-4
2	MED-TVC	150	70	151-189	1.2-1.8
		120	70	189-231	1.2-1.8
3	MED	90	80	176-231	1.2-1.8
		80	70	235-294	1.2-1.8
		70	60	294-394	1.2-1.8
4	RO without energy recovery				7.1-8
5	RO with energy recovery				5.1-6

Table3: Thermal and electrical energy consumption by various desalination methods [6]

3.The novel concept of thermal-driven desalination with zero-waste discharge

3.1Variable Feed (with bleed steam)

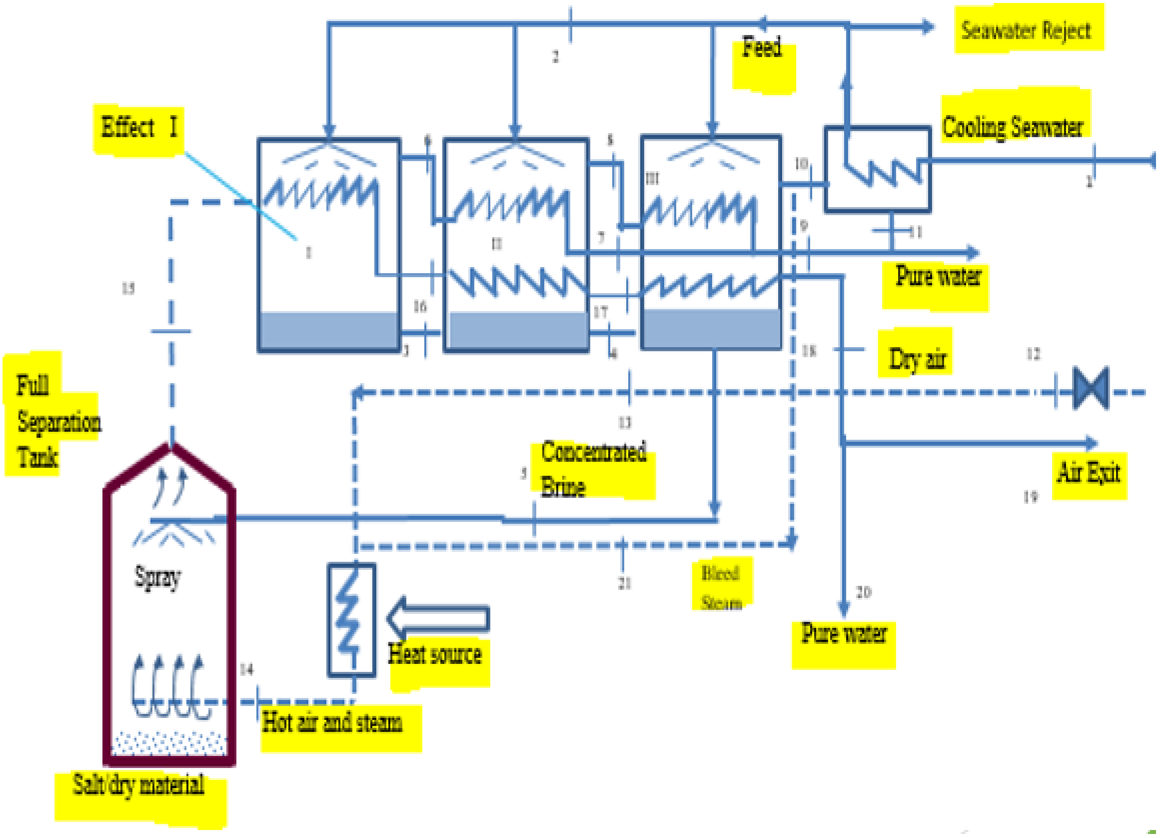


Figure 10 FS-MED Variable feed 3 effects diagram [7]

Description and step by step working

The above Figure 10 shows the novel prototype designed for desalination of brackish and sea water. The system is a thermal desalination process which utilizes both the MSF and MED techniques in conjunction. In the system, there are basic assemblies which are connected. The assemblies are the heat source, full separation tank (FST), the effects and the water recovery.

1. Let us start with the bottom of the system. The heat source is an electric heater or combination of heaters used in the system to heat air from temperature range of about 150-400 ˚C. The air is blown into the heaters and is then heated to very high temperatures.

2. The air then enters the FST (full separation tank) the procedure of full separation will be dealt with separately in the next few chapters. Here in the full separation tank, there are 2 entities as shown in the Figure 10 The brine solution from the third effect is pumped and then sprayed on top of the separation tank. The hot air and the brine solution interact to separate the salt from the water droplets and thus salts are collected at its bottom and the hot air rises to the top.

3. Now let us start looking at the effects. The feed water (brackish)is sprayed in the first effect from the top. The steam from the FST passes in the heat exchangers in the first effect. The steam and the feed interact at the surface of the heat exchanger. A part of the feed trickles down at the bottom as is and a part of it loses heat to be condensed to water and vapor in the exchanger tubes. A small part of it also flashes instantaneously due to large pressure difference and is converted to steam.

4. The steam because of flashing and the water that trickles down as is are shifted to the second effect. The water that trickled down in the first effect as is more saline than the feed water simply because a part of water is converted to steam due to flashing and another part of the incoming feed interacts on heat exchanger surfaces to be converted into vapor and water droplets due to heat loss of steam inside the exchanger tubes. Hence the salt is again collected at the bottom making the water at the bottom of first effect more saline than the feed.

5. Therefore, the same process happens again in the second effect and the third effect inside the exchanger tubes, except that the flashing is more prominent in the second and the third effect owing to the steam coming in from two sources, the first from flashing is first effect and the secondly from the heat exchanger tubes.

6. At the end of the third effect the water collected at the bottom is highly concentrated brine and has more salt content as compared to the feed water. The brine from this effect thus is pumped to the FST for separation. Also, the steam and vapor form the third effect is then transferred to the condenser, where fresh water is collected at the bottom. The condenser also has heat exchangers which has feed water flow and this cools down the incoming steam and water-steam combination from the last effect.

7. At the end of the third effect as well, we take out a part of the steam which flows from the effect three to the condenser and then supply it to the air heating and make up assembly. This hot steam with high temperature compared to the ambient air is mixed with the ambient air prior to the air entering the heater. This allows for the air to be preheated and so less amount of energy will be required to heat up the system. This air is essentially bled to the air make up and recovery and hence it is called as bleeds steam.

8. The water from the condenser is then pumped to the all the effects (three here). The water flowing into each effect is variable and can be controlled by flow controllers. Any amount of water can be permitted to enter the effects, hence calling it variable feed.

3.2 The counter-current flow (with bleed steam)

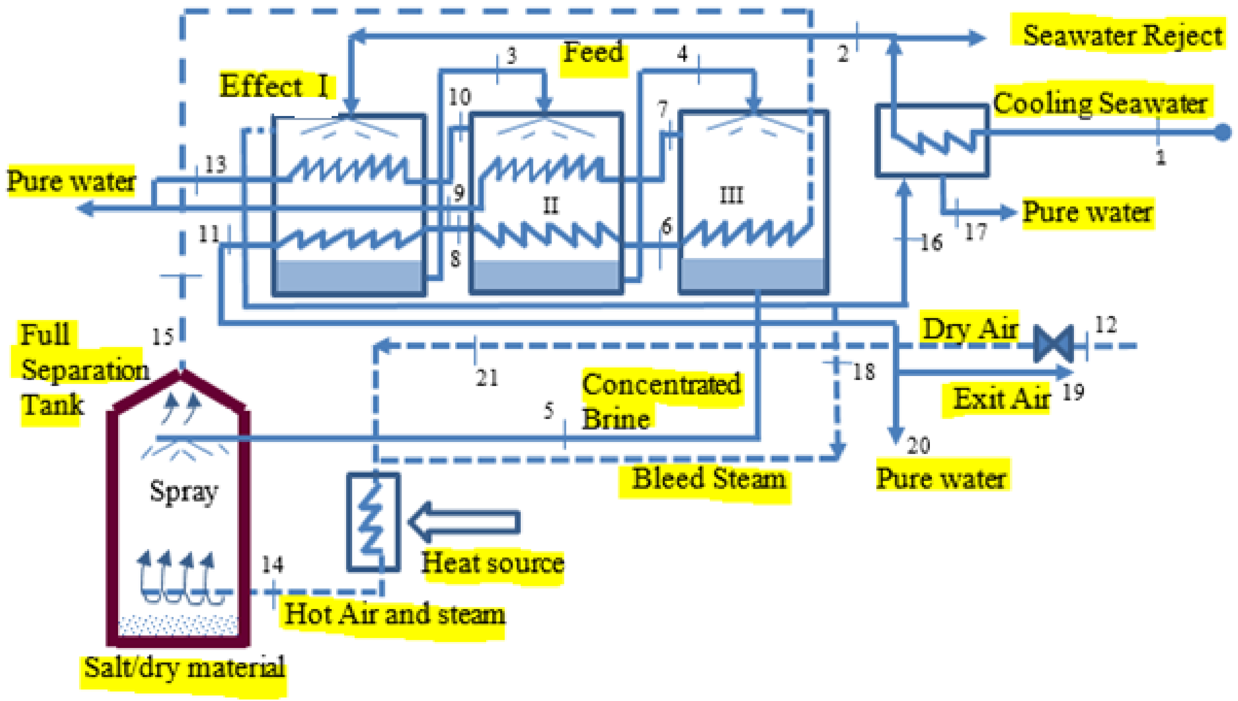


Figure 11 FS-MED counter current feed 3 effects diagram [6]

Description and step by step working

1. The counter current flow is another one of the novel schemes which has been explored (only simulation) for desalinating water. In principle, the major difference between the variable flow and the counter-current flow is that the direction of flow of the feed water and that of the dry air from the FST is opposite.

2. If only considering the design of the prototype the counter-current flow contains the same assemblies as the variable flow scheme which are the heat source, full separation tank (FST), the effects and the water recovery.

3. Let us again start at the bottom end of the scheme. The make-up of air in the heaters and the blower assembly is the same as that in the variable flow. The FST also functions in the same way as the variable does.

4. The change in the scheme comes as soon as we move on to the first effect. The first effect has the inlet of the steam and dry air from the FST, and it has the inlet of feedwater. The feedwater is sprayed on top in the first effect and it interacts with the heat exchanger surfaces. The exchanger surfaces have water and vapor in them. The interaction of feed water with the steam from FST converts the feed to vapor and additionally its interaction

with the exchanger surfaces and its contents force some of the water to flash and convert to steam directly. The large portion of the feed though is trickled down and collected at the bottom. The flow of the steam is from effect 3 to effect 1 horizontally as seen in Figure 11.

5. Even in the first effect itself we can see that the direction of incoming flow of steam and that of the feed water is opposite. The direction of water is from effect 1 to effect 3 horizontally and that of flowing steam is from effect 3 to effect horizontally. The steam and water mix from the effect 1 is taken and fed to the condenser, since this will then be separated as the feed water cools the vapor in the condenser to collect pre-water at the bottom.

6. Another interesting aspect to look in this scheme is the effect 3. Like the variable feed scheme the effect 3 even in counter current flow, the saline water from the effect 3 is pumped to the FST for separation. If we look at the effect 3 in Figure 11 we can see that the steam formed due to flashing in the effect 3 is taken and then transferred to the effect 2 and then from the effect 2 to effect 1.

7. The bleed steam is therefore collected just before it is passed to the condenser, hence in this case the steam from effect is taken and then bled to the air make up assembly to pre-heat dry before it enters the heater.

8. The basic latent heat losses and principles will remain the same as we will see in the mathematical modeling. Another difference between the two schemes is that the feed water to each effect is not variable. The feed given to effect 1 is taken and the water that is left as is in effect 1 is then transferred as feed to the effect 2 and similarly from effect 2 to effect 3. Therefore, mass of feed after feed to effect 1 is calculated and it is a fraction of the feed to effect 1. The mass of feed in effect 2 and effect 3 is calculated inside the program itself.

4. Mathematical Modelling (analysis of mass and energy balance)

This section provides the assumptions, equations, computation methods and relevant properties related to the simulation. The governing equations are developed based on mass, energy and salinity balance. The relevant properties of sea water and their behavior under various circumstances is given also discussed along with the problems of fouling.

4.1 Assumptions

The following are the assumptions made while developing the program for simulation [7] -

- The system is in steady state.
- Each effect is assumed to be at saturated condition and at constant temperature difference. Thus, the properties of steam entering and exiting are known.
- Vapor produced in effect is saturated vapor and brine from each effect in saturated liquid.
- There is no pressure loss in the system
- The system is completely insulated, thus there is no leakage of vapor.
- Non-Equilibrium Allowance (NEA) is assumed to be zero. Thus, the temperature of brine coming in from previous effect after flashing in the current effect is equal to temperature of current effect.
- Air is always dry.
- Specific heat of air is taken as 1.035 kJ/kg K.
- If the value of the salinity goes greater than 300 g/Kg, then the correlation fails and in that case a linear fit equation is used to extrapolate the data.

4.2 Properties of Sea water

The knowledge of seawater properties is important in the development and design of desalination systems. The data for various properties of sea water is obtained from experimental measurements and this data usually spans for a limited rage of temperature and salinity. Data outside these ranges is either interpolated or extrapolated at the conditions of interest.

The most important properties of seawater/brine are very similar that of the pure water, which are described by the functions of temperature and pressure. The sea water though is considered as the binary mixture of the water and sea salts, so in its case a third independent property which influences the properties is salinity (mass of dissolved salts per unit mass of water). It is therefore important to understand the properties of sea water to design ant desalination system.

Temperature and salinity are by far the most important properties of any desalination system and they in turn determine the other physical and thermal properties of desalination systems at near atmospheric pressure. The effect of pressure though in most cases does not exceed more than 10% of the atmospheric pressure in any thermal desalination. Therefore, pressure effects are generally ignored and in addition the equations which govern the modelling of brine at temperature higher than normal Boiling point are assumed to be a saturation pressure.

4.2.1 Specific Enthalpy

Specific enthalpy is the most important property of brine which is being used in the system. The correlation used for calculating enthalpy of brine is shown in Equation (1). This correlation [10] is valid for the **salinity range of 0-120 g/kg and temperature range of 0-120 °C**. The upper limit of salinity range is because of unavailability of data for heat of mixing of salt and pure water. The effect of pressure on enthalpy is negligible for saturated and super cooled liquid. Hence the correlation is a function of temperature and salinity of brine. The enthalpy is always measured as a change of enthalpy relative to a specified datum. The Figure 12 gives the variation of the specific enthalpy with respect to the temperature. If the value of the salinity goes **greater than 300 g/Kg**, then the correlation fails and in that case a linear fit equation is used to extrapolate the data [8].

$$\begin{aligned} h_{f,brine} = {} & h_{f,w} - S(a_1 + a_{2.}.S + a_3.S^2 + a_4.S^3 + a_5.T + a_6.T^2 + a_7.T^3 \\ & + a_8.S.T + a_9.S^2.T + a_{10}.S.T^2) \end{aligned}$$

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

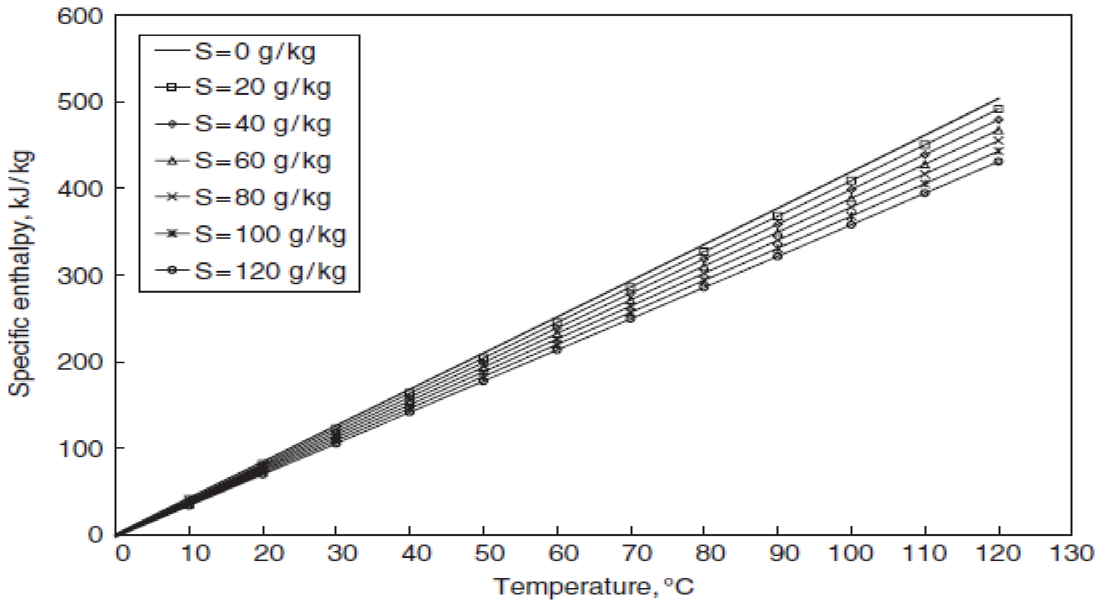


Figure 12 Graph of Specific enthalpy versus temperature at various salinity values for sea water [8]

4.3 Governing equations

4.3.1 variable feed with bleed steam

We will look at each component of the system one at a time and then apply three basic principles of mass balance, energy balance and the salinity balance to calculate the desires mass flow rates and the energy requirements for the respective effects. Below is each component analyzed one by one. All calculations are done since the system is at steady state. The starting up and shutting down conditions are vastly different and hence not considered during this simulation.

Full separation Tank (FST)

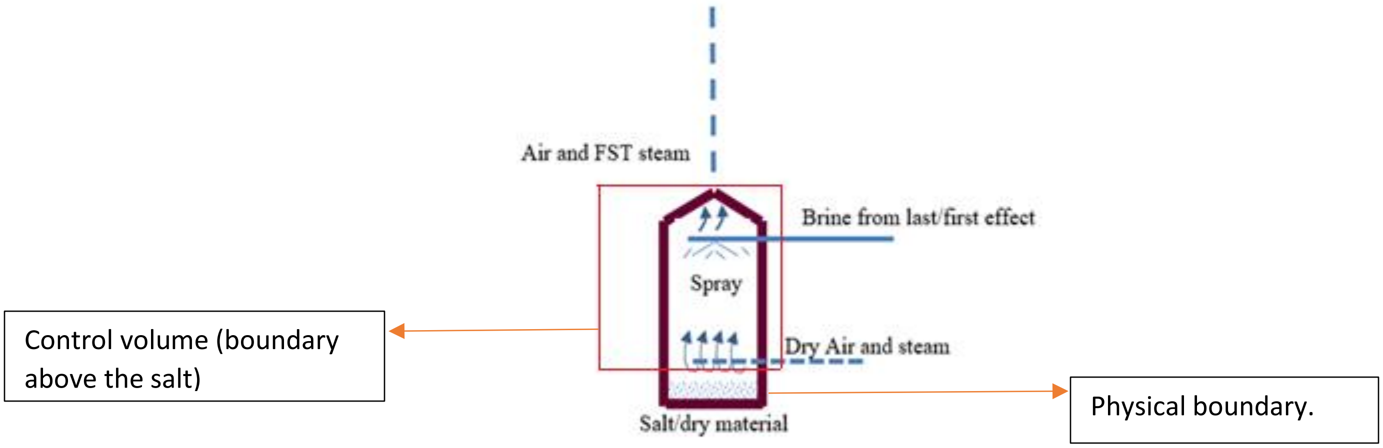


Figure 13 FST diagram [6]

Mass Balance:

$$\dot{m}_{brine,leff} + \dot{m}_{bs} = \dot{m}_{salt} + \dot{m}_{FST} \tag{1}$$

The mass balance is a simple equation that balances the incoming and outgoing quantities. As can be seen from the figure the input quantities to the FST are the brine from the last effect and the mass of bleed steam after the third effect. The outlet quantities are the steam and dry air mixture generated inside the FST and the mass of salt produced during the evaporation of the outlet.

Energy balance:

$$\begin{aligned} \dot{m}_{a}.Cp_{air}.(T_{hs} - T_{FST}) + \dot{m}_{bs}.\left(h_{g,bs,hs} - h_{g,FST}\right) \\ = \dot{m}_{salt}.Cp_{salt}.\left(T_{FST} - T_{brine,leff}\right) + \dot{m}_{f,water}.(h_{g,FST} \\ - h_{f,leff}) \end{aligned} \tag{2}$$

The above shown Equation (2) is for the energy balance the left-hand side quantities are all the incoming quantities and the terms on the right-hand side are the produced or outgoing quantities of the FST. Another fact to be noted is that the equations for the FST remains the same for any configurations which are discussed above. The incoming feed is taken as water and salt and not together as brine. The respective enthalpy values are then taken and the equations is arranged as shown. The term $\dot{m}_{\boldsymbol{bs}}.\left(\boldsymbol{h_{g,bs,hs} - h_{g,FST}}\right)$ represents the energy or enthalpy of the incoming bleed steam after the last effect, where the steam is considered in gaseous phase saturated condition assumption. The term $\dot{m}_{\boldsymbol{a}}.\boldsymbol{Cp_{air}}.(\boldsymbol{T_{hs} - T_{FST}})$ means the latent heat lost by the incoming dry air and steam during its interaction with the incoming brine to evaporate the brine droplets.

On the RHS, the term $\dot{m}_{\boldsymbol{f,water}}.(\boldsymbol{h_{g,FST} - h_{f,leff}})$ means the energy or the enthalpy carried by the produced steam and air mix as it goes out of the FST and the term $\dot{m}_{\boldsymbol{salt}}.\boldsymbol{Cp_{salt}}.(\boldsymbol{T_{FST} - T_{amb}})$ represents the latent heat lost by the droplets for the production of the salt.

Salinity Balance:

$$\dot{m}_{salt} = \frac{\dot{m}_{brine,leff}.X_{brine,leff}}{1000} \tag{3}$$

In the above salinity balance equations, the mass of salt produced is calculated by the program along with the mass of brine and the term $\boldsymbol{X_{brine,leff}}$ is the salinity of the brine in last effect.

