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Modelling of Flashing Stage Internals for a Multistage Flash Desalination

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Acknowledgment

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Abstract

Natural water resources have become a global crisis, which most countries in the world try to overcome this problem in many ways. As the population of human is increasing, the development of industries and demand of water on agriculture sector have boosted up this water shortage problems to the critical zone. Over the decades, desalination technology has become the most effective alternative way to supply fresh water throughout the world. The multistage flash desalination and reverse osmosis processes are examples of desalination technology that is available in the market nowadays. [James E. Miller, 2003]

Desalination is basically a process of separation between salt and water. Water that has been desalinated must be salt free to be considered as a successful product for human consumption. This thesis is basically a report on the efficiency of the mathematical model of the multistage flash desalination with recirculating brine that was developed by Hisham T. El-Dessouky & Hisham M. Ettouney, (2002). The evaluation of the modelling equation is done by simulating the model inside the Aspen Custom Modeler. [James E. Miller, 2003]

The literature review of desalination has covered the importance of desalination and the available desalination technologies. Desalination is the most demanded technology in supplying fresh water. The desalination process is divided into two types, which are membrane technique and thermal technique. Every process that falls under those two techniques is explained in details. The process operations for each of the processes are provided so that the differences between processes can be seen and understood. [James E. Miller, 2003]

Then, the development of the mathematical equations of the system are introduced. The list of equation that have been used in this thesis is given and assumptions while developing those equations are discussed. Important operational variables have been highlighted to show that these variables play an important role in making the process more effective. Effectiveness of variables are been tested on the effect of value changes to the process.

The method that been used was by testing the model of the system in the Aspen Custom Modeler software. The evaluation of the system effectiveness was by study the effect of the number of stages against the performance ratio of the system. As the number of stages increases the performance ratio of the system also increased. Another important variable is top brine temperature, it gave same effect to the system performance as its value increasing. The information gained from the study is the existence of demister will affect the vapour velocity of the system.
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List of Symbols

\( M_f \) = Feed seawater flow rate
\( M_b \) = Blow down brine flow rate
\( M_d \) = Total distillate flow rate
\( M_r \) = Flow rate of recycle brine
\( M_{cw} \) = Cooling seawater flow rate
\( M_s \) = Steam flow rate
\( \Delta T \) = Temperature drop per stage
\( T_1 \) = Temperature (stage 1)
\( T_2 \) = Temperature (stage 2)
\( T_{r1} \) = Temperature leaving condenser (1\textsuperscript{st} stage)
\( T_{r2} \) = Temperature leaving condenser (2\textsuperscript{nd} stage)
\( T_{jn} \) = Seawater temperature leaving the condenser (last stage)
\( T_{av} \) = Average stage temperature
\( T_{cw} \) = Intake seawater temperature
\( T_o \) = Top brine temperature
\( T_s \) = Steam temperature
\( T_n \) = Temperature of brine leaving the last stage
\( A_b \) = Heat transfer area (Brine preheater)
\( A_r \) = Heat transfer area (1\textsuperscript{st} stage condenser, recovery section)
\( A_j \) = Heat transfer area (last stage condenser, rejection section)
\( X_b \) = Brine salt concentration
\( X_f \) = Intake seawater salt concentration
\( X_r \) = Salt concentration in recycle stream
\( V_{vn} \) = Vapour velocity at the last stage
\( V_b \) = Brine mass flow rate per stage width
\( y \) = Ratio of stage sensible and latent heat
\( C_p \) = Heat capacity of liquid streams
\( C_d \) = Weir friction coefficient
\( H \) = Height of brine pool
\( GH \) = Gate height
\( j \) = Number of heat rejection stages
\( n \) = Number of recovery and rejection sections
\( D \) = Amount of flashing brine at 1\textsuperscript{st} stage
\( \lambda_{av} \) = Average latent heat
1. Introduction