The First effect

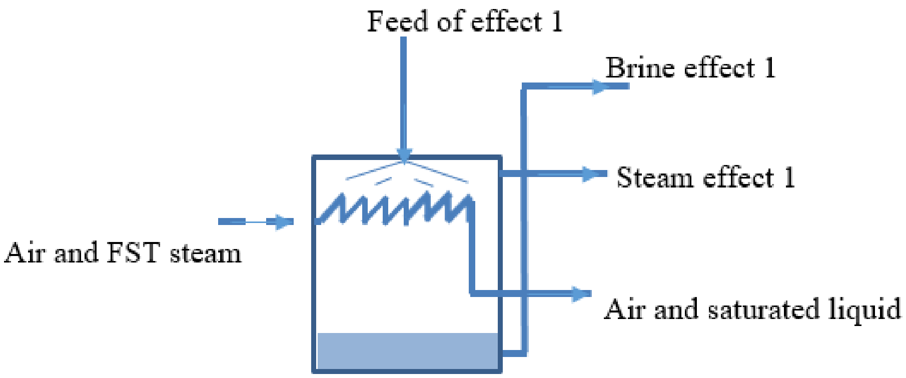


Figure 14 Figure of First effect [6]

Mass Balance:

$$\dot{m}_{feed,1} = \dot{m}_{s,1} + \dot{m}_{brine,1} \tag{4}$$

The mass balance for the first effect is shown in the above Equation (4) The incoming is the feed from the top which is, $\dot{m}_{\boldsymbol{feed},\mathbf{1}}$ and the outgoing is the left-over brine accumulated as is at the bottom, $\dot{m}_{\boldsymbol{brine},\mathbf{1}}$ the steam produced due to flashing which is $\dot{m}_{\boldsymbol{s},\mathbf{1}}$.

Energy balance:

$$\dot{m}_a . Cp_{air} . (T_{FST} - T_{1,out}) + \dot{m}_{feed,1} . h_{f,feed,1,wh} + \dot{m}_{FST} . h_{g,FST}$$
$$= \dot{m}_{s,1} . h_{g,s,1,out} + \dot{m}_{brine,1} . h_{f,brine,1,out} \tag{5}$$
$$+ \dot{m}_{FST,f} . h_{f,1,out}$$

In the Energy Balance Equations (5), $\dot{m}_{\boldsymbol{feed},\mathbf{1}} . \boldsymbol{h}_{\boldsymbol{f},\boldsymbol{feed},\mathbf{1},\boldsymbol{wh}}$ means the energy of the incoming brine. $\dot{m}_{\boldsymbol{FST}} . \boldsymbol{h}_{\boldsymbol{g},\boldsymbol{FST}}$ gives the enthalpy of the incoming steam and the term $\dot{m}_{\boldsymbol{a}} . \boldsymbol{Cp}_{\boldsymbol{air}} . (\boldsymbol{T}_{\boldsymbol{FST}} - \boldsymbol{T}_{\mathbf{1},\boldsymbol{out}})$ gives the latent heat lost by the incoming air and steam mix during the interaction on the heat exchanger tubes surface with the feed water dripping from the top. It is the latent lost by the heater lost by the air and steam mix during the phase change of the feed water on exchanger surface (from liquid to gas). On the RHS, the $\dot{m}_{\boldsymbol{s},\mathbf{1}} . \boldsymbol{h}_{\boldsymbol{g},\boldsymbol{s},\mathbf{1},\boldsymbol{out}}$ gives the enthalpy of the steam formed due to flashing going out. $\dot{m}_{\boldsymbol{brine},\mathbf{1}} . \boldsymbol{h}_{\boldsymbol{f},\boldsymbol{brine},\mathbf{1},\boldsymbol{out}}$ gives the enthalpy of the brine going out and $\dot{m}_{\boldsymbol{FST},\boldsymbol{f}} . \boldsymbol{h}_{\boldsymbol{f},\mathbf{1},\boldsymbol{out}}$ gives the enthalpy due to condensation of air and steam mix during the interaction in the exchanger tubes, which eventually goes out to the next effect.

Salinity Balance:

$$X_{brine,1} = \frac{\dot{m}_{feed,1}.X_{sw}}{m_{brine,1}} \qquad (6)$$

The above salinity Equation (6) is like that developed during the FST modelling and term $\boldsymbol{X_{sw}}$ represents the salinity value of the feed sea water which is sprayed in the first effect and its value is taken from the user at the start of the program.

The last effect:

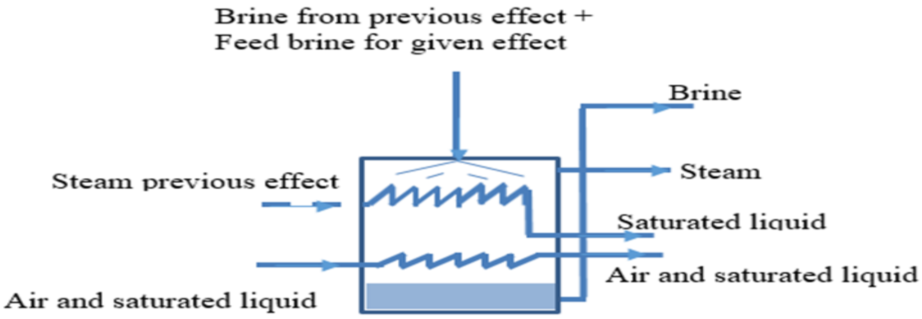


Figure 15 Diagram of last effect [6]

Mass Balance:

$$\dot{m}_{brine,2l} + \dot{m}_{feed,leff} = \dot{m}_{s,leff} + \dot{m}_{brine,leff} \qquad (7)$$

Energy balance:

$$\begin{aligned} &\dot{m}_{feed,leff}.h_{f,feed,leff,wh} + \dot{m}_{a}.Cp_{air}.\left(T_{2l,out} - T_{leff,out}\right) \\ &+ \dot{m}_{FST}.Cp_{water}.\left(T_{2l,out} - T_{leff,out}\right) \\ &+ \dot{m}_{brine,2l}.h_{f,brine,2l,out} + \dot{m}_{s,2l}.h_{g,s,2l,out} \qquad (8) \\ &= \dot{m}_{s,leff}.h_{g,s,leff,out} + \dot{m}_{brine,leff}.h_{f,brine,leff,out} \\ &+ \dot{m}_{s,2l}.h_{f,leff,out} \end{aligned}$$

Salinity Balance:

$$X_{brine,leff} = \frac{\dot{m}_{brine,2l}.X_{brine,2l} + \dot{m}_{feed,leff}.X_{sw}}{\dot{m}_{brine,leff}} \tag{9}$$

The equations for the last effect are also like the first effect. The leftover brine in the second last effect, a fraction of the feed brine, the steam generated in the penultimate effect and the dry air-saturated liquid mixture form the penultimate effect are the inlet substances. The steam generated in the last effect, along with the air-saturated liquid mixture, the leftover brine and the saturated liquid obtained from the cooling of the steam coming for previous effect are outlets of the last effect. The steam generated in this effect is split in two, one is sent to the feed water preheater and the second to the FST. The air-saturated liquid mixture is sent to the cyclone for separation. Leftover brine is sent to the FST. Saturated liquid obtained from the cooling of the steam coming for previous effect is removed from the system.

General equations for other effects

The given below Equations (10), (11) & (12) represents the mass, energy and salinity balance for the nth effect that might be used in this scheme.

Energy balance:

$$\begin{aligned} &\dot{m}_a.Cp_{air}.\left(T_{i,out} - T_{j,out}\right) + \dot{m}_{FST}.Cp_{water}.\left(T_{i,out} - T_{j,out}\right) \\ &\quad + \dot{m}_{brine,i}.h_{f,brine,i,out} + \dot{m}_{s,i}.h_{g,s,i,out} \\ &\quad + \dot{m}_{feed,j}.h_{f,feed,j,wh} \\ &\quad = \dot{m}_{s,j}.h_{g,s,j,out} + \dot{m}_{brine,j}.h_{f,brine,j,out} + \dot{m}_{s,i}.h_{f,s,j,out} \end{aligned} \tag{10}$$

Mass Balance:

$$\dot{m}_{brine,i} + \dot{m}_{feed,j} = \dot{m}_{s,j} + \dot{m}_{brine,j} \tag{11}$$

Salinity Balance:

$$X_{brine,j} = \frac{\dot{m}_{brine,i}.X_{brine,i} + \dot{m}_{feed,j}.X_{sw}}{\dot{m}_{brine,j}} \tag{12}$$

Equation for air heater

The air pre-heater is used just before ambient air pushed into the FST. The air is first mixed with the bleed steam just after the last effect. This raises the temperature of the input air and then the mixture is passed through air heaters to raise the temperature of inlet air to 150-400 ˚C.

$$\dot{m}_a.C_{p,air}.((T_{leff,out})\text{-}(T_{amb}+15))= \dot{m}_a.C_{p,air}.(T_{AH,out}-T_{Amb}) \qquad (13)$$

In the above equation, the LHS term is latent heat of the incoming air and in the RHS is the latent heat of outgoing air after treatment from the air pre-heater. The energy lost on the LHS term is gained by the term on RHS. The equation can be used as the same in each scheme.

Equation of the condenser

The same equation is used for every scheme and for any number of effects.

Energy balance:

$$(1-\beta).\dot{m}_{s,leff}.\left(h_{g,s,leff,out}-h_{f,leff,out}\right) = \dot{m}_{csw}.\left(h_{f,sw,wh}-h_{f,sw,amb}\right) \qquad (14)$$

4.3.2 Counter-current feed

In the counter current feed, the equations of the FST, air preheater and the condenser remain the same, hence they are not re derived and explained here. We will therefore first look at the first effect of the counter current feed and then develop a general equation for any other effect.

First Effect

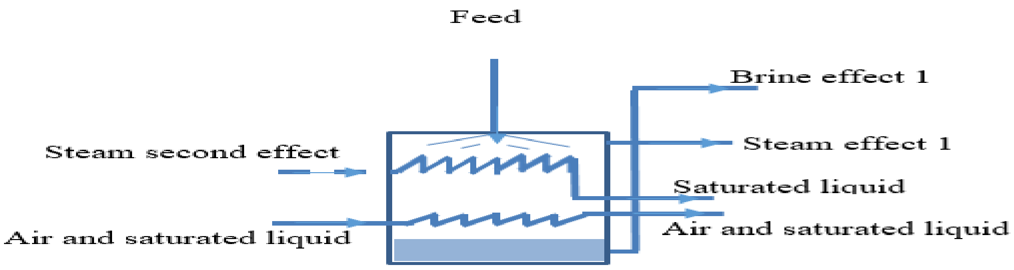


Figure 16 First effect for counter-current feed [7]

The above Figure 17 represents the first effect of the counter-current feed scheme. From Equation (15) for mass balance we can see that the input to the effect is the feed sea water term $\dot{m}_{\boldsymbol{sw}}$ and the outgoing quantities are the steam formed after flashing which is given by $\dot{m}_{\boldsymbol{s,1}}$ and left over brine which does not interact and trickled down given by $\dot{m}_{\boldsymbol{brine},\boldsymbol{1}}$. The steam which condenses and to a saturated liquid within the exchanger is not taken because there it simply transferred to the next effect. The latent heat of evaporation is gained by the incoming feed from the steam and it is evaporated. The energy effects of this steam incoming from second effect is considered in the energy balance but not in mass balance because saturation condition assumption allows us to imply that all the steam will be converted to the saturated liquid.

Mass Balance:

$$\dot{m}_{sw} = \dot{m}_{s,1} + \dot{m}_{brine,1} \tag{15}$$

Energy balance:

$$\begin{aligned} &\dot{m}_{sw}.h_{sw,wh} + \dot{m}_{a}.Cp_{air}.\left(T_{2,out} - T_{1,out}\right) \\ &\qquad + \dot{m}_{FST}.Cp_{water}.\left(T_{2,out} - T_{1,out}\right) + \dot{m}_{s,2}.h_{g,s,2,out} \\ &\qquad = \dot{m}_{s,1}.h_{g,s,1,out} + \dot{m}_{brine,1}.h_{f,brine,1,out} + \dot{m}_{s,2}.h_{f,1,out} \end{aligned} \tag{16}$$

The Equation (16) gives the energy balance for the first effect in the counter current feed scheme. Let us understand the meaning of the terms. $\dot{m}_{\boldsymbol{sw}}.\boldsymbol{h_{sw,wh}}$ gives the energy of the feed sea water at the inlet. $\dot{m}_{\boldsymbol{s,2}}.\boldsymbol{h_{g,s,2,out}}$ gives the enthalpy of the saturated steam inlet to the first effect exiting from the second effect as shown in Figure (16) $\dot{m}_{\boldsymbol{a}}\boldsymbol{Cp_{air}}.\left(\boldsymbol{T_{2,out}} - \boldsymbol{T_{1,out}}\right)$ gives the energy lost by the air and the saturated liquid mix as it enters and then leaves the first effect. $\dot{m}_{\boldsymbol{FST}}.\boldsymbol{Cp_{water}}.\left(\boldsymbol{T_{2,out}} - \boldsymbol{T_{1,out}}\right)$ gives the energy gained by the inlet water. At the outgoing end, we will observe the terms which are in the RHS in the Equation (16) for energy balance for the counter current feed. $\dot{m}_{\boldsymbol{s,1}}.\boldsymbol{h_{g,s,1,out}}$ gives the enthalpy of the exiting steam produced in the effect 1. $\dot{m}_{\boldsymbol{brine,1}}.\boldsymbol{h_{f,brine,1,out}}$ gives the enthalpy of the brine which is being transferred to the effect 2 from the effect which trickles down at the bottom. $\dot{m}_{\boldsymbol{s,2}}.\boldsymbol{h_{f,1,out}}$ gives the energy of the saturated liquid exiting the effect 1.It is essentially the energy of the steam which was input from effect 2 and converted to saturated liquid and then exits the effect 1.

Salinity Balance:

$$X_{brine,1} = \frac{\dot{m}_{sw}.X_{sw}}{\dot{m}_{brine,1}} \tag{17}$$

The above Equation (17) is the salinity balance. In the counter current feed scheme, feed brine, the steam generated in the second effect and the dry air- saturated liquid mixture coming from the second effect are the inlet substances. The steam generated due to evaporation in the first effect, the air-saturated liquid mixture, the leftover feed brine and the saturated liquid obtained from the cooling of the steam coming for second effect are exited from the first effect chamber. The steam generated in this effect is split in two, one is sent to the feed water preheater and the second to the FST. The air-saturated liquid mixture is sent to the cyclone for separation. Leftover feed brine is sent to the second effect. Saturated liquid obtained from the cooling of the steam coming for the second effect is removed from the system.

Last effect equations

The below Figure 17 is for the last effect in the series of multiple effects of distillation. The leftover feed brine in the second last effect, the dry air- steam mixture form the FST are the inlet substances. The steam generated in the last effect, along with the air-saturated liquid mixture, the leftover feed brine and the saturated liquid obtained from the cooling of the steam coming for previous effect are outlets of the last effect. The leftover brine is sent to the FST. All other substances that exit the last effect are sent to the previous (second last) effect.

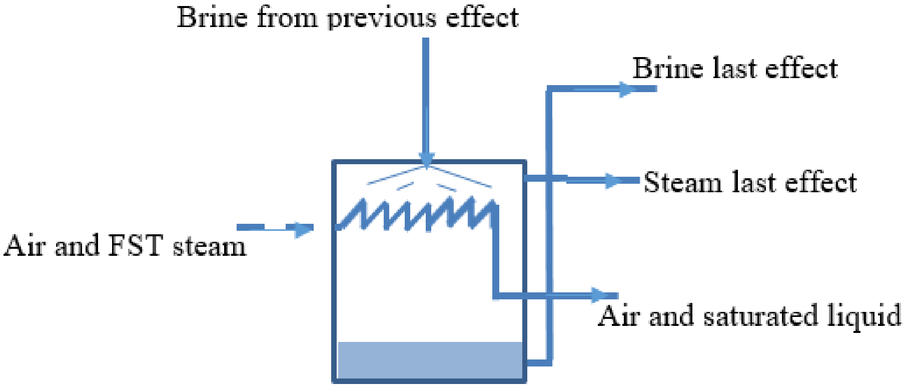


Figure 17 Last effect for counter current feed [7]

Mass Balance:

$$\dot{m}_{brine,2l} = \dot{m}_{s,leff} + \dot{m}_{brine,leff} \quad (18)$$

Salinity Balance:

$$X_{brine,leff} = \frac{\dot{m}_{brine,2l} . X_{brine,2l}}{\dot{m}_{brine,leff}} \tag{19}$$

The above Equation (18) is the mass balance equation and the Equation (19) is the salinity balance equation. Both the equations are like all the previous equations analyzed. In the mass balance equation, the brine from the previous effect is the input and the outlets are the steam formed due to flashing in the last effect the brine exiting the last effect. The air and FST steam is converted to air and saturated liquid and due to saturation condition assumption, all the inlet air and FST steam is converted and hence they do not appear in mass balance but will be analyzed in energy balance.

Energy balance:

$$\begin{aligned} \dot{m}_{a} . Cp_{air} . \left(T_{FST} - T_{leff,out}\right) + \dot{m}_{brine,2l} . h_{brine,2l,out} + \dot{m}_{FST} . h_{FST,g} \\ = \dot{m}_{s,leff} . h_{g,s,leff,out} + \dot{m}_{brine,leff} . h_{f,brine,leff,out} \\ + \dot{m}_{FST,f} . h_{f,leff,out} \end{aligned} \tag{20}$$

In the energy balance Equation (20) for the last effect in counter current feed at the inlet we have the energy of the brine from the previous (in the case of three effect system, the second effect) given by $\dot{m}_{\boldsymbol{brine,2l}} . \boldsymbol{h_{brine,2l,out}}$ and the enthalpy of steam from the FST given by $\dot{m}_{\boldsymbol{FST}} . \boldsymbol{h_{FST,g}}$.The term $\dot{m}_{\boldsymbol{a}} . \boldsymbol{Cp_{air}} . \left(\boldsymbol{T_{FST} - T_{leff,out}}\right)$ gives the latent heat lost by air and steam mixture when it interacts with the incoming feed from the previous effect. The incoming temperature is of that of the FST and exiting is that of that in the last effect. The terms $\dot{m}_{\boldsymbol{s,leff}} . \boldsymbol{h_{g,s,leff,out}}$, $\dot{m}_{\boldsymbol{brine,leff}} . \boldsymbol{h_{f,brine,leff,out}}$ and $\dot{m}_{\boldsymbol{FST,f}} . \boldsymbol{h_{f,leff,out}}$ represents the energy or enthalpy of the exiting steam from the last effect (also produced due to flashing), the energy of the brine exiting the last effect which trickles down at the bottom and the energy of air and saturated liquid (inlet from FST) but leaving the last effect) as saturated liquid.

Equations of other effects

The shown below Equations (21), (22) and (23) are the equations for the intermediate effects between the first and the last effect and are applicable to any general (nth) effect.

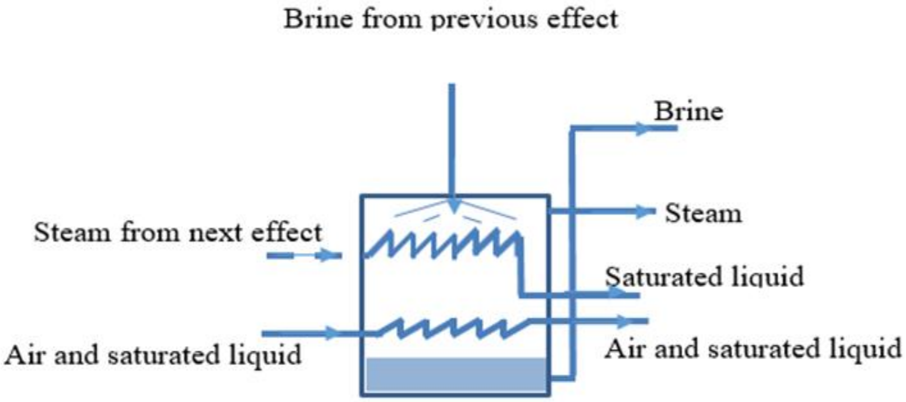


Figure 18 Other effects for counter current feed [7]

Mass Balance:

$$\dot{m}_{brine,i} = \dot{m}_{s,j} + \dot{m}_{brine,j} \tag{21}$$

Salinity Balance:

$$X_{brine,j} = \frac{\dot{m}_{brine,i}.X_{brine,i}}{\dot{m}_{brine,j}} \tag{22}$$

Energy balance:

$$\begin{aligned} &\dot{m}_a.Cp_{air}.\left(T_{k,out} - T_{j,out}\right) + \dot{m}_{FST}.Cp_{water}.\left(T_{k,out} - T_{j,out}\right) \\ &\quad + \dot{m}_{brine,i}.h_{f,brine,i,out} + \dot{m}_{s,k}.h_{g,s,k,out} \\ &\quad = \dot{m}_{s,j}.h_{g,s,j,out} + \dot{m}_{brine,j}.h_{f,brine,j,out} + \dot{m}_{s,i}.h_{f,j,out} \end{aligned} \tag{23}$$

4.4 Computational Methods

The equations derived in previous section are nonlinear and a program was developed using MATLAB to solve these. The energy and mass balance equations were re-written in the form of $F(k)$=0, and passed on as argument to the solver in the MATLAB. For example, the equation for FST energy balance can be arranged as follows:

$$F(1) = m_a . Cp_{air} . (T_{hs} - T_{FST}) + m_{brine,leff} . h_{f,brine,leff} + m_{bs} . h_{g,bs,hs} \\ - (m_{salt} . Cp_{salt} . (T_{FST} - T_{amb}) + m_{FST} . h_{g,FST})$$

The equations for salinity were not considered as components of $F(x)$ because salinity for any stream of brine is not an independent variable.

1. Open folder of required system. For example, if we wish to run simulation for concurrent feed system with 3 effects. Open: Desalination_Code/Concurrent_ feed/3effects. Copy the contents of the folder to the MATLAB working directory along with folder 'XSteam_Matlab_v2.6' and 'SEAWATER_MATLAB_2012-07-17'.

2. Open program "Desalination_concurrent_3effects.m" and run it. Input data asked by the program, i.e.: Temperature of heat source, exit temperature form FST, specific heat capacity of salt, inlet and outlet temperatures for hot air and steam mixture for each effect, exit temperature of brine for each effect, initial salinity of system, ambient temperature, bleed fraction of system

3. The programs simulate the system by evaluating the mass and energy balances equation using the user inputs to calculate the following: mass flow rate of required dry air, mass flow rates of brine and steam of produced in each effect, mass flow rates of cooling seawater. Other value calculated by the program include energy and mass difference and thermal energy consumption of system.

4.5 Fouling and scaling

Precipitation of Calcium Sulfate causes serious problems for any heat exchanger or evaporator. As in this case the water is untreated and the evaporation effects downstream handle high concentration brine. This increases the chances of scaling many times. Calcium sulfate solubility curves show that the solubility decreases with increase in temperature of brine. This imposes an **upper limit** for temperature of the effects with ordinary heat exchanger tubes. Figure 19 below shoes the variation of the calcium sulphate deposition with respect to temperature and salinity values [11].

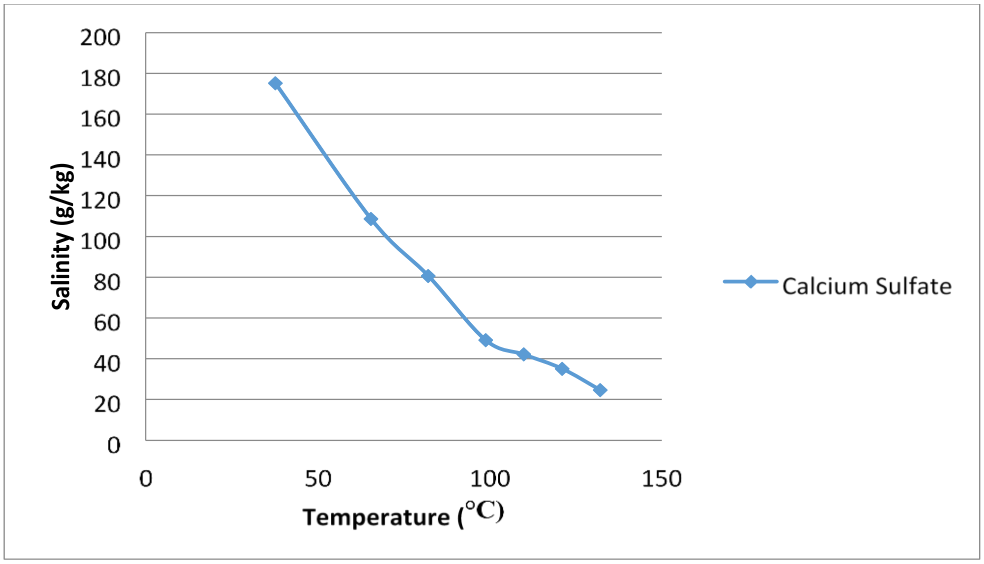


Figure 19 Variation of salinity versus temperature for calcium sulfate [9]

4.6 Results and discussion

4.6.1 Thermal energy comparison between different schemes

The basis of fabricating a new thermal driven desalination system is energy consumption. In the scope of this research we compare two schemes, variable feed and counter-current feed. The two feeding schemes are compared in terms of **Energy consumed in KWh per 1000-gallon water** feeding. Below given Figure 20 compares these two schemes from 3 to 9 effects with increasing hot air inlet temperature. Clearly we can observe that variable feed takes less amount of energy and hence we fabricate the 3-effect variable feed scheme for our experiment in this research.

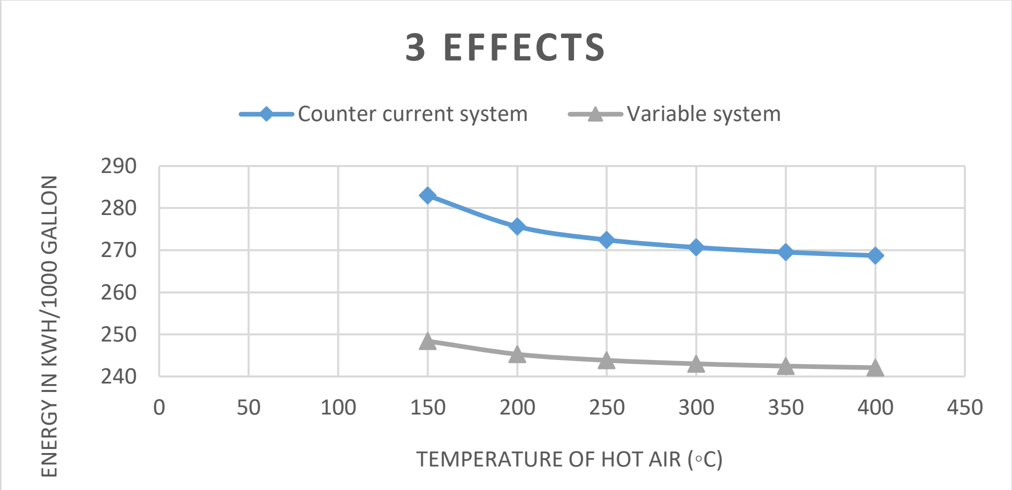


Figure 20 graph of comparison energy consumption for 3 effects

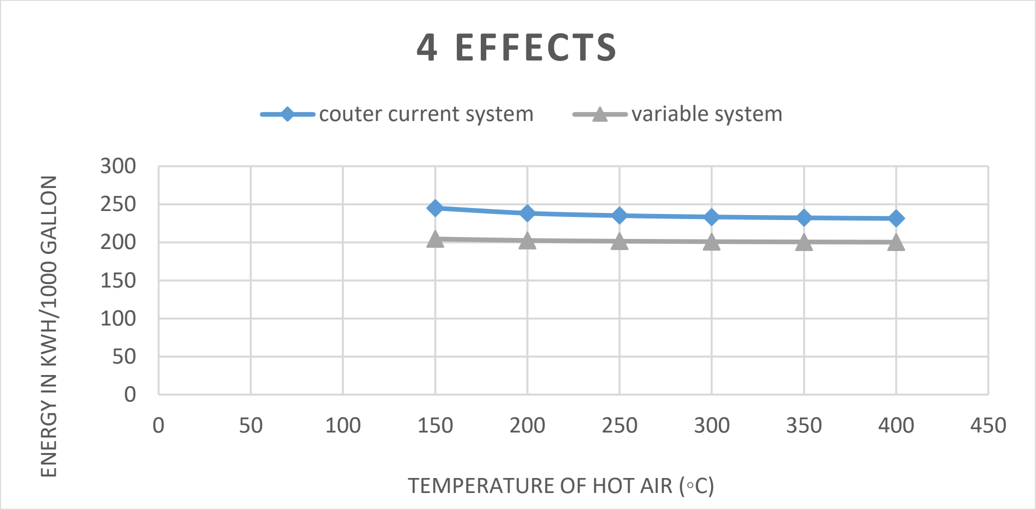


Figure 21 graph of comparison energy consumption for 4 effects

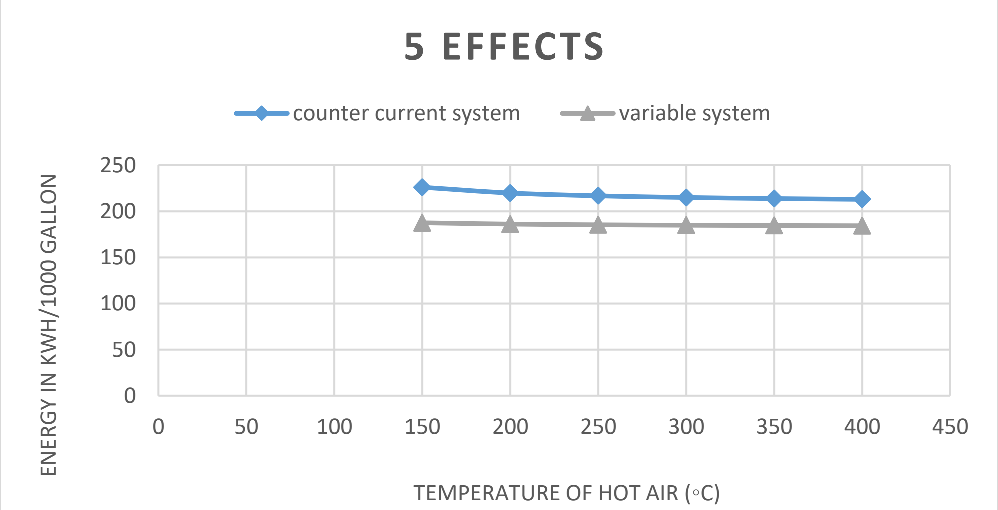


Figure 22 graph of comparison energy consumption for 5 effects

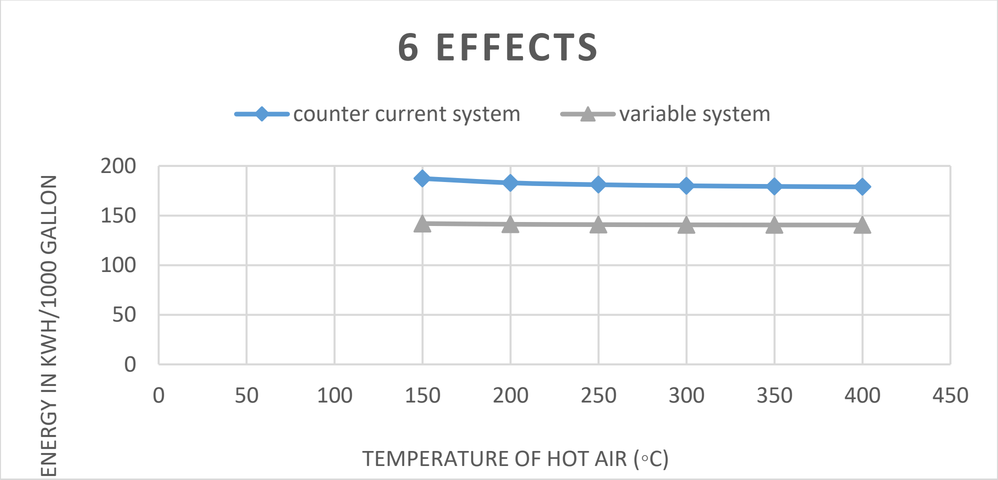


Figure 23 graph of comparison energy consumption for 6 effects

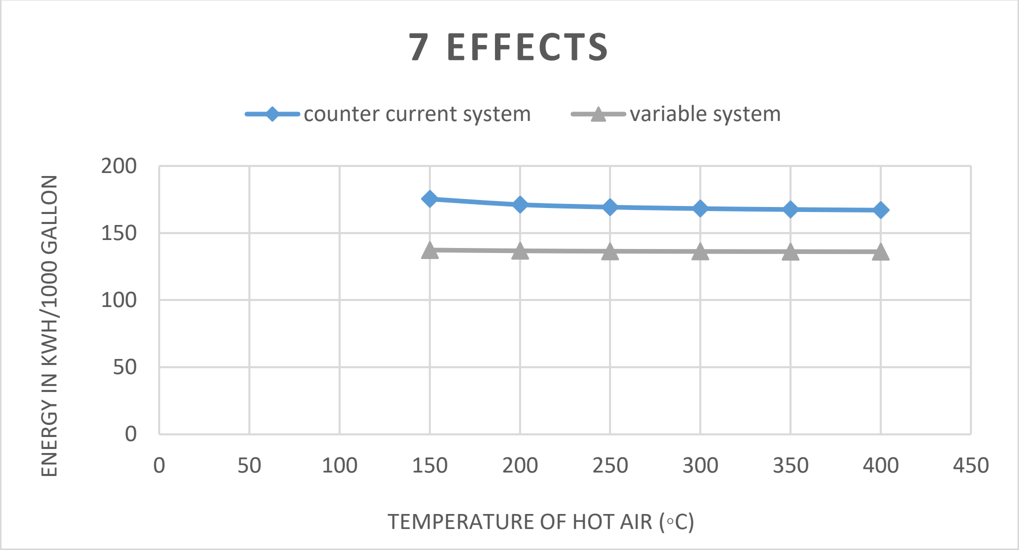


Figure 24 graph of comparison energy consumption for 7 effects

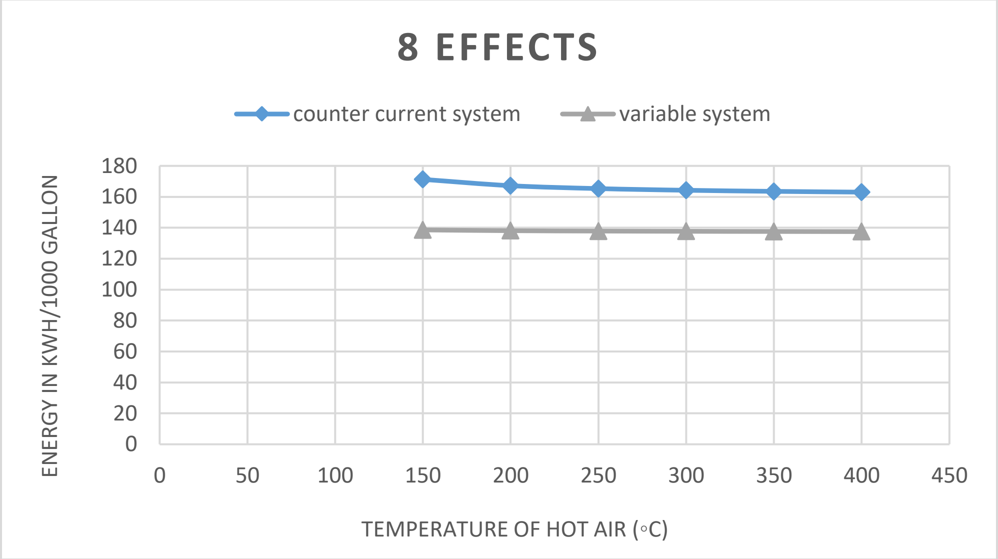


Figure 25 graph of comparison energy consumption for 8 effects

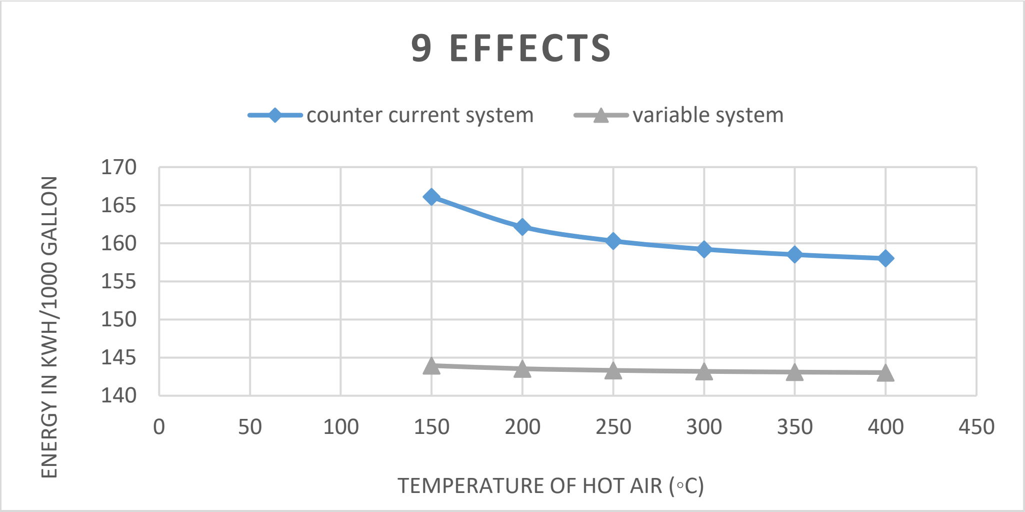


Figure 26 graph of comparison energy consumption for 9 effects

4.6.2 Energy consumption vs number of effects

The Figure 28 and Figure 29 below show the energy consumed by the counter current feed and variable feed scheme as we increase the number of effects. In both the graphs we observe that as we increase the number of effects from 3 to 9, the **energy requirement decreases significantly**. This comparison has been made at a hot air temperature of 150˚C.We can observe from section 8.3 in the appendix that the mass flow of the feed in each effect decreases as we go on increasing the number of effects. Therefore, mass flow of feed being a dominating factor gives a reason the energy requirement decreases.

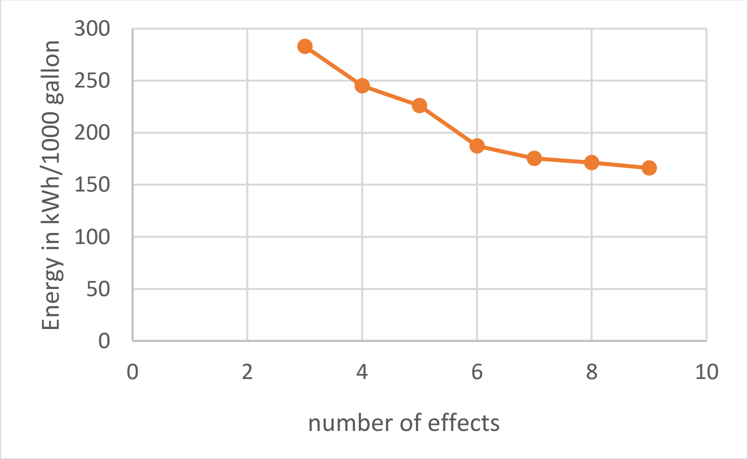


Figure 27 Graph of Thermal energy variation for counter-current feed from 3-9 effects

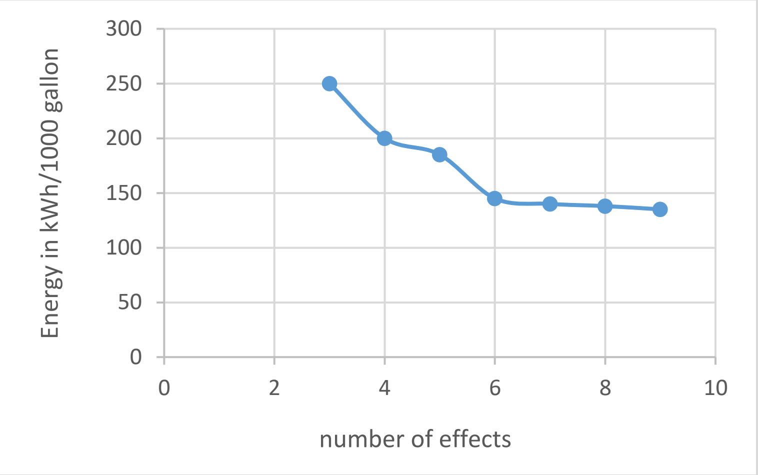


Figure 28 Graph of Thermal energy variation for variable feed from 3-9 effects

4.6.3 Evaporation factor

Evaporation ratio or evaporation factor can be defined as the ratio of **amount of steam produced to that of the incoming brine from the previous effect**. It can also be used to approximate the change in salinity of brine i.e. Salinity of the input feed compared to that left behind at the bottom of the effects. The evaporation ratio is also influenced by bleed steam which can defined as the ratio of amount of steam bled from the last effect to that of amount of steam produced in the last effect. Therefore, we can understand that as the value of the bleed steam increases the value of the evaporation ratio goes down. For hot air temperature of 150˚C going from bleed fraction of 0.3 to 0.6, steam produced went from **0.0335 kg/s to 0.0315 kg/s** in case of variable feed. This can be since the mass flow of the incoming brine is lower as compared to the other effects. Since brine is less, less will be the percentage of brine to be evaporated and thus less steam is produced.

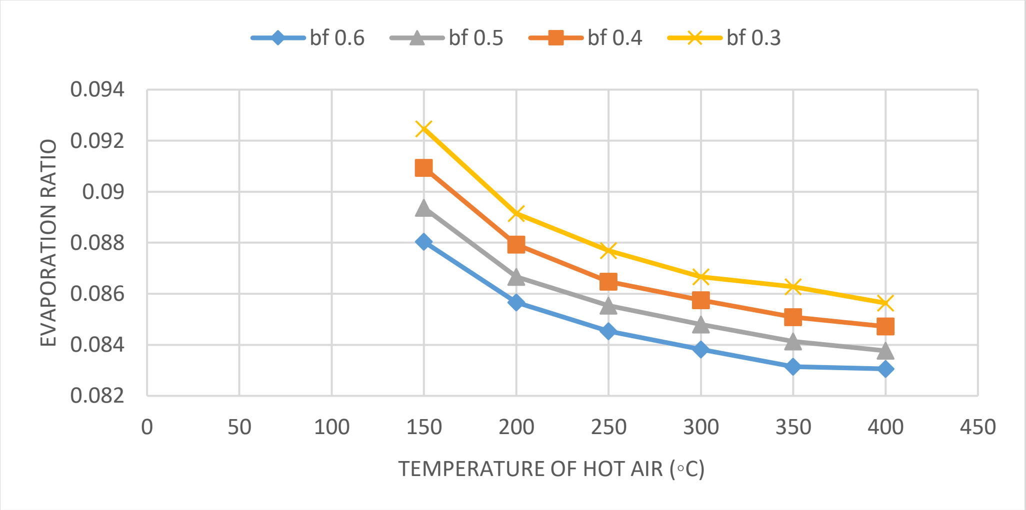


Figure 29 Evaporation ratio versus temperature of hot air at various bleed fractions for variable feed.