1.1 The Important of Water Desalination

Water shortage is a global problem where most of the countries in the world are suffering due to lack of water, especially fresh clean water. The increasing in population, life styles, industrial and agricultural activities have required a huge amount of fresh water [James E. Miller, 2003]. Currently the available fresh water resources like lake, river and ground water are limited and are becoming worse because these resources are decreasing at a critical rate. Countries that are mostly affected by this water shortage problem are Middle East and North Africa. [James E. Miller, 2003]

The earth is mostly covered by water, but the problem is the percentage of fresh water from the earth’s water is too small. Most of the water is seawater but this type of water is not suitable for human consumption, agriculture and industrial usage because this water contains salt. Desalination technology is used to remove salt and produced fresh water. [Akili D, Ibrahim K. & Jong-Mihn Wie, 2008]

Desalination has become a new alternative for human to get fresh water and this technology has become a great demand because it can provide fresh water for a long-term period. Multistage Flash desalination process is the most popular seawater desalination process because this system can produce much more fresh water compared to other seawater desalination processes.

1.2 Research Aims

Desalination technology is the best solution so far in order to get fresh water and without doubt the demand for this technology at Arabian Gulf Region is very high. A better understanding of this process could bring lot of benefits. There are two ways to improve this system, which are technology and management. In terms of technology, improvements that can be made are like:

- Heat-transfer technology
- Chemical selection
- Corrosion protection
- Control on the operational variables

Nowadays, technology that used to improve and redesign the control system of desalination. The system of Multistage Flash Desalination Plant is being studied by understanding the mathematical model. By using computer-based simulation technique, Aspen Custom Modeller (ACM), the efficiency Multistage Flash Desalination is being evaluated and presented.
This project is focused on the mathematical modelling of Multistage Flash desalination with recycled brine introduced by Hisham T. El-Dessouky & Hisham M. Ettouney, (2002). The model is presented in reference to focus on the study of steady state condition of the MSF desalination system. The model equations are solved by calculating the mass and energy balance equations which is less complicated and this has made it easy to understand. There are few other researchers who has been using the same modelling and solution methods as presented by El-Dessouky & Ettouney:

- Ettouney, El-Dessouky, & Al-Juwayhel (2002)
- Abdel-Jabbar, Qiblawy, Mjalli, & Ettouny (2007)
- El-Dessouky & Bingulac (1996)

1.3 Research Scope

Based on the aims of the project, the scope of this thesis is focused on the following:

1. To do research on the literature review of the desalination technology, the available technology of desalination, concept of operation for each of the process, the ability of each process to produce fresh water and the advantages of the process.
2. To select the suitable steady state mathematical model equation presented by any references and implement the model equation into Aspen Custom Modeler.
3. To study model simulation by using Aspen Custom Modeler.
4. To understand the steady state behaviour of the mathematical model equation of the multistage flash desalination with recirculating brine plant. The evaluation of the system operation is based on the results gained from the simulation in Aspen Custom Modeler.
5. To study the effect of different number of stages to the production of the distillate product. The range of testing will cover from 14 stages to 24 stages. The variables that been observed while testing the effect of number of stages are as follows:
   - Specific heat transfer area
   - Performance ratio
   - Specific flowrate of cooling seawater
   - Specific flowrate of recirculating brine
6. Other conditions that will be tested in terms of efficiency of model used is the effect of Top Brine Temperature. The range of testing will cover from 90 °C to 110 °C.
7. To study all the operational variables of the multistage flash desalination with recirculating brine. This study will cover the available operational variables, the roles of each of the variables, the effect on value changing and the limitation of the operational variables.
8. To implement the physical correlation properties to the mathematical model equations so that more information can be gained on process behaviour and efficiency.

9. To study the internal design of multistage flash desalination with recirculating brine and the effect of changing this internal design to the production of the distillate product.