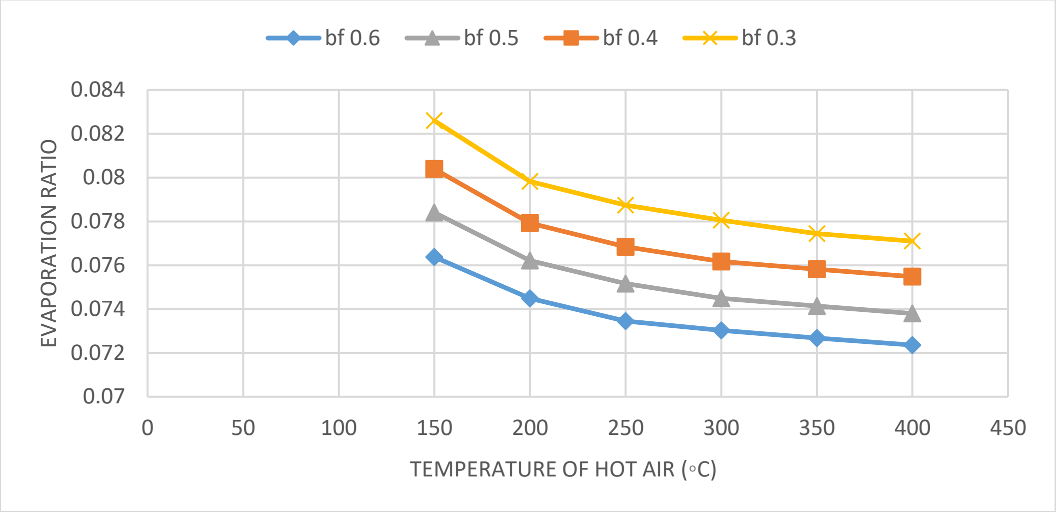


Figure 30 Evaporation ratio versus temperature of hot air at various bleed fractions for counter current feed.

5. Prototype development and design

5.1 Scheme Selection and reasons

The prototype which is fabricated is per the variable scheme for 3 effects. Although other schemes were explored during this research work but there are several reasons as to why variable feeding with full separation and bleed steam was developed. The first reason and the most important reason is the type of feeding in the variable scheme as shown in Figure 20. The input feed water which flows in the corresponding effects is variable in terms of mass flow. Each effect can have either the same mass flow of the feed or completely different. This gives us the flexibility to control the amount of feed going inside the effects.

Other reasons include thermal energy consumption reasons. As seen from appendix a comparison of the countercurrent flow and the variable flow shows that the energy consumption of the variable feed is around 250 KWh/1000 gallons of input feed whereas the same parameter value for concurrent feed is around 280 KWh/1000 gallons of input feed. The lesser the amount of energy required, the better is the efficiency of the system and the easier it is becoming to integrate the system with Renewable energy sources.

Another factor that influences the decision is the evaporation ratio as seen in Figure 29 & 30. The evaporation ratio for a bleed fraction of 0.3 at the temperature of about 150˚C is considered for both the various schemes. From Figure 29 and Figure 30 it can be easily seen that evaporation ratio for variable feed is 0.093 and that of counter current feed is 0.083, hence the variable feed is selected since Evaporation factor or ratio is the ratio of mass flow of steam produced to the mass flow of brine coming from the previous effect, therefore the higher the higher the value the better the system.

The below is the system which is selected for fabrication. The mass flow of a 3-effect full separation variable feed system is labelled in the Figure 31 along with temperature of air and steam exiting and entering each effect. In the actual fabrication, only a 3-effect system was considered for ease and only demonstration of the technology.

The labelled figure of FS MED variable feed scheme with temperatures and mass flow

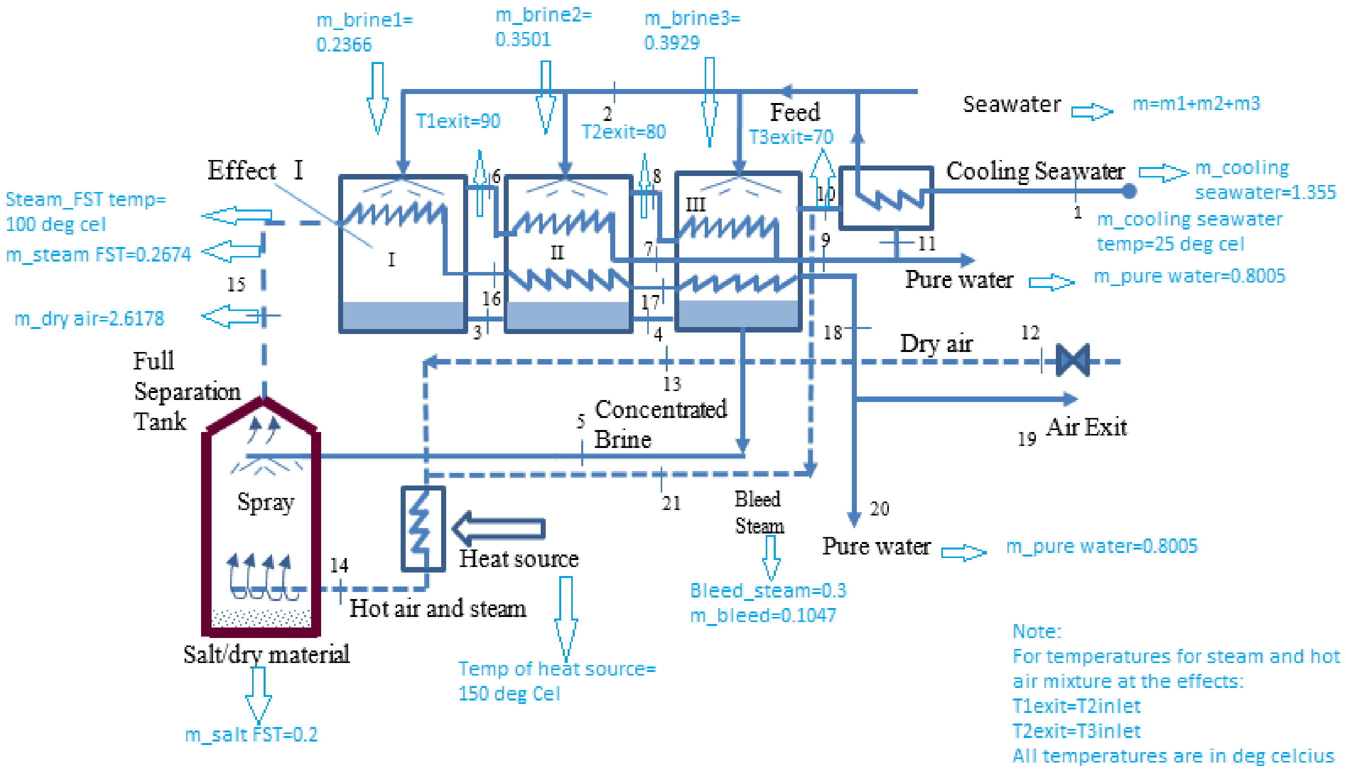


Figure 31 FS-MED variable feed labelled

5.2 Full separations concept

The full separation technique is used while developing the system as shown in the Figure 32. The concept of full separation is unique in this research and has been utilized so that the brine which is discharged in the traditional thermal desalination schemes can be used. As seen from the Figure 31 the brine from the third effect which is discharged is pumped to the FST. In the FST the dry air and bleed steam with very high temperature interact with this brine and force complete evaporation of the highly saline droplets. During this process the salt is collected at the bottom of the FST and air which goes to the first effect gets heated by gaining latent heat from the droplets. The simulation of brine droplets being separated is a separate work and was carried out in the Fuel cell and energy Lab by **Dr Penghua Guo, Dr Peiwen Li and Jingyin Li** [10].

Generally, there are two stages during the vaporization process of a droplet. The first stage is the preheating process. The droplet is heated up and its temperature increases with time until eventually it reaches the wet-bulb temperature. The second stage is the equilibrium mode, in which the droplet stays at the wet-bulb temperature during the remaining lifetime and the heat reaching the droplet surface supplies the latent heat of vaporization. In some cases, such as the fuel droplet combustion, the ambient temperature is so high that the time of preheating process is very short.

The preheating process is usually neglected and only the equilibrium mode is considered. Both the stages are shown in Figure 32.

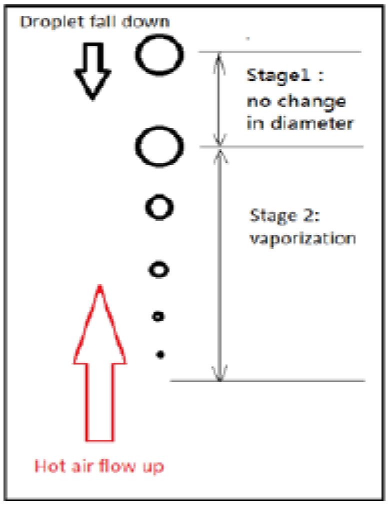


Figure 12 Figure showing droplet fall down stages and sizes inside the FST. [10]

A simplified non-equilibrium vaporization model is adopted to describe the movement and evaporation behavior of a single water droplet in the FST, in which both the preheating and equilibrium process are considered. The droplet lifetime has been calculated over a wide range of ambient temperatures and injection velocities (i.e. 473-673 K and 0-30 m/s, respectively) as shown in Figure 33.

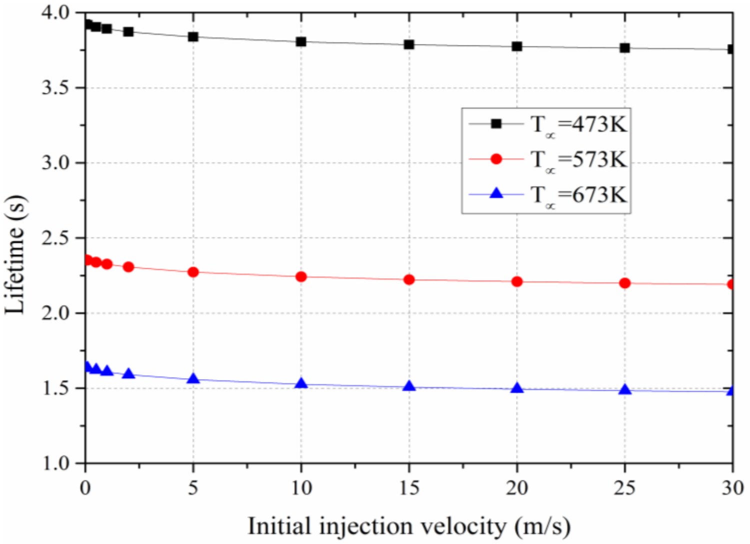


Figure 13 Graph of Lifetime of droplet versus Injection velocity inside FST. [10]

The droplet lifetime is significantly affected by the ambient temperature. A larger ambient temperature will lead to a shorter lifetime of the droplet. As seen in Figure 34 the droplet lifetime increases with an increase in droplet diameter but decreases with an increase in the ambient temperate. To get a more detailed picture, the lifetime and falling distance under different diameters and temperatures are compared in Figure 34 and Figure 35. Both the lifetime and falling distance decrease with the ambient temperature increase in a non-linear fashion, with a gradually decrease in the slope. These figures can help us to identify the suitable droplet size, temperature of the hot air and the height of FST. For example, if the limitation of the **FST height is about 3 m** and the hot air temperature is 673 K, then the droplet diameter cannot exceed 450 µm to be evaporated completely.

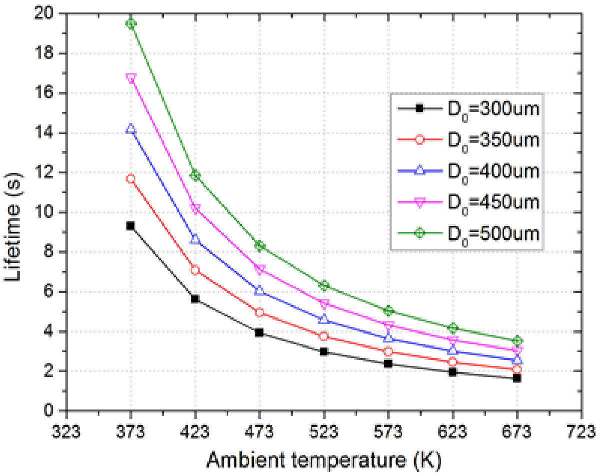


Figure 14 Lifetime versus temperature of droplet [10]

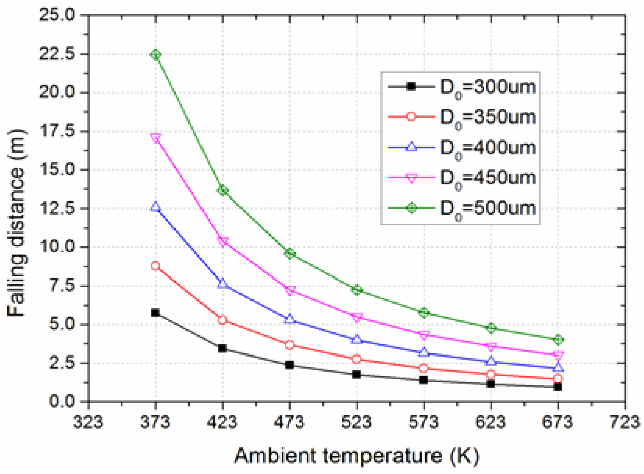
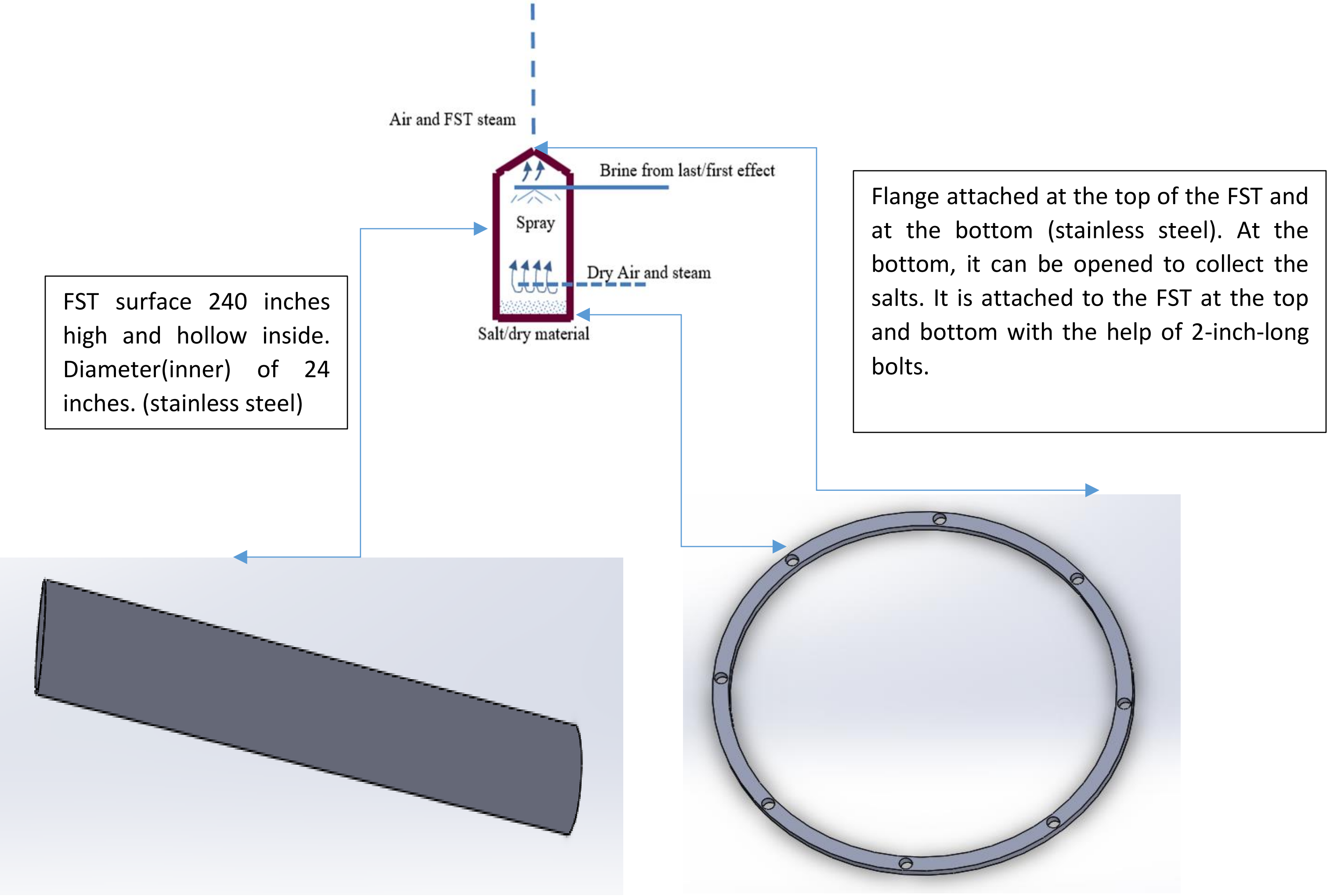


Figure 35 Falling distance versus temperature of droplet [10]

5.2.1 Design and fabrication of FST

The 3-D modelling of the FST is done on solid works.The FST is developed out of stainless steel T-304.It is around **240 inches high (almost 6 m) with a thickness of 1 inch** and the inner diameter of 24 inches and the outer diameter of 25 inches.There is an additional covering cap at the top of the FST to cover the open end at the top.Both the topmost and the bottomost ends have a flange so that the FST can be opened and closed.The FST is covered with an insulation made of moisture venting polyurthane foam with an R value of 6.5 per inch.At the top end of the covering cap is a inch opening which is used to attch the 2 inch thick pipe . This 2 inch thik pipe carries the steam from the FST to the first effect. The length of the pipe almost being 200 inches and is covered with same inculation to avoid heat losses.The Figures 36 below show the modelling of the FST and then Figures 36 show the actual pictures of the FST as standing on ground.Additional supports are also present at the top end and the middle end so that the pipe does not sway due to winds and stays firm.There are 3 supports with a 6 inch threads (to make it adjustable) and a claw shaped stainless steel support at each ends.This also helps to not break the fittings at the top end of the **2 inch pipe**.

Solid modelling:

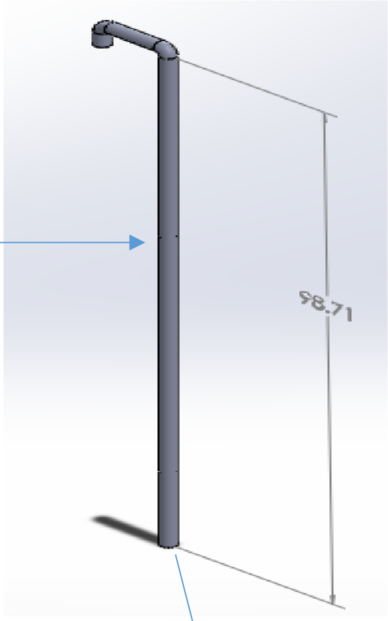


FST surface 240 inches high and hollow inside. Diameter(inner) of 24 inches. (stainless steel)

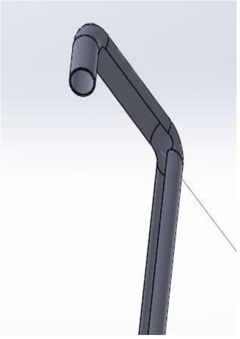
Flange attached at the top of the FST and at the bottom (stainless steel). At the bottom, it can be opened to collect the salts. It is attached to the FST at the top and bottom with the help of 2-inch-long bolts.

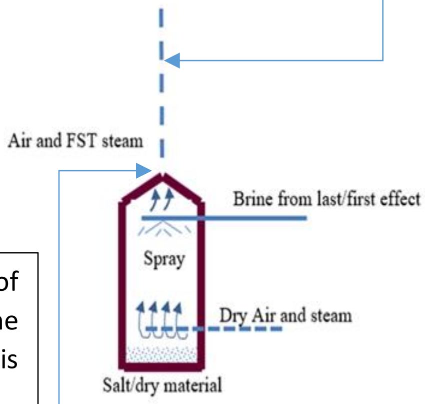
Figure 36 Flange and FST structure (3-D modelled)

The 2-inch pipe to carry the FST steam (stainless steel) and 2 inch in diameter. Length of about 200 inches.

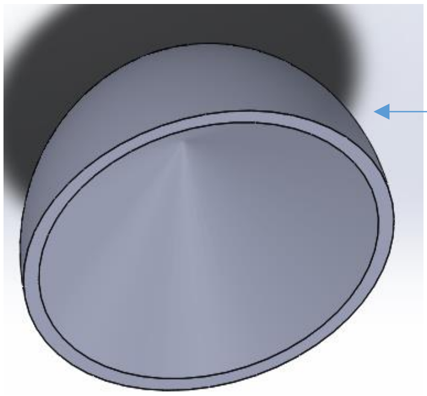


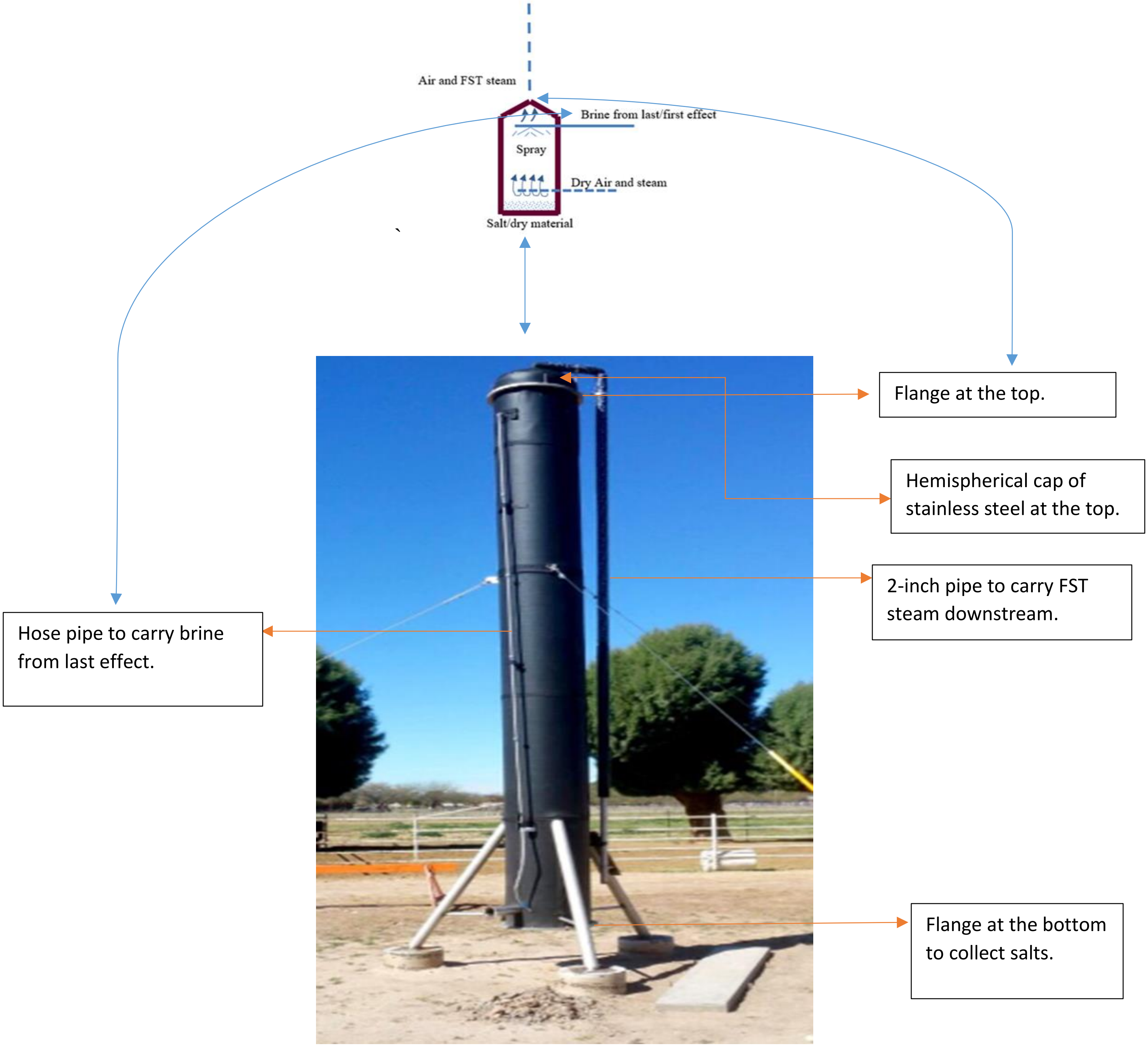
Section of pipe shown magnified.





The hemispherical cap made of stainless steel. It is put at the top of the flange and the above shown pipe is attached at the top of this cap.





Flange at the top.

Hemispherical cap of stainless steel at the top.

2-inch pipe to carry FST steam downstream.

Hose pipe to carry brine from last effect.

Flange at the bottom to collect salts.

Figure 37 FST implementation

5.3 Effect Tanks

The 3-D modelling of the effect tanks is done on solid works.In this FST MED variable feed model , we consider the number of effects as 3, this number is chosen for the purpose of east of fabrication and due to simulation data being present as well.The effect tanks each are made of stainles steel T-304. The height of the effect tanks is **42 inches** (3 feet) .The length and width of the effect tanks are **18 inches** (1.5 feet) respectively. The top of the effet tanks has 2 opening of 1 inch each.The opening at the middle is used for the spray nozzle which sprays the brine feed and the other opening is used for measuring pressure. A pressure transducer is used to measure the pressure and at this other opening , the transducer is threaded.The effect tanks are covered with insulation to reduce heat loss moisture venting polyurethane foam is used as insulation because of very high R value of 6.5 per inch. The tanks also have a small rectangular flange , incase we need to open the tanks to remove salt from the heat exchangers or simply replace the exchangers.The flange and is sealed to the effct tanks with the help of silicone as a sealant.There are 2 heat exchangers used in each of the effect tanks, the slots for which are shown in Figure 38.The bottom of each effect tanks also has a **½ inch opening** to facilitate the flow of brine from effect 1 to effect 2.

Solid modelling

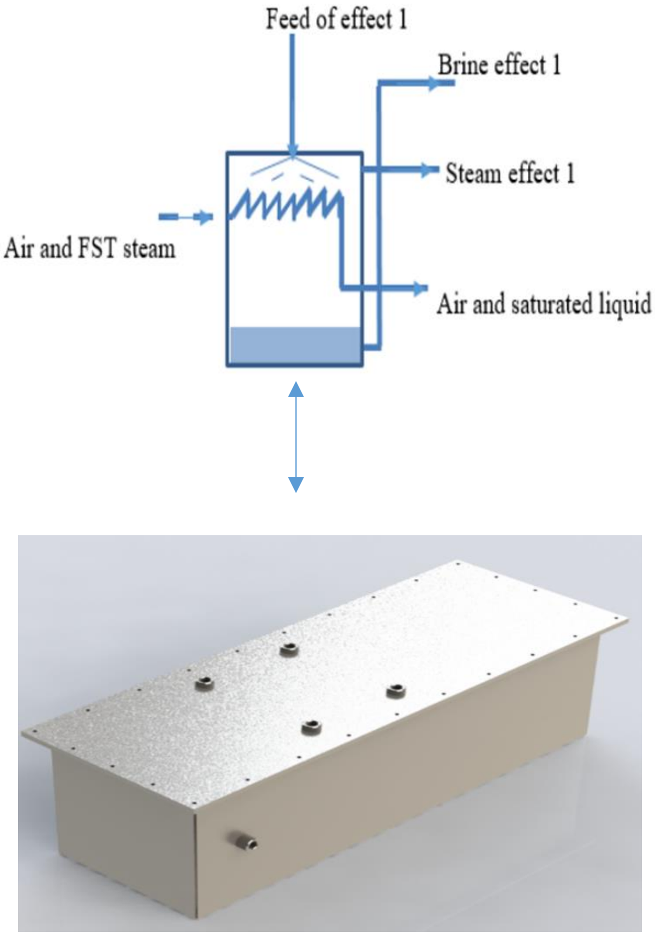


Figure 38 Effects 3-D modelling

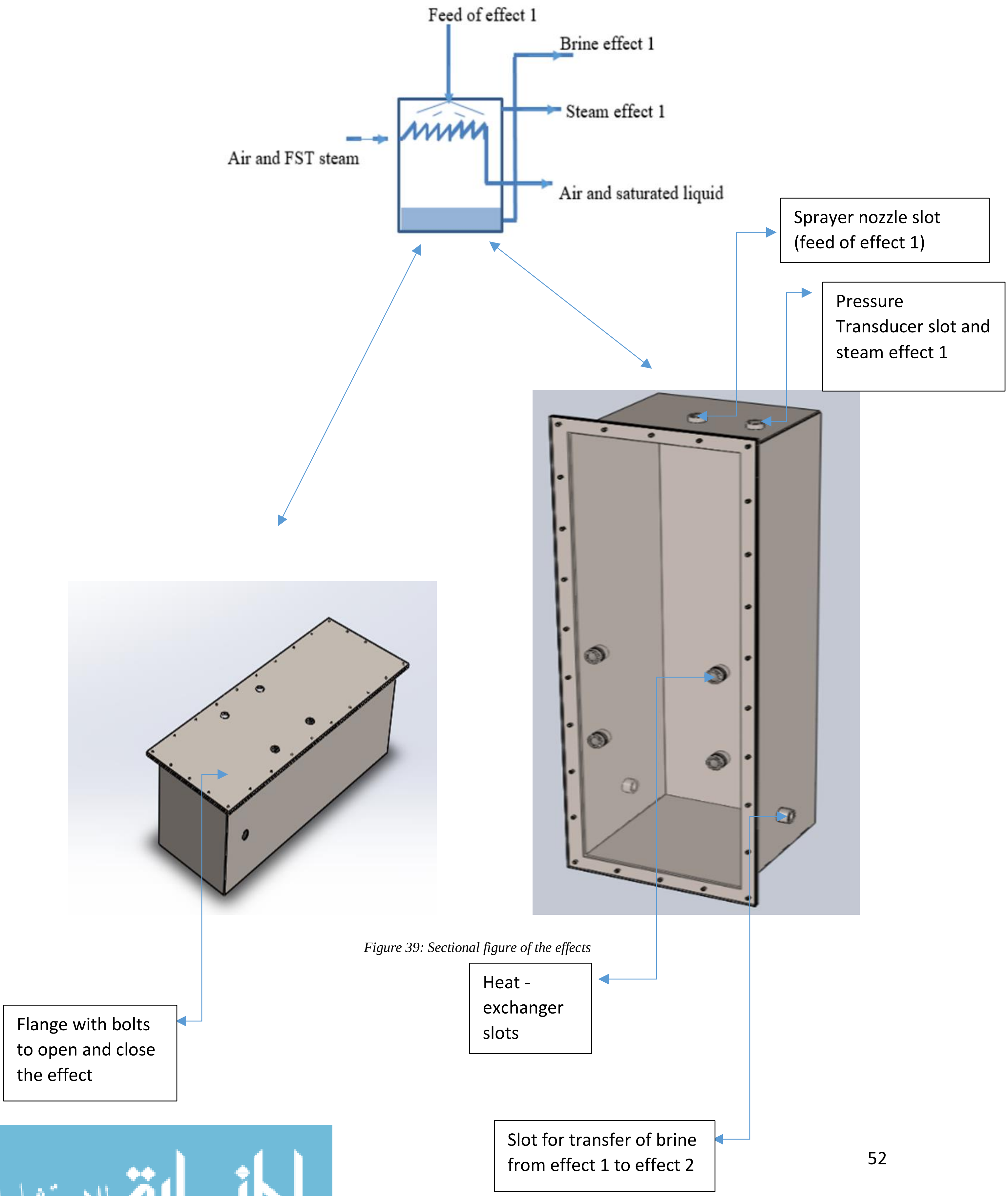


Figure 39: Sectional figure of the effects

FST

FST hemispherical cap

2-inch pipe to carry steam from FST

Feed1

Steam formed due to flashing in effect1

Effect 1

Steam from FST to effect 1

Effect 2

Effect 3

Connection to transfer brine from effect 2 to 3 and similarly used for all

Feed2

Feed3

Steam formed due to flashing in effect 2

Condenser

Steam from the multi-effects given to condenser to form pure water

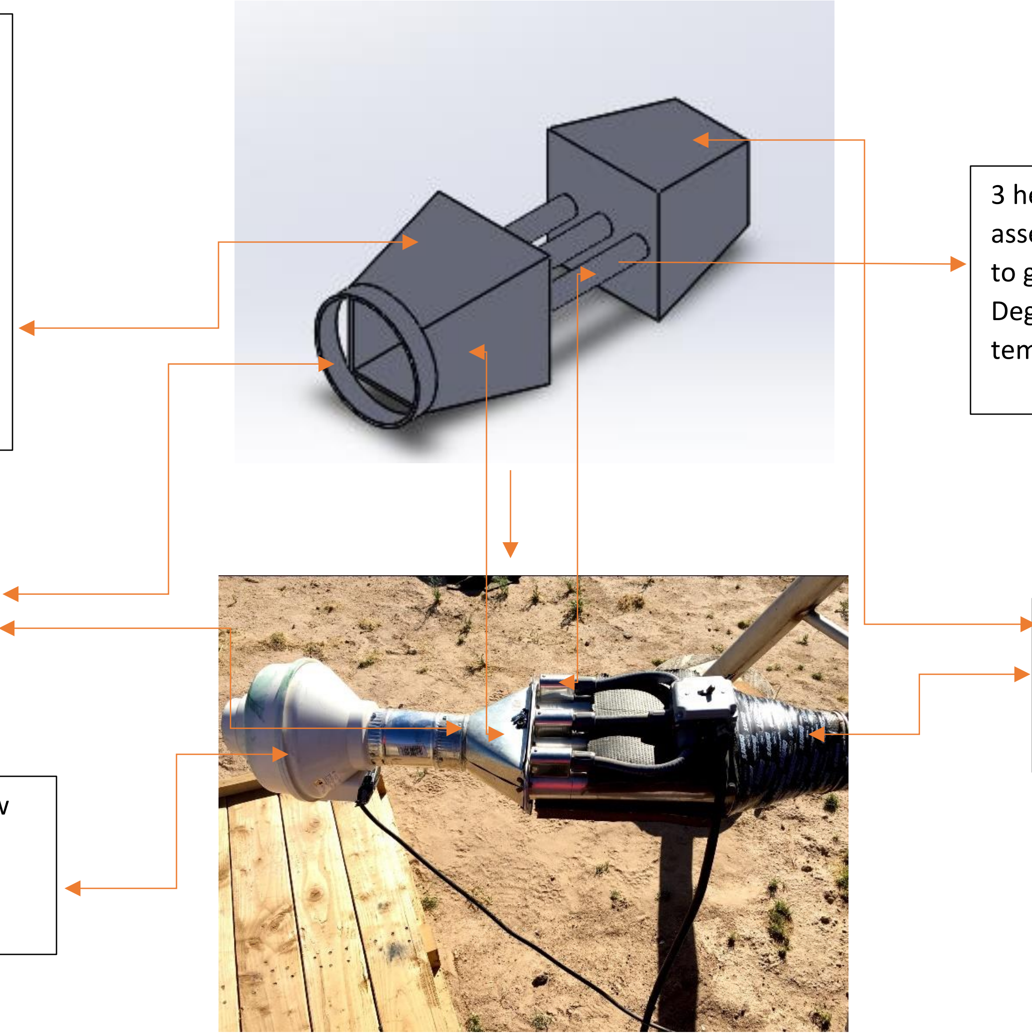
Condensed steam and water formed due to heat exchange inside the effects on surface of fin tubed heat exchanger.

Figure 40 Implementation of the system with effects and FST

5.4 The Heating Strategy

The heating strategy for this novel desalination system is very important. Since we want to utilise the waste dischareg brine , therefore the hot air and steam interacting with this brine must have sufficent thermal energy. For heating the air and steam mixture we use the air heaters.We use three air heaters in order to provide a heating capability of **150˚C to 400˚C**.The heaters 240 volts, **2000 watts each** and draws a current of **8.33 Amp** each. The heater by itself cannot function alone and hot air needs to be pushed inside by the means of a pump. We therefor use an air pump in conjunction with an air heater manifold.The pump is thermally protected with a coating outside and draws 0.58 Amps at 115 volts.The pump works at a frequency of 60 Hz and at a power of 67 watts. The air pump has a flow rate of about **150 CFM**. In the actual implementation of this assembly, air pump is attached to the FST at the bottom in series with the heater manifold . There is a 4 inch long stainless steel fitting which separates the heaters from the pump for the purpose of safety.

3-D modelling of heater manifold:



Front and back end of the manifold. All the air mixed together and goes through as one inlet to the FST and all air from the air blower goes as one to the heating manifold.

3 heater elements assembled together to give hot air to 400 Degree Celsius temperature.

Flange at both front and the back end.

Back end of the manifold, which forces air into FST.

Air blower to blow air into the elements.

Figure 41 Implementation and 3-D modelled of heater manifold.

5.5 Flow control and temperature-pressure control

The flow of inlet feed water needs to be controlled at each and every effect. The inlet feed water going inside the effects are controlled according to the values obtained in simulation and shown in Figure 42.For this purpose we use an LCR water flow controller with a valve at downstream end and pipe fittings at both the ends.This controller is straightforward and we simply connect it at the top of the effect tanks as shown in Figure 42.The flow controller opeartes at a range of about **7-30 Volts DC** drawing a current of **0.04 mA**. The standard opearting temperature range is 10-50 ˚C and opearting prssure is **200 psig**.It is made up of stainless steel 316 L to avoid any rusting and corrosion and has a flow rate range of about **0-10 LPM**.

Similar to the flow, there needs to be a control of temperature at each and every effect as well.The temperatre in each effect is controlled indirectly through presure transducers.This strategy was temporary and as will be mentioned in experiments and errors section.This was eventually replaced by a pressure switch.The pressure in each effect is measured through a pressure transducer Figure 42.The transdcuer is placed at the top of each effect as shown in Figure 42.This transducer then converts the pressure to a current value.The pressure value is controlled and compared by a controller-LAB VIEW system.The system as also mentioned previously employs saturation state assumption. This means that if the temperature for steam in a certain effect is to be 90 ˚C then its corresponsing saturation presure is **70.14 KPa** for gaseous state. The LAB View program then compares the pressure at an instant to this 70.14 KPa value and if the value is less , then the controller signals the steam fans as ‘on’ to increase the pressure the pressure inside the effects so that it reaches 70.14 KPa.The three effects are connected with three steam fans for this purpose.

Figures of implementation in actual system:

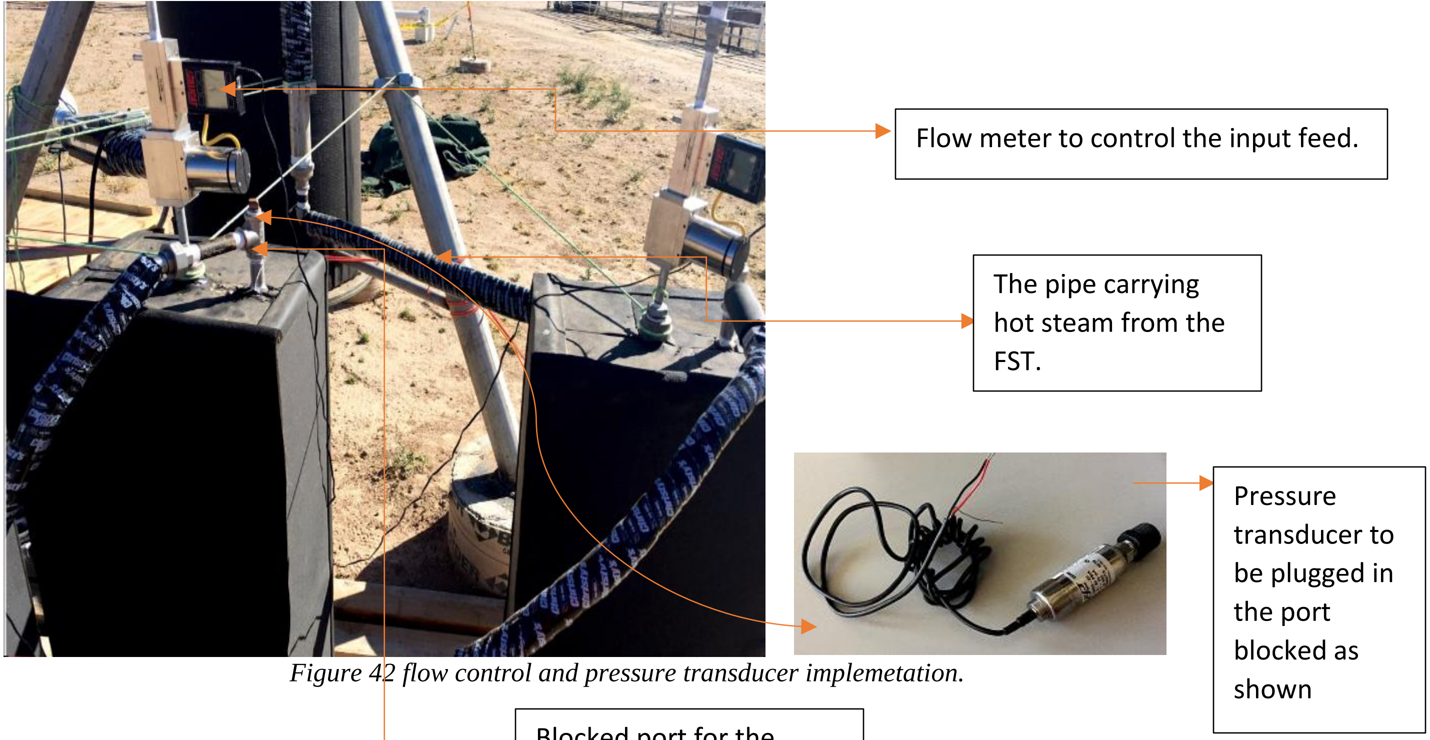


Figure 42 flow control and pressure transducer implemetation.

5.6 Preliminary Heat Exchanger design

The heat exchanger used in the system is a finned tube heat exchanger made of stainless steel. The stainless steel material is chosen in order to avoid corrosion, fouling and scaling on the top surface of the fins and inside the tubes of the exchanger.To analyse the heat exchanger we look at the processes occouring inside and outside the tube as shown in Figure 43.The process outisde of the tubes and on the fins is film evaporation.The process inside the tubes is divided into upstream end and downstream end. The upstream end is condensation with air and the downstream end is convective heat transfer.The condensation process on the upstream end inside the exchanger translates to convectove heat transfer with the mix of water and air. The Figure 43 below represents these process occouring in effect 1 with the temperature of air and steam mix entering the exchanger at 100˚C and leaving at the 90˚C. As the processes take place on the heat exchange surfaces, the volume of air is large as compared to the water (liquid) and hence the convection due to water is ignored.All the states are saturation states and the conduction through the wall is ignored.From this study we are able to verify that pressure in desalination systems does not make a significant impact on the latent heat but the saturation temperature does.Secondly , the we try and calculate the area of the heat exchanger by taking a suitable temperetaure difference. The calculated area is then compared with the actual employed area to justify the temperatures we take at the inlet and the outlet of the effects.