10. To give recommendation on possible future work.
1.4 Available Desalination Technologies

As discussed in the previous section, desalination means the process of removing fresh water from saline water. Desalination technologies can be divided into two main separation techniques which are water separation and salt removal. The classification of the desalination technologies is shown in Table 1 below. [Akili D, Ibrahim K. & Jong-Mihn Wie, 2008]

*Table 1: Available Desalination Technologies according to the separation mechanism [Akili D, Ibrahim K. & Jong-Mihn Wie, 2008]*

<table>
<thead>
<tr>
<th>Technique</th>
<th>Energy</th>
<th>Desalination Process</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Separation</td>
<td>Electrical and thermal</td>
<td>Distillation</td>
<td>Thermal Vapour Compression</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Solar Desalination</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Distillation and filtration</td>
<td>Multi Effect Distillation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Multi Stage Flash</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crystallization</td>
<td>Freezing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Formation of hydrates</td>
</tr>
<tr>
<td></td>
<td>Electrical</td>
<td>Distillation</td>
<td>Reverse Osmosis</td>
</tr>
<tr>
<td></td>
<td>Ionic Filtration</td>
<td></td>
<td>Mechanical Vapour Compression</td>
</tr>
<tr>
<td>Salt Removal</td>
<td>Chemical</td>
<td>Others</td>
<td>Ionic Exchange</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Extraction</td>
</tr>
<tr>
<td></td>
<td>Electrical</td>
<td>Ionic Migration</td>
<td>Electro dialysis</td>
</tr>
</tbody>
</table>

Based on Table 1, this table shows the separation desalination processes are being divided according to the source of energy that used to allow certain processes to occur [Hisham T.El-Dessouky & Hisham M.Ettouney, (2002)]. This energy could be electrical, thermal, chemical or combination of these energies. Most of these energies are used to heat up the feed water to initiate the evaporation and condensation (distillation) processes. This is one of the oldest techniques but most commonly used in the desalination industry. The fresh water obtained from the distillation method tends to be better in quality compared to other types of methods such as membrane process and crystallization. [Akili D, Ibrahim K. & Jong-Mihn Wie, 2008]
Regardless of the types of energy used in the desalination technology, the research on the desalination is focused on the basis of the separation process used. In Table 2 the desalination technology has been scaled down into two types which are conventional thermal and membrane desalination processes.

Table 2: Conventional thermal and membrane desalination process [Akili D, Ibrahim K. & Jong-Mihn Wie, 2008]

<table>
<thead>
<tr>
<th>Conventional Desalination Process</th>
<th>Name</th>
<th>Type of system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>Multi Stage Flash</td>
<td>Brine Circulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Once Through</td>
</tr>
<tr>
<td></td>
<td>Multi Effect Distillation</td>
<td>(Parallel Feed)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mechanical Vapour Compression</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Parallel Feed)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thermal Vapour Compression</td>
</tr>
<tr>
<td></td>
<td>Single Effect Distillation</td>
<td>Mechanical Vapour Compression</td>
</tr>
<tr>
<td>Membrane</td>
<td>Reverse Osmosis</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Electro dialysis</td>
<td>-</td>
</tr>
</tbody>
</table>

1.4 Classification of Desalination Processes

1.4.1 Membrane Processes
The membrane desalination process is the most efficient and economical way to obtain fresh water from saline water. This membrane acts as a physical barrier that will only allow certain compound to move through. This movement is limited to physical or chemical properties of compounds itself Ahsan [Munir, 2006]. The system that falls under the membrane desalination process is Reverse Osmosis (RO) and Electro Dialysis (ED).

1.4.1.1 Reverse Osmosis (RO)
Osmosis is a natural occurring process where solvent such as water passing through a semi-permeable barrier. This semi-permeable barrier or membrane allows some components to pass through it but not others. In nature the flow through the membrane is from less concentration solution such as fresh water to higher concentration solution such as seawater until equilibrium is achieved. Reverse osmosis is when the opposite direction occurs by pressuring the flow of the solution of seawater through the membrane to fresh seawater. [Munir, 2006]
A high-pressure pump increases the pressure of the seawater up to 1000 psi as the pressure needs to be sufficiently high to overcome the natural occurring of osmosis process. The reverse osmosis membrane can be thought as number of seals envelope that connected at their open end to a tube. There are spaces between envelopes to allow water to across the membranes. The membrane envelopes and spacers are then wound around the tube like a paper towels. [Khawla AbdulMohsen Al-Shayji, 1998]

The efficiency of Reverse Osmosis (RO) is dependent on the membrane itself. The efficiency of membrane is as follows: [Khawla AbdulMohsen Al-Shayji, 1998]

- Types of membranes
- Separation ability
- Resistance to the chemical and environment effects

The principle of reverse osmosis can be seen in Figure 1 and Figure 2.