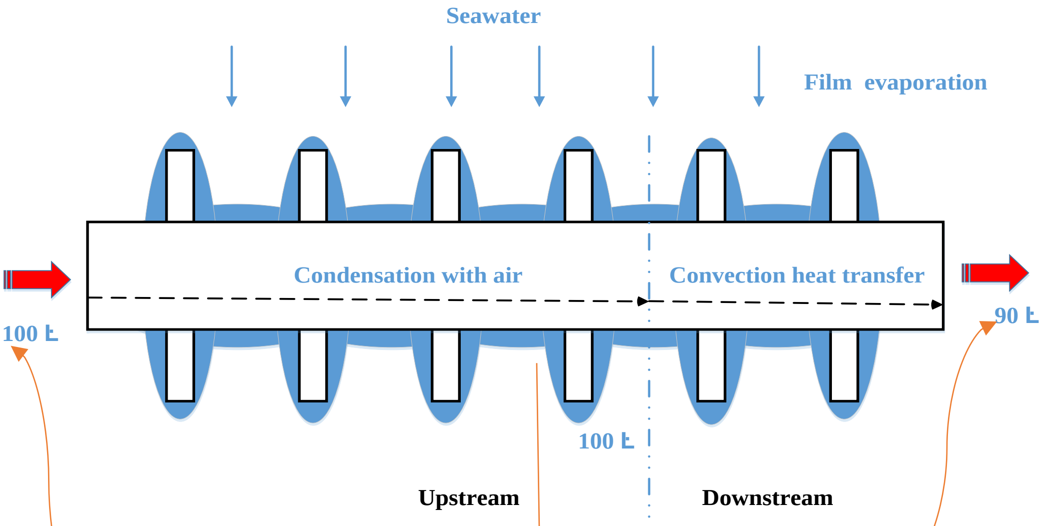


Figure 43 The heat exchanger model

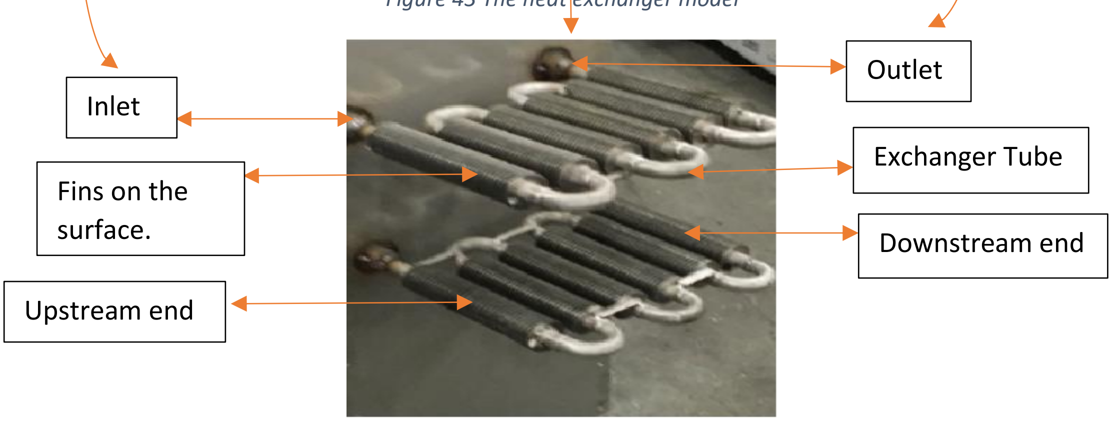


Figure 44 Heat exchanger implemented

Convective heat transfer using Dittus-Boelter correlation

The earliest correlation for turbulent heat transfer in a smooth tube appears to have been provided by Dittus and Boelter. A common form to be used for fluids with Prandtl number in the approximate range 0.7-100, and tubes with L/D>60 is given as below [11]

$$Nu=0.023\ Re^{0.8}\ Pr^{n} \qquad (24)$$

Here, n = 0.4 if the fluid is being heated, that is, if the wall is at a higher temperature than the entering fluid, and n = 0.3 if the fluid is being cooled. All the physical properties used in the Dittus-Boelter correlation are evaluated at the average bulk temperature of the fluid. This is the arithmetic average of the bulk average temperatures at the entrance and the exit. The usual recommendation is to use the Dittus-Boelter correlation for Re>10,000, but in practice it is used even at lower Reynolds numbers so long as the flow is turbulent, because it is a simple correlation to use. The correlation used in this study is given as below [11,13]:

$$\mathrm{Nu}=0.023\mathrm{Re}^{0.8}\ \mathrm{Pr}^{0.3} \qquad (25)$$

The heat transfer area is calculated using the following equations (26) to (30):

$$A_{\mathrm{tot}}=A_{\mathrm{down}}+A_{\mathrm{up}}$$

$$Q_{\mathrm{up}}=m_{\mathrm{stream}}h_{fgw}$$

$$Q_{\mathrm{up}}=\frac{1}{\dfrac{1}{h_{\mathrm{con}}}+\dfrac{1}{h_{\mathrm{eva}}}}A_{\mathrm{up}}(T_{\mathrm{sat\_w}}-T_{\mathrm{sat\_sw}})$$

$$Q_{\mathrm{down}}=m_{\mathrm{stream}}\ c_{p,1}\ (T_{\mathrm{in}}-T_{\mathrm{ou}})+m_{\mathrm{air}}\ c_{p,\mathrm{air}}\ (T_{\mathrm{in}}-T_{\mathrm{ou}})$$

$$Q_{\mathrm{down}}=\frac{1}{\dfrac{1}{h_{\mathrm{conv}}}+\dfrac{1}{h_{\mathrm{eva}}}}A_{\mathrm{down}}\left[\left(T_{\mathrm{in}}+T_{\mathrm{ou}}\right)/2-T_{\mathrm{sat\_sw}}\right]$$

symbol	meaning
Tin	inlet temperature
Tou	outlet temperature
hfgw	enthalpy of water
hcond	heat transfer co-efficent for condensation
hevap	heat transfer co-efficent for evaporation
Tsat_sw	saturation temperature of sea water

Film Evaporation

Film evaporation process consist of vertically arranged heating surfaces.From these, a liquid flows off in the form of a thin film and is evaporated by the addition of heat. Frequently, in such a process, a solvent is to be extracted by evaporation from a solution consisting of a solvent (water or organic solvent) and the substances dissolved in it (salts or other substances). Examples are the recovering of solvents during the production of lacquer, or the extraction of fresh water from sea water.This process can applied while designing the heat exchanger because the heat transfer coefficients are very large and, depending upon the properties of the solution to be evaporated, lie between 700 and 4000W/m^{2}K.Another advantage of this process is that practically no pressure differences occur as a result of the static head of liquid, and the frictional pressure drop is usually small, so these equations relating to film evaporation can be applied to this system. The system designed in this study matches these conditions and thus it makes sense to apply these equations to evaluate the area of the exchanger. [12,13]

$$\mathrm{Nu} = \left(\frac{3}{4}\mathrm{Re}\right)^{-1/3} \qquad 0<\mathrm{Re}<30 \qquad (31)$$

$$\mathrm{Nu}=0.822\mathrm{Re}^{-0.22} \qquad 30<\mathrm{Re}<\mathrm{Retr} \qquad (32)$$

$$\mathrm{Nu} = 0.0038\,\mathrm{Re}^{-0..4}\,\mathrm{Pr}^{0.65} \qquad \mathrm{Retr}<\mathrm{Re} \qquad (33)$$

$$\mathrm{Retr}=5800\mathrm{Pr}^{-1.06} \qquad (34)$$

$$\frac{D\_\mathrm{tube}}{\left(\upsilon^2/g\right)^{1/3}} = -\frac{\mathrm{Pr}}{4\mathrm{Ja}}\int_{\mathrm{Re}0}^{\mathrm{ReL}} \frac{d\,\mathrm{Re}}{\mathrm{Nu}} \qquad (35)$$

$$\overline{\mathrm{Nu}}_{eva} = \frac{\mathrm{Pr}}{4\mathrm{Ja}}\,\frac{\left(\upsilon^2/g\right)^{1/3}}{D\_\mathrm{tube}}\left(\mathrm{Re}_0 - \mathrm{Re}_L\right) \qquad (36)$$

5.6.1 Iterative computation and Known, unknown parameters

The solution is calculated iteratively for both the upstream and the downstream end. The first step is to calculate to assume a wall temperature in both cases and then calculate the heat transfer coefficient for film evaporation. In the next step for the both the streams, the heat transfer coefficient for condensation is calculated. Then to check our calculation a new value of wall temperature is then assumed which then checks the error and the program finally gives the output parameters. This methodology is shown in Figure 45 below.

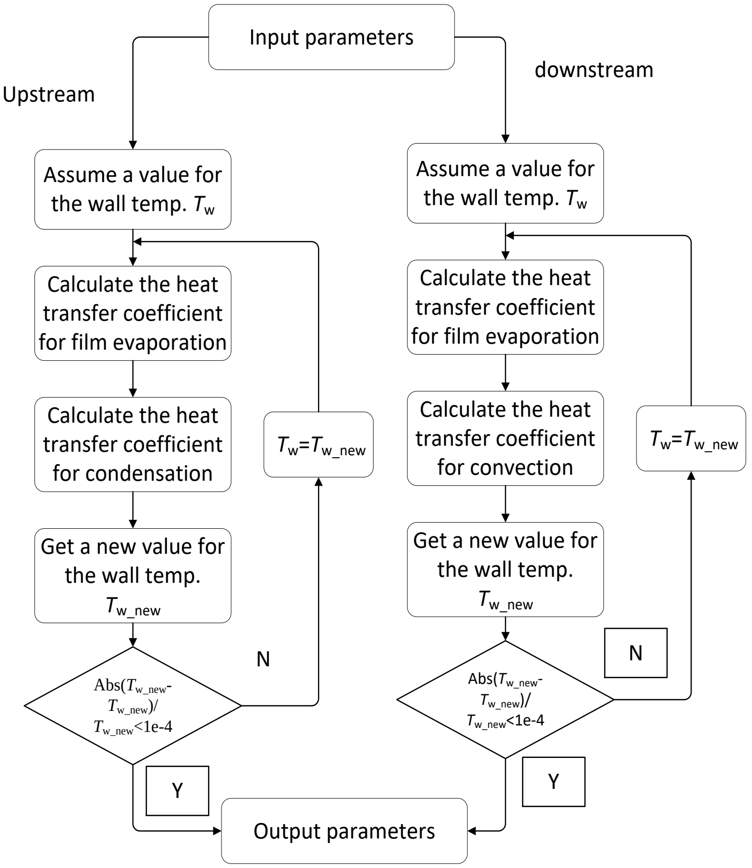


Figure 45 flowchart for computation of the area

Known Parameter	Calculated Parameter
Properties of sea water	
Properties of pure water and air	
Inlet temperature of mix of steam and air	**Saturation Temperature of sea water in effects**
Outlet temperature of mix of steam and air	**Heat transfer area**
Temperature of feed water	
Diameter of heat exchanger tube	
Mass flow rates	

Table 4 Known and calculated parameters for heat exchange program

5.6.2 Solutions and Interpretation

The Figure 46 below is the first figure that we obtain from the program. From the graph, we can infer that pressure has very low impact on the latent heat (within 10% change only), whereas the impact of saturation temperature is significant. This verifies our assumption that we can take the temperatures in the effects as saturation temperatures and all the states as saturation states, and that while calculating the properties of seawater, they will be only the function of temperature and not pressure.

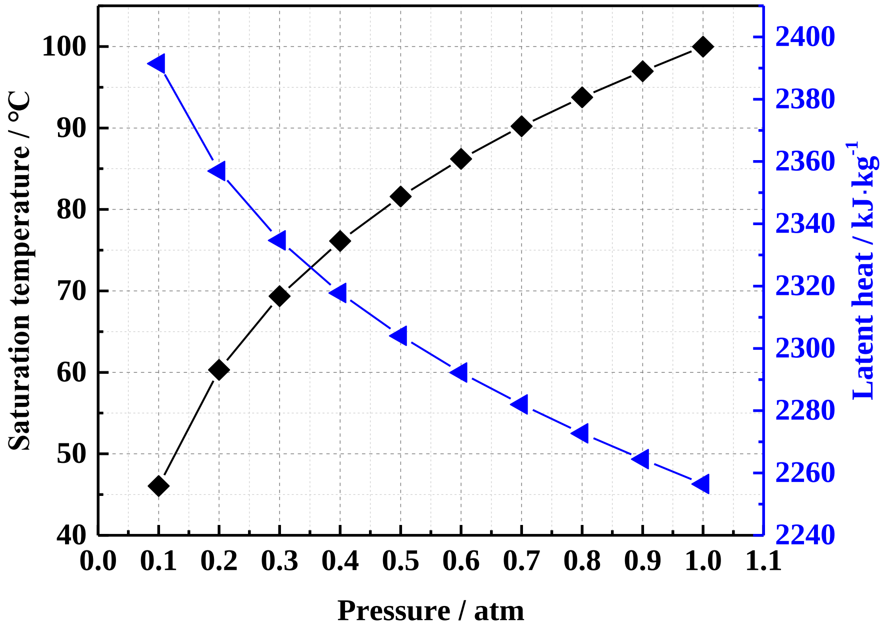


Figure 46 Relationship between pressure, saturation temperature and latent heat

The second parameter that we obtain from this calculation is the expected area of the heat exchanger. The actual employed area in the experimental system is 1252 in^2. Compared to this the theoretical area obtained from the above given method is 1318 in^2. This area is obtained from the computation is larger than to the area obtained from the area employed. We therefore must use more area for perfect heat transfer. The Temperatures used in the theoretical calculations are 100˚C at the inlet and 90˚C at the outlet (comparing here only for effect 1).

To cause this temperature difference to happen perfectly inside the effect 1 we must employ more area on the exchangers, but the area employed currently is not significantly less and can work to a certain degree of accuracy. The same calculation can be performed for effects 2,3 and so on in various other schemes as well.

6. Experimentation, problems encountered and proposed Solutions.

- The experimentation for the novel thermal driven desalination variable feed system with 3 effects was done at the campus agricultural farms (CAC), to verify the concept. In essence all the test runs were done in order to check all the concept sdeveloped in theory were applicable or not. The experimentation gave some useful comclusions and some parts of the system require more research and engineering.

- During the various test runs the inlet feed water used was the simple hose underground water available at the test site. During most of the tests, the heating startegy worked perfettctly with the heater and air pump working together.The air was hot enough as checked by rudimentary means and the pump did force sufficent air through the heaters.The water feed inlet system to the effects, in the initial tests gave problems of leaking through the various fittings. The fittings were then made more leak proof by aplying pipe threads and matching the threads tightly. The inlet feed mechanism was then tested succesfully when simulation data for the feed was given to the contrllers and the flow controllers controlled the inlet feed as m1=0.2966 Kg/s, m2=0.3301 Kg/s and m3=0.3628 Kg/s.

- There were however various problems which were encountered. There was a major leak discovered in the first effect tank at the bottom as shown in Figure 47.Water therefore accumulated at the bottom of this first effect leaked out. To solve this problem the tank was was opened again and again sealed with more silicon to avoid for such leaks.

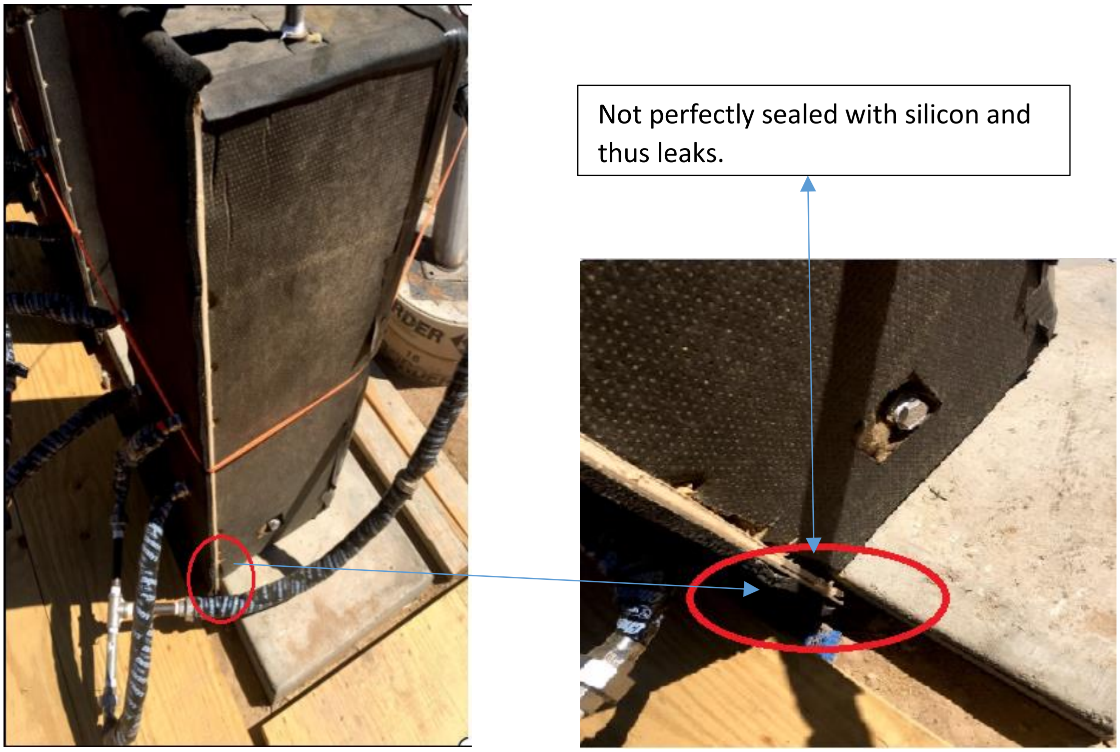


Figure 47 Detecting the leak in the 1st effect

- Another problem which occoured was that the pump which is used to send the water up high to the FST had very less pressure head.The pressure head was so low that the water couldn't be pumped up to obersve the process of salt collection inside the FST. This can be attributed to the error of selecting the pump with insuffcient head.The Figure 48 shows that no flow was being observed by the flow meter.

Pump to send water upward to a height of 4 meter to the FST.

2-way valve to control the flow.

Flow meter shows insufficient flow from the pump.

Figure 48 Detecting insufficient flow rate from the pump

- There were two significant changes which were made after the teste runs. The first change that was made was that to control the tempertaure.Instead of using the pressure transducer and the controller , a pressure switch will be used so as to do away with the controller. A pressure switch can perform the functions of the controller and the transducer for a given set point value.Another change was made to the condenser used in the system. The condenser is essentially the same as the effect box with the same dimensions and materials. It's sole function is to condense the pure steam and steam and air mix to droplets of water through the interaction with heat exchanger. The design of the condenser was changed and the heat exchanger was placed at an upper point and the and an additional inlet was made as shown in.This inlet is then used , so that instead of steam coming from the top and interacting at the exchanger surface, it now arrives from bottom and then goes up to the heat exchanger surface. This change was made for better and more efficient collcetion of pure water.

7.Conclusions

There are 2 schemes which are studies through the MATLAB program in this research work i.e. Variable feed and concurrent feed. The variable feed gave us a low thermal energy comsumption of 133.87KJ/s as compared to that of countercurrent feed of 147.89 KJ/s. In both the schemes it was observed that as we increase the number of effects in the system , the energy consumption decreases. Therefore both the above mentioned values are reflective of a 9-effect system.

There were reasons such as better evaporation ratio of variable feed as compared to counter current feed. At a bleed fraction of 0.3 and the hot air teperature of 150˚C, the counter current feed gave a ratio of 0.083 compared to 0.093 of the variable feed. Another advantage that was observed for the variable feed was the ability to control the amount of feed going in.Due to these reasons the Variable feed scheme for 3-effect was fabricated and tested.

The testing of the variable was not completed perefctly and due to errors and problems mentioned in the previous sections , data was not collected and matched with the simulation schemes. However individual assemblies along with heating strategy and input feed control were succesfully tested . The problems encountered during the experimentation were also adressed and measures of improvement and implemetation are already mentioned in chapter 6.Another problem of salinity and its effects is yet to be studied in detail. Results for salinity analysis from the program were not completely accurate, hence some improvements needs to be done in the program for salinity analysis.

Further some analysis on heat exchanger design was achieved.Based on this study the temeperature of each effect was set . It helped in calibrating the area for heat transfer,for the exchangers that we use and whether there is sufficent area for a 10˚C temperature difference or not. The tempertaure differeneces for different number of effects (3,4,5….9) are mentioned in the appendix.One of the results for the heat exchange area established the fact that the pressure is an insignificant parameter as compared to saturation temperature plotted against latent heat. Therefore this helped us verify our assumptions.The calculated area from the program is more than that applied in the actual system. An error is present.The calculated area is more than the area employed and so more area must be used in the system fabrication than already in place.The exchangers may not be perfectly be able to cause the required temperature difference but they will be sufficent to verify the concept.

8. Appendix

8.1 Code

A MATLAB code is used to simulate the varioys flow parameters and 2 schemes , the counter-current and the variable feed schemes have been set up.The simulation has been performed for 3 -9 effects for both schemes and the data sheets are given in the following sections.

8.2 Known and calculated parameters

Below are all the known/input parameters and the calculated parameters for each and every component involved in the simulation.

	FST	
input/known parameters		**calculated parameters**
inlet temperature of hot air		mass flow rate of dry air
temperature of brine incoming from last effect		mass flow rate of steam leaving the FST
exit temperature of air and steam		mass of salt collected at the bottom of the FST
specefic heat of air and salt		

input/known parameters	**effect tanks**	**calculated parameters**
inlet mass flow rate of brine		mass flow rate of steam created in all effects
inlet temperature of air and steam mix		mass flow rate of brine leaving each effect
outlet temperature of air and steam mix for all effects		
exit temperature of brine for all effects		
initial salinity value		
bleed fraction		

input/known parameters	**Heat source**	**calculated parameters**
temperature of dry air		Thermal energy consumption
temperature of bleed steam from last effect		

input/known parameters	**condenser**	**calculated parameters**
Inlet temperature of steam coming from the last effect		mass flow rate of cooling sea water
outlet temperature of the steam		
ambient temperature		
tenperature of cooling sea water		

8.3 Data sheets

8.3.1 variable feed

FS-MED Variable Scheme (3 effects)

Heat source Temperature	150	200	250	300	350	400
m_dry air	2.6178	1.5157	1.0344	0.7644	0.5913	0.4707
m_brine3	0.3628	0.3693	0.3722	0.3739	0.375	0.3757
m_steam FS tank	0.2674	0.272	0.2741	0.2752	0.276	0.2765
m_steam eff1	0.2459	0.2456	0.2455	0.2455	0.2455	0.2454
m_brine1	0.2366	0.2369	0.237	0.237	0.237	0.2371
m_steam eff2	0.2175	0.2143	0.213	0.2122	0.2117	0.2113
m_brine2	0.3301	0.3335	0.335	0.3358	0.3363	0.3367
m_steam eff3	0.1745	0.1714	0.1699	0.1691	0.1686	0.1682
m_cooling sea water	1.355	1.3308	1.3196	1.3132	1.309	1.3061
m_bleed steam	0.1047	0.1028	0.102	0.1015	0.1011	0.1009
salinity_brine1	281.7435	281.4435	281.3332	281.2768	281.2427	281.2198
salinity_brine2	403.8939	399.802	398.0497	397.076	396.4554	396.0244
salinity_brine3	551.2221	541.5213	537.291	534.9203	533.4018	532.3442
m_pure water	0.8005	0.8005	0.8005	0.8005	0.8005	0.8005
flow difference	-5.35E-04	-5.35E-04	-5.35E-04	-5.35E-04	-5.35E-04	-5.35E-04
% error in flow difference	-5.35E-04	-5.35E-04	-5.35E-04	-5.35E-04	-5.35E-04	-5.35E-04
Energy in (kJ)	318.8834	304.2434	292.1658	280.9311	270.0125	259.1944
Energy out (kJ)	308.8584	304.5718	302.5953	301.4585	300.7193	300.1992
% error in energy diff	0.0314	-0.0011	-0.0357	-0.0731	-0.1137	-0.1582
salt	0.2	0.2	0.2	0.2	0.2	0.2
Energy input by heat source kJ/s per kg/s of sea water	232.4995	229.5761	228.2284	227.4533	226.9494	226.5948
kWh/1000 gal						
Conversion to kWh/1000 gal	248.3969	245.2736	243.8337	243.0056	242.4673	242.0884
1000/ (0.26*3600)						

FS-MED Variable Scheme (4 effects)

Heat source Temperature	150	200	250	300	350	400
m_dry air	1.9313	1.1843	0.8352	0.6327	0.5005	0.4071
m_brine4	0.3567	0.3622	0.3649	0.3665	0.3675	0.3682
m_steam FS tank	0.2249	0.2293	0.2314	0.2326	0.2334	0.2339
m_steam eff1	0.1996	0.2005	0.2009	0.2011	0.2013	0.2014
m_brine1	0.2225	0.2216	0.2212	0.2209	0.2207	0.2206
m_steam eff2	0.1803	0.1784	0.1776	0.1771	0.1768	0.1766
m_brine2	0.3142	0.3152	0.3156	0.3158	0.316	0.3161

m_steam eff3	0.1508	0.1481	0.1468	0.1461	0.1456	0.1452
m_brine3	0.3447	0.3483	0.35	0.351	0.3517	0.3521
m_steam4	0.1141	0.1122	0.1112	0.1106	0.1102	0.11
m_cooling sea water	1.5953	1.5681	1.5545	1.5464	1.5409	1.5371
m_bleed steam	0.0685	0.0673	0.0667	0.0664	0.0661	0.066
salinity_brine1	224.7369	225.6325	226.0715	226.3319	226.5044	226.6273
salinity_brine2	318.2563	317.2943	316.874	316.6389	316.4885	316.3839
salinity_brine3	435.1664	430.6214	428.5336	427.3339	426.5542	426.0059
salinity_brine4	560.7561	552.1129	548.0734	545.7323	544.2028	543.1238
m_pure water	0.8011	0.8011	0.8011	0.8011	0.8011	0.8011
flow difference	-0.0011	-0.0011	-0.0011	-0.0011	-0.0011	-0.0011
% error in flow difference	-0.0011	-0.0011	-0.0011	-0.0011	-0.0011	-0.0011
Energy in (kJ)	311.6243	307.7368	305.7948	304.632	303.8574	303.3037
Energy out (kJ)	311.8376	307.9504	306.0086	304.8459	304.0713	303.5177
% error in energy diff	-6.84E-04	-6.94E-04	-6.99E-04	-7.02E-04	-7.04E-04	-7.05E-04
salt	0.2	0.2	0.2	0.2	0.2	0.2
Energy input by heat source kJ/s per kg/s of sea water	191.3848	189.5469	188.6299	188.0811	187.7156	187.4544
kWh/1000 gal	204.4709	202.5074	201.5277	200.9413	200.5508	200.2718
Conversion to kWh/1000 gal						
1000/ (0.26*3600)						

FS-MED Variable Scheme (5 effects)

Heat source Temperature	150	200	250	300	350	400
m_dry air	1.6115	1.0371	0.753	0.5834	0.4707	0.3902
m_brine5	0.3543	0.3596	0.3622	0.3638	0.3649	0.3656
m_steam FS tank	0.201	0.2054	0.2076	0.2089	0.2097	0.2104
m_steam eff1	0.1731	0.1746	0.1754	0.1759	0.1762	0.1764
m_brine1	0.2139	0.2124	0.2116	0.2111	0.2108	0.2106
m_steam eff2	0.1561	0.1552	0.1547	0.1545	0.1543	0.1542
m_brine2	0.3072	0.3066	0.3062	0.306	0.3059	0.3058
m_steam eff3	0.1346	0.1323	0.1312	0.1305	0.1301	0.1298
m_brine3	0.3388	0.3405	0.3412	0.3417	0.342	0.3422
m_steam eff4	0.1064	0.1042	0.1031	0.1025	0.102	0.1017
m_brine4	0.348	0.3518	0.3537	0.3549	0.3556	0.3561
m_steam5	0.0789	0.0775	0.0767	0.0763	0.0759	0.0757
m_cooling sea water	2.2316	2.1914	2.1699	2.1565	2.1474	2.1408
m_bleed steam	0.0474	0.0465	0.046	0.0458	0.0456	0.0454

salinity_brine1	361.84	364.4734	365.8229	366.6431	367.1946	367.5914
salinity_brine2	414.2964	415.1506	415.6195	415.9137	416.1153	416.2621
salinity_brine3	473.7729	471.4813	470.401	469.7727	469.3617	469.0715
salinity_brine4	527.628	521.9282	519.1511	517.5072	516.4196	515.646
salinity_brine5	566.3548	558.1285	554.0556	551.6244	550.0076	548.8535
m_pure water	0.8028	0.8028	0.8028	0.8028	0.8028	0.8028
flow difference	-0.0034	-0.0034	-0.0034	-0.0034	-0.0034	-0.0034
% error in flow difference	-0.0034	-0.0034	-0.0034	-0.0034	-0.0034	-0.0034
Energy in (kJ)	343.7531	339.3908	337.0585	335.6104	334.624	333.9084
Energy out (kJ)	344.1456	339.7837	337.4516	336.0036	335.0173	334.3017
% error in energy diff	-0.0011	-0.0012	-0.0012	-0.0012	-0.0012	-0.0012
salt	0.2007	0.2007	0.2007	0.2007	0.2007	0.2007
Energy input by heat source kJ/s per kg/s of sea water	175.5577	174.2251	173.5145	173.0738	172.7738	172.5563
kWh/1000 gal	187.5616	186.138	185.3788	184.9079	184.5874	184.355
Conversion to kWh/1000 gal						
1000/ (0.26*3600)						

FS-MED Variable Scheme (6 effects)

Heat source Temperature	150	200	250	300	350	400
m_dry air	1.5534	0.931	0.6564	0.5016	0.4023	0.333
m_brine6	0.3513	0.3548	0.3564	0.3573	0.3579	0.3583
m_steam FS tank	0.1792	0.1822	0.1836	0.1843	0.1848	0.1852
m_steam eff1	0.1582	0.1597	0.1603	0.1607	0.1609	0.1611
m_brine1	0.2518	0.2503	0.2497	0.2493	0.2491	0.2489
m_steam eff2	0.144	0.144	0.144	0.144	0.144	0.144
m_brine2	0.3558	0.3544	0.3537	0.3534	0.3531	0.353
m_steam eff3	0.1267	0.1255	0.125	0.1247	0.1245	0.1243
m_brine3	0.3809	0.3807	0.3806	0.3805	0.3805	0.3804
m_steam4	0.1017	0.1001	0.0993	0.0989	0.0987	0.0985
m_brine4	0.3733	0.3748	0.3754	0.3757	0.3759	0.3761
m_steam5	0.0723	0.071	0.0704	0.0701	0.0699	0.0697
m_brine5	0.3602	0.363	0.3642	0.3649	0.3653	0.3656
m_steam6	0.0468	0.046	0.0457	0.0454	0.0453	0.0452
m_cooling sea water	0.4322	0.425	0.4216	0.4197	0.4184	0.4175
m_bleed steam	0.0281	0.0276	0.0274	0.0273	0.0272	0.0271
salinity_brine1	246.6551	578.5192	754.2718	834.2118	879.776	909.3223
salinity_brine2	235.4999	446.5586	553.6528	607.0584	638.7789	659.7729
salinity_brine3	230.2135	374.4439	443.2111	479.0065	500.9109	515.6902

salinity_brine4	229.975	330.701	374.7433	397.6755	411.7997	421.3876
salinity_brine5	234.6274	303.4057	330.3294	343.9382	352.213	357.791
salinity_brine6	244.5864	286.9994	301.156	307.8328	311.7436	314.3183
salinity_brine7	325.6827	327.5881	328.4468	328.9355	329.2511	329.472
salinity_brine8	369.8544	371.3465	372.0239	372.4106	372.6609	372.8363
salinity_brine9	425.2159	425.4415	425.5615	425.6346	425.6836	425.7187
m_pure water	484.2568	482.3941	481.5956	481.1519	480.8693	480.6735
flow difference	534.6856	530.6765	528.9244	527.9418	527.3126	526.8748
% error in flow difference	569.8215	564.201	561.7186	560.3194	559.4207	558.7942
Energy in (kJ)	165.4205	164.1872	163.6077	163.2716	163.0521	162.8974
Energy out (kJ)	165.6179	164.3846	163.8052	163.4691	163.2495	163.0948
% error in energy diff	0.3	0.3	0.3	0.3	0.3	0.3
salt	0.2002	0.2002	0.2002	0.2002	0.2002	0.2002
Energy input by heat source kJ/s per kg/s of sea water	132.8465	132.1549	131.83	131.6416	131.5186	131.4318
kwh/1000 gal	141.93	141.1911	140.8441	140.6427	140.5113	140.4186

FS-MED Variable Scheme (7 effects)

Heat source Temperature	150	200	250	300	350	400
m_dry air	1.4268	0.8817	0.6327	0.4901	0.3977	0.3328
m_brine7	0.3503	0.3539	0.3555	0.3565	0.3571	0.3575
m_steam FS tank	0.1691	0.1723	0.1737	0.1745	0.1751	0.1755
m_steam eff1	0.1463	0.148	0.1488	0.1493	0.1496	0.1498
m_brine1	0.2537	0.252	0.2512	0.2507	0.2504	0.2502
m_steam eff2	0.1324	0.1328	0.133	0.1331	0.1331	0.1332
m_brine2	0.3633	0.3612	0.3602	0.3596	0.3593	0.359
m_steam eff3	0.1183	0.1175	0.1171	0.1169	0.1167	0.1166
m_brine3	0.3931	0.3918	0.3912	0.3909	0.3906	0.3905
m_steam4	0.0986	0.097	0.0963	0.0959	0.0956	0.0954
m_brine4	0.3863	0.3866	0.3868	0.3868	0.3869	0.3869
m_steam5	0.0737	0.0722	0.0715	0.0711	0.0708	0.0706
m_brine5	0.3704	0.3723	0.3731	0.3736	0.3739	0.3741
m_steam6	0.0496	0.0486	0.0481	0.0478	0.0476	0.0475
m_brine6	0.3578	0.3607	0.362	0.3627	0.3632	0.3636
m_steam7	0.0315	0.0309	0.0306	0.0304	0.0302	0.0302
m_cooling sea water	0.3511	0.3437	0.3401	0.338	0.3366	0.3356
m_bleed steam	0.0189	0.0185	0.0183	0.0182	0.0181	0.0181
salinity_brine1	315.3137	317.5001	318.5218	319.1137	319.5001	319.7722
salinity_brine2	353.4318	355.5043	356.4764	357.0405	357.409	357.6689

salinity_brine3	402.0226	403.3078	403.9209	404.2794	404.5147	404.6811
salinity_brine4	456.5644	456.1806	456.0337	455.9574	455.911	455.8799
salinity_brine5	507.3565	504.8483	503.7313	503.0993	502.6926	502.4089
salinity_brine6	545.9737	541.6106	539.6349	538.508	537.7793	537.2691
salinity_brine7	578.688	572.8959	570.2471	568.7289	567.7443	567.0537
m_pure water	0.8006	0.8006	0.8006	0.8006	0.8006	0.8006
flow difference	-0.0034	-0.0034	-0.0034	-0.0034	-0.0034	-0.0034
% error in flow difference	557.6068	549.6311	546.1803	544.2569	543.0309	542.1812
Energy in (kJ)	154.989	153.8786	153.3342	153.0117	152.7983	152.6467
Energy out (kJ)	155.1359	154.0255	153.4812	153.1586	152.9453	152.7936
% error in energy diff	0.4	0.4	0.4	0.4	0.4	0.4
salt	0.2027	0.2027	0.2027	0.2027	0.2027	0.2027
Energy input by heat source kJ/s per kg/s of sea water	128.5289	127.9719	127.6988	127.5369	127.4298	127.3537
kwh/1000 gal	137.3172	136.7222	136.4303	136.2574	136.143	136.0617

FS-MED Variable Scheme (8 effects)

Heat source Temperature	150	200	250	300	350	400
m_dry air	1.3692	0.8688	0.6329	0.4957	0.4059	0.3425
m_brine8	0.3499	0.3536	0.3554	0.3564	0.3571	0.3576
m_steam FS tank	0.1629	0.1662	0.1678	0.1687	0.1693	0.1698
m_steam eff1	0.1379	0.14	0.1409	0.1415	0.1419	0.1421
m_brine1	0.2556	0.2535	0.2526	0.252	0.2516	0.2514
m_steam eff2	0.1238	0.1245	0.1248	0.125	0.1252	0.1253
m_brine2	0.3699	0.3671	0.3658	0.365	0.3645	0.3641
m_steam eff3	0.1113	0.1108	0.1105	0.1104	0.1103	0.1102
m_brine3	0.4043	0.402	0.4009	0.4003	0.3999	0.3996
m_steam4	0.0953	0.0939	0.0932	0.0928	0.0925	0.0924
m_brine4	0.3993	0.3985	0.3981	0.3979	0.3977	0.3976
m_steam5	0.0743	0.0726	0.0718	0.0714	0.0711	0.0708
m_brine5	0.3818	0.3827	0.3831	0.3833	0.3835	0.3836
m_steam6	0.0521	0.0508	0.0502	0.0498	0.0495	0.0494
m_brine6	0.3661	0.3683	0.3693	0.3699	0.3703	0.3706
m_steam7	0.034	0.0331	0.0327	0.0324	0.0322	0.0321
m_brine7	0.3558	0.3589	0.3604	0.3612	0.3618	0.3622
m_steam8	0.0217	0.0211	0.0208	0.0206	0.0205	0.0204
m_cooling sea water	0.3029	0.2946	0.2904	0.2879	0.2862	0.2849
m_bleed steam	0.013	0.0126	0.0125	0.0124	0.0123	0.0122
salinity_brine1	307.9473	310.415	311.6085	312.3122	312.7762	313.1054

salinity_brine2	341.5286	344.0926	345.3363	346.0703	346.5548	346.8987
salinity_brine3	384.5637	386.693	387.7327	388.3482	388.7552	389.0443
salinity_brine4	434.5925	435.4409	435.8769	436.1411	436.318	436.4448
salinity_brine5	484.2132	483.0715	482.5712	482.291	482.1119	481.9876
salinity_brine6	524.9486	521.7717	520.3074	519.4649	518.9174	518.533
salinity_brine7	553.4133	548.6321	546.3953	545.0989	544.2526	543.6565
salinity_brine8	583.4842	577.3897	574.5121	572.8364	571.7394	570.9653
m_pure water	0.8003	0.8003	0.8003	0.8003	0.8003	0.8003
flow difference	-0.0045	-0.0045	-0.0045	-0.0045	-0.0045	-0.0045
% error in flow difference	557.6068	549.6311	546.1803	544.2569	543.0309	542.1812
Energy in (kJ)	152.5509	151.4648	150.9108	150.5757	150.3513	150.1906
Energy out (kJ)	152.6303	151.5442	150.9903	150.6552	150.4308	150.2701
% error in energy diff	0.1	0.1	0.1	0.1	0.1	0.1
salt	0.2042	0.2042	0.2042	0.2042	0.2042	0.2042
Energy input by heat source kJ/s per kg/s of sea water	129.7186	129.2573	129.0216	128.8788	128.7832	128.7146
kwh/1000 gal	138.5883	138.0954	137.8436	137.6911	137.5889	137.5156

FS-MED Variable Scheme (9 effects)

Heat source Temperature	150	200	250	300	350	400
m_dry air	1.3538	0.879	0.6486	0.5125	0.4226	0.3588
m_brine9	0.3502	0.3541	0.3561	0.3572	0.358	0.3585
m_steam FS tank	0.1592	0.1628	0.1646	0.1656	0.1663	0.1668
m_steam eff1	0.132	0.1344	0.1355	0.1362	0.1367	0.137
m_brine1	0.2575	0.2551	0.254	0.2533	0.2528	0.2525
m_steam eff2	0.1172	0.1182	0.1187	0.1191	0.1193	0.1194
m_brine2	0.376	0.3726	0.3709	0.3699	0.3692	0.3687
m_steam eff3	0.1056	0.1054	0.1053	0.1053	0.1052	0.1052
m_brine3	0.4146	0.4114	0.4098	0.4088	0.4082	0.4078
m_steam4	0.0921	0.0909	0.0902	0.0899	0.0896	0.0895
m_brine4	0.4118	0.4099	0.409	0.4084	0.408	0.4077
m_steam5	0.0743	0.0725	0.0717	0.0712	0.0708	0.0706
m_brine5	0.3938	0.3937	0.3936	0.3935	0.3935	0.3934
m_steam6	0.0542	0.0526	0.0518	0.0513	0.051	0.0508
m_brine6	0.3756	0.3771	0.3778	0.3782	0.3784	0.3786
m_steam7	0.0364	0.0352	0.0347	0.0343	0.0341	0.0339
m_brine7	0.3627	0.3653	0.3666	0.3673	0.3678	0.3681
m_steam8	0.0235	0.0228	0.0224	0.0221	0.022	0.0219
m_brine8	0.3548	0.3582	0.3599	0.3608	0.3615	0.3619
m_steam9	0.0154	0.0148	0.0145	0.0143	0.0142	0.0141

m_cooling sea water	0.2877	0.2773	0.2718	0.2684	0.2662	0.2645
m_bleed steam	0.0092	0.0089	0.0087	0.0086	0.0085	0.0085
salinity_brine1	302.553	305.322	306.7057	307.5354	308.0884	308.4833
salinity_brine2	332.5391	335.5698	337.0881	337.9996	338.6075	339.0419
salinity_brine3	371.1477	374.0167	375.4591	376.3263	376.9052	377.319
salinity_brine4	417.0154	418.9456	419.9307	420.527	420.9266	421.2131
salinity_brine5	464.7113	464.8512	464.9674	465.0504	465.1109	465.1567
salinity_brine6	506.3894	504.3957	503.4755	502.9462	502.6025	502.3613
salinity_brine7	537.3608	533.5083	531.6753	530.6039	529.9011	529.4044
salinity_brine8	558.1099	552.8537	550.3194	548.8279	547.8453	547.149
salinity_brine9	571.6165	565.2774	562.1947	560.3723	559.1684	558.3136
m_pure water	0.8007	0.8007	0.8007	0.8007	0.8007	0.8007
flow difference	-8.87E-04	-8.87E-04	-8.87E-04	-8.87E-04	-8.87E-04	-8.87E-04
% error in flow difference	-8.87E-04	-8.87E-04	-8.87E-04	-8.87E-04	-8.87E-04	-8.87E-04
Energy in (kJ)	156.4205	155.2571	154.6415	154.2616	154.004	153.818
Energy out (kJ)	156.535	155.3718	154.7561	154.3763	154.1188	153.9327
% error in energy diff	-7.33E-04	-7.39E-04	-7.42E-04	-7.44E-04	-7.45E-04	-7.46E-04
salt	0.2002	0.2002	0.2002	0.2002	0.2002	0.2002
Energy input by heat source kJ/s per kg/s of sea water	134.7387	134.3573	134.1543	134.0287	133.9434	133.8817
1000/ (0.26*3600)						
kwh/1000 gal	143.9516	143.5442	143.3273	143.1931	143.1019	143.036

8.3.2 Counter-current feed

FS-MED Counter Current Scheme (3 effects)

Heat source Temperature	150	200	250	300	350	400
m_dry air	2.9692	1.6914	1.1444	0.8402	0.6463	0.5115
m_brine3	0.3668	0.3738	0.3769	0.3787	0.3798	0.3806
m_steam FS tank	0.2933	0.2958	0.2969	0.2976	0.298	0.2983
m_steam eff1	0.2108	0.2033	0.2	0.1982	0.1971	0.1962
m_brine1	0.7892	0.7967	0.8	0.8018	0.8029	0.8038
m_steam eff2	0.2102	0.2081	0.2071	0.2066	0.2062	0.206
m_brine2	0.5791	0.5887	0.5929	0.5952	0.5967	0.5977
m_steam eff3	0.2123	0.2148	0.2159	0.2165	0.2169	0.2172
bleed fraction	1.6366	1.5784	1.5532	1.5392	1.5302	1.5239
m_bleed steam	0.1265	0.122	0.12	0.1189	0.1182	0.1177
salinity_brine1	253.4068	251.0247	250.0076	249.443	249.0831	248.8333

salinity_brine2	345.3908	339.7504	337.3527	336.0243	335.1788	334.5924
salinity_brine3	545.259	535.0084	530.6172	528.1759	526.6192	525.5381
m_pure water	0.8	0.8	0.8	0.8	0.8	0.8
flow difference	0	0	0	0	0	0
% error in flow difference	0	0	0	0	0	0
Energy in (kJ)	388.2166	376.9515	372.0754	369.3507	367.6079	366.395
Energy out (kJ)	271.0349	260.1395	255.408	252.76	251.0649	249.8844
% error in energy diff	0.3018	0.3099	0.3136	0.3157	0.317	0.318
salt	0.2	0.2	0.2	0.2	0.2	0.2
Energy input by heat source kJ/s per kg/s of sea water	264.8671	257.9856	255.0064	253.3416	252.2767	251.5355
kWh/1000 gal	282.9777	275.6256	272.4428	270.6641	269.5264	268.7345