![Reverse Osmosis](http://greenliving.lovetoknow.com/environmental-issues/how-desalination-plants-work)
1.4.1.2 Electro Dialysis (ED)

Theoretically, in Electro Dialysis desalination the separation process occurs by electrochemical force. The ions are transferred by using direct current (DC) voltage. In seawater, there is a mixture of water and salt. As this salt is dissolved in water, it breaks into individual ions which move freely in the solution. [Fernando V., Angel B. and Ramón A, 2011]

The positively charged ions like sodium are called cation, and negatively charged ions like chloride are called anion. An ion such as salt has the ability to move in water when the direct current (DC) is applied to the water. The negatively charged chloride ion moves to the positively charged anode under the influences of the electricity. The positively charged sodium ion moves to the negatively charged cathode. [Fernando V., Angel B. and Ramón A, 2011]

Electro dialysis is an advanced technology that utilizes the ions movement to desalinate water. With the electro dialysis, the ions move through a special membranes and create two separate streams, which are desalinated stream and concentrated salt stream. Electro dialysis also uses electricity to clean up the electro dialysis cell. [Fernando V., Angel B. and Ramón A, 2011]
Figure 3: Principle of Electro Dialysis
1.4.2 Thermal process

Thermal separation processes are based on the concept of absolute laws of conservation in momentum, energy and mass, and also kinetic and phase equilibrium methods in order to model the heat and material transfer flows. It is necessary to perform practical experiments to get a better understanding of the process principle such as counter-current and parallel flow and multi stage processes. [Khawla AbdulMohsen Al-Shayji, 1998]

The system that falls under the thermal desalination process is Multistage Flash Desalination (MSF), Multi Effect Desalination (MED) and Single Effect Desalination (SED). The Single Effect Distillation has only one type of system, which is Mechanical Vapour Compression but the Multi Effect Desalination has two types of system which are Mechanical Vapour Compression and Thermal Vapour Compression. Both types have the same configuration, which is parallel feed. Configurations like feed backwards and feed-forward are not being used in desalination processes. [Khawla AbdulMohsen Al-Shayji, 1998]

1.4.2.1 The Mechanical Vapour Compression (MVC)

Mechanical energy is used in this Mechanical Vapour Compression (MVC) distillation rather than thermal energy like most of other desalination systems. Most of the vapour compression plants only use single effect configuration but for a larger capacity production, a multi effect configuration is more convenient [Khawla AbdulMohsen Al-Shayji, 1998]. This system is based on simple principles. At first the feed seawater is preheated by the heat produced from the discharged brine. Then the seawater is sprayed to the evaporator to form vapours, which will be compressed either by mechanical (compressor) or thermal (steam force ejector). This compression section will cause the increase in pressure and temperature of the vapour. This vapour then will be discharged to the heat transfer tube bundle to reduce the temperature and allow condensation to occur. The system schematic diagram can be seen in Figure 4. [Fredi L & Abraham O, 2007]
Review on Mechanical Vapour Compression (MVC)

The Mechanical Vapour Compression (MVC) process only consumes a small amount of energy that leads to low operating cost but this process has limitation on the capacity in the system, because of that the amount of product produced is less compared to other distillation processes. The good part is less maintenance needed for this Mechanical Vapour Compression (MVC) process. [Khawla AbdulMohsen Al-Shayji, 1998]
1.4.2.2 Multi Effect Distillation

Multi effect distillation was introduced in the early 1960s. This was the first process that could produce a significant amount of distillate water. The distillation process occurs in a series of vessels (effect) where the vapour is formed in the first effect and then is used as heating media for the next effect. As a result, the feed water boils up in every series of effect without the need to supply additional steam right after the first effect. The reason is this process uses the principle of reducing the ambient pressure in each of the effect. The performance ratio of the system is directly proportional to the number of vessels or effects. Multi effect distillation heat exchanger can be classified into three configurations, which are vertical tube, horizontal tube or vertically stacked tube bundles. [Khawla AbdulMohsen Al-Shayji, 1998]