FS-MED Counter Current Scheme (4 effects)

Heat source Temperature	150	200	250	300	350	400
m_dry air	2.2909	1.3722	0.9543	0.7152	0.5601	0.4512
m_brine4	0.359	0.3655	0.3685	0.3703	0.3714	0.3722
m_steam FS tank	0.2538	0.2561	0.2572	0.2578	0.2583	0.2586
m_steam eff1	0.158	0.151	0.1478	0.1459	0.1447	0.1439
m_brine1	0.842	0.849	0.8522	0.8541	0.8553	0.8561
m_steam eff2	0.1544	0.1511	0.1496	0.1487	0.1482	0.1478
m_brine2	0.6876	0.6979	0.7026	0.7053	0.7071	0.7084
m_steam eff3	0.1582	0.1586	0.1588	0.1589	0.1589	0.159
m_brine3	0.5294	0.5393	0.5438	0.5465	0.5482	0.5494
m_steam4	0.1704	0.1738	0.1753	0.1762	0.1768	0.1772
m_cooling sea water	1.7825	1.7035	1.6672	1.6463	1.6327	1.6232
m_bleed steam	0.0948	0.0906	0.0887	0.0875	0.0868	0.0863
salinity_brine1	237.5229	235.5632	234.6737	234.1653	233.8358	233.6045
salinity_brine2	290.8552	286.5775	284.6473	283.5472	282.8356	282.3366
salinity_brine3	377.7704	370.8701	367.755	365.9794	364.8306	364.0252
salinity_brine4	557.0799	547.2057	542.7044	540.1266	538.4542	537.2796
m_pure water	0.8	0.8	0.8	0.8	0.8	0.8
flow difference	0	2.22E-16	0	-2.22E-16	0	0
% error in flow difference	0	2.22E-16	0	-2.22E-16	0	0
Energy in (kJ)	363.6411	351.3772	345.7409	342.4994	340.3908	338.9072
Energy out (kJ)	271.1897	259.6283	254.3009	251.233	249.2359	247.8299
% error in energy diff	0.2542	0.2611	0.2645	0.2665	0.2678	0.2687
salt	0.2	0.2	0.2	0.2	0.2	0.2
Energy input by heat source kJ/s per kg/s of sea water	229.2909	222.9844	220.0849	218.4171	217.3321	216.5686

kWh/1000 gal	244.9689	238.2312	235.1335	233.3517	232.1925	231.3768

FS-MED Counter Current Scheme (5 effects)

Heat source Temperature	150	200	250	300	350	400
m_dry air	1.6115	1.0371	0.753	0.5834	0.4707	0.3902
m_brine5	0.3543	0.3596	0.3622	0.3638	0.3649	0.3656
m_steam FS tank	0.201	0.2054	0.2076	0.2089	0.2097	0.2104
m_steam eff1	0.1731	0.1746	0.1754	0.1759	0.1762	0.1764
m_brine1	0.2139	0.2124	0.2116	0.2111	0.2108	0.2106
m_steam eff2	0.1561	0.1552	0.1547	0.1545	0.1543	0.1542
m_brine2	0.3072	0.3066	0.3062	0.306	0.3059	0.3058
m_steam eff3	0.1346	0.1323	0.1312	0.1305	0.1301	0.1298
m_brine3	0.3388	0.3405	0.3412	0.3417	0.342	0.3422
m_steam eff4	0.1064	0.1042	0.1031	0.1025	0.102	0.1017
m_brine4	0.348	0.3518	0.3537	0.3549	0.3556	0.3561
m_steam5	0.0789	0.0775	0.0767	0.0763	0.0759	0.0757
m_cooling sea water	2.2316	2.1914	2.1699	2.1565	2.1474	2.1408
m_bleed steam	0.0474	0.0465	0.046	0.0458	0.0456	0.0454
salinity_brine1	361.84	364.4734	365.8229	366.6431	367.1946	367.5914
salinity_brine2	414.2964	415.1506	415.6195	415.9137	416.1153	416.2621
salinity_brine3	473.7729	471.4813	470.401	469.7727	469.3617	469.0715
salinity_brine4	527.628	521.9282	519.1511	517.5072	516.4196	515.646
salinity_brine5	566.3548	558.1285	554.0556	551.6244	550.0076	548.8535
m_pure water	0.8028	0.8028	0.8028	0.8028	0.8028	0.8028
flow difference	-0.0034	-0.0034	-0.0034	-0.0034	-0.0034	-0.0034
% error in flow difference	-0.0034	-0.0034	-0.0034	-0.0034	-0.0034	-0.0034
Energy in (kJ)	343.7531	339.3908	337.0585	335.6104	334.624	333.9084
Energy out (kJ)	344.1456	339.7837	337.4516	336.0036	335.0173	334.3017
% error in energy diff	-0.0011	-0.0012	-0.0012	-0.0012	-0.0012	-0.0012
salt	0.2007	0.2007	0.2007	0.2007	0.2007	0.2007
Energy input by heat source kJ/s per kg/s of sea water	175.5577	174.2251	173.5145	173.0738	172.7738	172.5563
kWh/1000 gal	187.5616	186.138	185.3788	184.9079	184.5874	184.355

FS-MED Counter Current Scheme (6 effects)

Heat source Temperature	150	200	250	300	350	400
m_dry air	2.0108	1.169	0.8073	0.6059	0.4774	0.3882
m_brine5	0.3555	0.3598	0.3617	0.3628	0.3635	0.364
m_steam FS tank	0.2143	0.2159	0.2165	0.2169	0.2172	0.2174

m_steam eff1	0.0981	0.0934	0.0914	0.0902	0.0895	0.089
m_brine1	0.9019	0.9066	0.9086	0.9098	0.9105	0.911
m_steam eff2	0.0993	0.0963	0.0949	0.0942	0.0937	0.0934
m_brine2	0.8026	0.8103	0.8137	0.8156	0.8168	0.8176
m_steam eff3	0.101	0.0997	0.0991	0.0987	0.0985	0.0984
m_brine3	0.7016	0.7107	0.7146	0.7168	0.7182	0.7192
m_steam4	0.1042	0.1045	0.1046	0.1046	0.1047	0.1047
m_brine4	0.5974	0.6062	0.61	0.6122	0.6136	0.6145
m_steam5	0.1113	0.113	0.1137	0.1142	0.1144	0.1146
m_brine5	0.4862	0.4932	0.4963	0.498	0.4991	0.4999
m_steam6	0.1307	0.1334	0.1346	0.1352	0.1356	0.1359
m_cooling sea water	0.9061	0.8625	0.8436	0.8331	0.8264	0.8217
bleed steam	0.0589	0.056	0.0548	0.0541	0.0537	0.0534
salinity_brine1	221.7606	220.6056	220.1096	219.8336	219.6576	219.5354
salinity_brine2	249.1925	246.8107	245.7927	245.2274	244.8674	244.6177
salinity_brine3	285.0608	281.4201	279.8683	279.0077	278.4599	278.0802
salinity_brine4	334.7591	329.9119	327.8457	326.6998	325.9705	325.465
salinity_brine5	411.3582	405.4911	402.9813	401.5872	400.699	400.083
salinity_brine6	0	0	0	0	0	0
m_pure water	0.8	0.8	0.8	0.8	0.8	0.8
flow difference	0.0538	0.0541	0.0542	0.0543	0.0543	0.0544
% error in flow difference	0.0538	0.0541	0.0542	0.0543	0.0543	0.0544
Energy in (kJ)	243.6409	236.267	233.0762	231.294	230.155	229.3632
Energy out (kJ)	243.4152	236.039	232.8472	231.0644	229.9251	229.1331
% error in energy diff	9.26E-04	9.65E-04	9.83E-04	9.92E-04	9.99E-04	0.001
salt	0.1462	0.1459	0.1458	0.1457	0.1457	0.1456
Energy input by heat source kJ/s per kg/s of sea water	175.3466	171.259	169.49	168.5019	167.8704	167.4313
kWh/1000 gal	187.3361	182.9691	181.0791	180.0234	179.3487	178.8796

FS-MED Counter Current Scheme (7 effects)

Heat source Temperature	150	200	250	300	350	400
m_dry air	1.7811	1.0655	0.748	0.5685	0.4531	0.3725
m_brine7	0.353	0.3572	0.3592	0.3603	0.361	0.3615
m_steam FS tank	0.1996	0.2011	0.2018	0.2022	0.2024	0.2026
m_steam eff1	0.0778	0.0731	0.071	0.0698	0.0691	0.0685
m_brine1	0.9222	0.9269	0.929	0.9302	0.9309	0.9315
m_steam eff2	0.0875	0.0843	0.0829	0.0821	0.0815	0.0812
m_brine2	0.8347	0.8426	0.8461	0.8481	0.8494	0.8503

m_steam eff3	0.0873	0.0855	0.0847	0.0843	0.084	0.0838
m_brine3	0.7474	0.7571	0.7614	0.7638	0.7654	0.7665
m_steam4	0.088	0.0876	0.0875	0.0874	0.0873	0.0873
m_brine4	0.6594	0.6694	0.6739	0.6765	0.6781	0.6793
m_steam5	0.0907	0.0916	0.092	0.0923	0.0924	0.0925
m_brine5	0.5688	0.5778	0.5819	0.5842	0.5857	0.5867
m_steam6	0.0979	0.0999	0.1008	0.1014	0.1017	0.1019
m_brine6	0.4709	0.4779	0.481	0.4828	0.484	0.4848
m_steam7	0.118	0.1207	0.1219	0.1226	0.123	0.1233
m_cooling sea water	0.866	0.8138	0.7905	0.7773	0.7688	0.7629
bleed steam	0.0467	0.0439	0.0426	0.0419	0.0414	0.0411
salinity_brine1	216.875	215.7791	215.293	215.0183	214.8415	214.7181
salinity_brine2	239.6147	237.3709	236.3805	235.8221	235.4634	235.2132
salinity_brine3	267.5901	264.1818	262.6822	261.8382	261.2965	260.9189
salinity_brine4	303.2902	298.7639	296.7748	295.656	294.9381	294.4379
salinity_brine5	351.6338	346.1373	343.7187	342.3574	341.4837	340.8748
salinity_brine6	424.7051	418.5118	415.775	414.2316	413.2397	412.5479
salinity_brine7	566.6517	559.8687	556.8522	555.1458	554.0473	553.2801
m_pure water	0.8	0.8	0.8	0.8	0.8	0.8
flow difference	0	0	0	0	0	2.22E-16
% error in flow difference	0	0	0	0	0	2.22E-16
Energy in (kJ)	229.3856	221.5272	218.0151	216.0234	214.7393	213.8416
Energy out (kJ)	229.3891	221.5307	218.0186	216.0269	214.7428	213.8451
% error in energy diff	-1.51E-05	-1.58E-05	-1.61E-05	-1.63E-05	-1.64E-05	-1.65E-05
salt	0.2	0.2	0.2	0.2	0.2	0.2
Energy input by heat source kJ/s per kg/s of sea water	164.1179	160.1882	158.4317	157.4356	156.7933	156.3443
kWh/1000 gal	175.3396	171.1412	169.2647	168.2004	167.5142	167.0345

FS-MED Counter Current Scheme (8 effects)

Heat source Temperature	150	200	250	300	350	400
m_dry air	1.6508	1.0135	0.7221	0.555	0.4465	0.3704
m_brine8	0.3515	0.3559	0.3579	0.3591	0.3599	0.3604
m_steam FS tank	0.1905	0.192	0.1927	0.1932	0.1934	0.1936
m_steam eff1	0.065	0.0602	0.058	0.0568	0.056	0.0554
m_brine1	0.935	0.9398	0.942	0.9432	0.944	0.9446
m_steam eff2	0.0749	0.0714	0.0698	0.0689	0.0683	0.0679
m_brine2	0.8602	0.8684	0.8721	0.8743	0.8757	0.8767
m_steam eff3	0.075	0.0729	0.0719	0.0713	0.0709	0.0707

m_brine3	0.7851	0.7955	0.8003	0.803	0.8048	0.8061
m_steam4	0.0757	0.0748	0.0744	0.0742	0.074	0.0739
m_brine4	0.7094	0.7207	0.7259	0.7289	0.7308	0.7322
m_steam5	0.0774	0.0777	0.0778	0.0779	0.078	0.078
m_brine5	0.632	0.643	0.648	0.6509	0.6528	0.6542
m_steam6	0.081	0.0825	0.0831	0.0835	0.0837	0.0839
m_brine6	0.551	0.5605	0.5649	0.5675	0.5691	0.5703
m_steam7	0.0892	0.0916	0.0927	0.0933	0.0937	0.094
m_brine7	0.4618	0.4689	0.4722	0.4742	0.4754	0.4763
m_steam8	0.1102	0.113	0.1143	0.1151	0.1156	0.1159
m_cooling sea water	0.9083	0.842	0.8114	0.7938	0.7824	0.7743
bleed steam	0.039	0.0361	0.0348	0.0341	0.0336	0.0332
salinity_brine1	213.8977	212.8182	212.3243	212.041	211.8571	211.7281
salinity_brine2	232.5133	230.3215	229.3238	228.753	228.3832	228.1238
salinity_brine3	254.7337	251.4227	249.9212	249.0639	248.5089	248.1201
salinity_brine4	281.92	277.5266	275.5385	274.4044	273.6709	273.1571
salinity_brine5	316.4322	311.062	308.6321	307.2462	306.3498	305.722
salinity_brine6	362.9692	356.827	354.0417	352.4514	351.4222	350.701
salinity_brine7	433.1193	426.5175	423.5097	421.7883	420.6727	419.8902
salinity_brine8	568.946	561.9923	558.804	556.9736	555.785	554.9503
m_pure water	0.8	0.8	0.8	0.8	0.8	0.8
flow difference	0	0	-2.22E-16	2.22E-16	-2.22E-16	0
% error in flow difference	0	0	-2.22E-16	2.22E-16	-2.22E-16	0
Energy in (kJ)	228.7652	219.9493	215.8855	213.5461	212.0245	210.9547
Energy out (kJ)	228.7689	219.953	215.8892	213.5498	212.0282	210.9585
% error in energy diff	-1.61E-05	-1.69E-05	-1.73E-05	-1.75E-05	-1.76E-05	-1.78E-05
salt	0.2	0.2	0.2	0.2	0.2	0.2
Energy input by heat source kJ/s per kg/s of sea water	160.3083	156.4895	154.7292	153.7157	153.0566	152.5931
kWh/1000 gal	171.2696	167.1897	165.3089	164.2262	163.522	163.0268

FS-MED Counter Current Scheme (9 effects)

Heat source Temperature	150	200	250	300	350	400
m_dry air	1.5259	0.9604	0.6944	0.5397	0.4385	0.3671
m_brine9	0.3502	0.3545	0.3566	0.3578	0.3586	0.3592
m_steam FS tank	0.1808	0.1823	0.183	0.1834	0.1837	0.1839
m_steam eff1	0.0511	0.0463	0.0441	0.0428	0.0419	0.0413
m_brine1	0.9489	0.9537	0.9559	0.9572	0.9581	0.9587
m_steam eff2	0.0677	0.0641	0.0624	0.0614	0.0608	0.0603

m_brine2	0.8811	0.8895	0.8935	0.8958	0.8974	0.8984
m_steam eff3	0.0675	0.065	0.0639	0.0632	0.0627	0.0624
m_brine3	0.8137	0.8245	0.8296	0.8326	0.8346	0.836
m_steam4	0.0675	0.0662	0.0656	0.0652	0.065	0.0648
m_brine4	0.7462	0.7583	0.764	0.7674	0.7696	0.7712
m_steam5	0.0681	0.0679	0.0678	0.0678	0.0677	0.0677
m_brine5	0.678	0.6903	0.6962	0.6996	0.7019	0.7035
m_steam6	0.0698	0.0706	0.071	0.0713	0.0714	0.0715
m_brine6	0.6083	0.6197	0.6252	0.6284	0.6305	0.632
m_steam7	0.0735	0.0753	0.0761	0.0766	0.0769	0.0772
m_brine7	0.5347	0.5444	0.549	0.5517	0.5535	0.5548
m_steam8	0.0818	0.0843	0.0855	0.0862	0.0867	0.087
m_brine8	0.4529	0.4601	0.4635	0.4655	0.4668	0.4678
m_steam9	0.1027	0.1056	0.1069	0.1077	0.1082	0.1086
m_cooling sea water	0.958	0.8684	0.8259	0.8011	0.7848	0.7733
bleed steam	0.0307	0.0278	0.0264	0.0257	0.0251	0.0248
salinity_brine1	210.7757	209.719	209.2214	208.9319	208.7424	208.6087
salinity_brine2	226.9777	224.84	223.8385	223.2575	222.8778	222.6101
salinity_brine3	245.797	242.5749	241.0717	240.2013	239.6334	239.2333
salinity_brine4	268.0355	263.7596	261.7702	260.6199	259.8699	259.3419
salinity_brine5	294.9646	289.7159	287.2765	285.8669	284.9481	284.3014
salinity_brine6	328.8058	322.7377	319.9153	318.2838	317.2202	316.4714
salinity_brine7	374.0134	367.3748	364.2783	362.4857	361.3162	360.4923
salinity_brine8	441.6012	434.7316	431.5113	429.6424	428.4211	427.5599
salinity_brine9	571.1689	564.1856	560.8919	558.9742	557.7186	556.8322
m_pure water	0.8	0.8	0.8	0.8	0.8	0.8
flow difference	0	0	0	-2.22E-16	0	0
% error in flow difference	0	0	0	-2.22E-16	0	0
Energy in (kJ)	227.6507	217.2363	212.2955	209.4102	207.5176	206.1797
Energy out (kJ)	227.6545	217.24	212.2992	209.414	207.5214	206.1835
% error in energy diff	-1.64E-05	-1.74E-05	-1.78E-05	-1.81E-05	-1.83E-05	-1.84E-05
salt	0.2	0.2	0.2	0.2	0.2	0.2
Energy input by heat source kJ/s per kg/s of sea water	155.4453	151.7829	150.0456	149.0312	148.3657	147.8954
kWh/1000 gal	166.0741	162.1612	160.3051	159.2213	158.5104	158.0079

8.4 Temperatures

8.4.1Variable feed

3 effects

	Inlet temperature of steam and air mixture	Outlet temperature of steam and air mixture
Effect 1	100	90
Effect 2	90	80
Effect 3	80	70

4 effects

	Inlet temperature of steam and air mixture	Outlet temperature of steam and air mixture
Effect 1	100	90
Effect 2	90	80
Effect 3	80	70
Effect 4	70	60

5 effects

	Inlet temperature of steam and air mixture	Outlet temperature of steam and air mixture
Effect 1	100	90
Effect 2	90	80

Effect 3	80	70
Effect 4	70	60
Effect 5	60	50

6 effects

	Inlet temperature of steam and air mixture	Outlet temperature of steam and air mixture
Effect 1	100	95
Effect 2	95	90
Effect 3	90	85
Effect 4	85	80
Effect 5	80	75
Effect 6	75	70

7 effects

	Inlet temperature of steam and air mixture	Outlet temperature of steam and air mixture
Effect 1	100	95
Effect 2	95	90
Effect 3	90	85

Effect 4	85	80
Effect 5	80	75
Effect 6	75	70
Effect 7	70	65

8 effects

	Inlet temperature of steam and air mixture	Outlet temperature of steam and air mixture
Effect 1	100	95
Effect 2	95	90
Effect 3	90	85
Effect 4	85	80
Effect 5	80	75
Effect 6	75	70
Effect 7	70	65
Effect 8	65	60

9 effects

	Inlet temperature of steam and air mixture	Outlet temperature of steam and air mixture
Effect 1	100	95
Effect 2	95	90
Effect 3	90	85
Effect 4	85	80
Effect 5	80	75
Effect 6	75	70
Effect 7	70	65
Effect 8	65	60
Effect 9	60	55

8.4.2Counter-current feed

3 effects

	Inlet temperature of feed brine	Outlet temperature of feed brine
Effect 1	55	65
Effect 2	65	70
Effect 3	70	75

4 effects

	Inlet temperature of feed brine	Outlet temperature of feed brine
Effect 1	45	50
Effect 2	50	60
Effect 3	60	70
Effect 4	70	75

5 effects

	Inlet temperature of feed brine	Outlet temperature of feed brine
Effect 1	35	40
Effect 2	40	45
Effect 3	45	50
Effect 4	50	55
Effect 5	55	60

6 effects

	Inlet temperature of feed brine	Outlet temperature of feed brine
Effect 1	55	58.33
Effect 2	58.33	61.666
Effect 3	61.666	65

Effect 4	65	68.333
Effect 5	68.333	71.666
Effect 6	71.666	75

7 effects

	Inlet temperature of feed brine	Outlet temperature of feed brine
Effect 1	55	60
Effect 2	60	62.5
Effect 3	62.5	65
Effect 4	65	67.5
Effect 5	67.5	70
Effect 6	70	72.5
Effect 7	72.5	75

8 effects

	Inlet temperature of feed brine	Outlet temperature of feed brine
Effect 1	50	55
Effect 2	55	57.85
Effect 3	57.85	60.7
Effect 4	60.7	63.55
Effect 5	63.55	66.4

Effect 6	66.4	69.25
Effect 7	69.25	72.1
Effect 8	72.1	75

9 effects

	Inlet temperature of feed brine	Outlet temperature of feed brine
Effect 1	40	45
Effect 2	45	48.75
Effect 3	48.75	52.5
Effect 4	52.5	56.25
Effect 5	56.25	60
Effect 6	60	63.75
Effect 7	63.75	67.5
Effect 8	67.5	71.5
Effect 9	71.5	75

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