![Diagram of Multi-Effect Distillation](http://www.separationprocesses.com/Distillation/DT_Chp07b.htm)
Review of Multi Effect Distillation

Multi Effect Distillation has a high heat-transfer efficiency compared to other thermal processes. As this process only operates in low operating temperatures, multi effect distillation plant has less scale formation so requires less maintenance. This low operating temperature also leads to a low operating cost. Other advantages of multi effect distillation are as follows: [Khawla AbdulMohsen Al-Shayji, 1998]

- Easy to operate
- Reliable
- System can continuously operate without supervision
- Feed seawater does not have to be pre-treated

2. Multistage Flash Desalination

2.1 General Process Principle
Generally the main concept used in multistage flash desalination process in order to produce distilled water is by boiling (evaporation) and condensation of seawater. Multistage flash desalination is a combination of single flash stage chamber. The pressure through all effects must decrease because the saturation temperature in each effect must go down due to using vapor from one effect to heat the following effect. The multistage flash desalination plant, there are two system configurations, which are Once-through multistage flash desalination and Brine-recirculation MSF. [Khawla AbdulMohsen Al-Shayji, 1998]
2.2 Once-through multistage flash desalination
In once-through (MSF) configuration, Figure 6, the system is consist of two main parts, which are as follows: [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]

1. Brine heater
2. Flashing stage chambers (Heat-Recovery Section)

![Figure 6: Schematic Diagram of Multistage Flash Desalination (Once-Through)](image)

2.3 Brine-Recirculation Multistage Flash Desalination
For brine circulation (MSF) configuration the system, Figure 7, is consist of three main parts which are: [Hala Faisal Al-Fulaj, 2011]

1. Brine heater
2. Heat recovery section
3. Heat rejection section
Brine circulation (MSF) configuration system is similar to once-through (MSF) configuration but with extra section which is called ‘Heat-Rejection Section’. The heat-rejection section has a role to ensure that the temperature of feed seawater is in control and to eliminate the excess heat formed by the brine heater. The design of the heat-rejection section is usually a combination of two to three flash stage chambers. In this design, part of the brine is recycled back from the last stage of the flash chamber to be mixed with the input stream of feed seawater to the heat-recovery section. The reason of this recirculating is to help preheat process of feed seawater during the winter season. The part of feed seawater is also recycled to the input stream. This is important to ensure that there is no reduction in the temperature of the feed seawater at the last stage. If there is a reduction in temperature then there will be an increase in certain variables such as: [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]

- Specific volume of the flashed-off vapor
- Vapor velocity
- Amount of entrained brine

The increasing in these variables will cause an increasing in product salinity in a few starting flash stages and this distillate product might exceed the product salinity’s requirement. [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]
2.4 Process Variables and Constraints

The term ‘Process’ is referred to changing or refining raw materials to produce end products. In order to produce the end product, the raw materials may go through some processes called mixing, heating, cooling filtering and transferring. [PACONTROL.com, 2006]

The raw materials may just pass through the processes that are introduced or may just remain in certain states such as gaseous (vapor), liquid, and solid or a mix of solids and liquids. In every process there are process variables that represent the features of the process. These process variables could change rapidly or slowly or may remain in a steady state. Common process variables that can affect the chemical and physical process are flow, temperature, pressure and level. [PACONTROL.com, 2006]

As this project is researched based on the multistage flash desalination system with brine recirculating, all the process variables that contribute to the process have been highlighted. The description of each of the variables and its effects on the system is discussed in the next section. [PACONTROL.com, 2006]
2.5 Details in process operation of Multistage Flash Desalination with Recycle Brine

The full schematic design of multistage flash desalination with recycle brine used for this thesis study is shown in Figure 8. In Figure 9 shows the same model variables symbol used in the simulation programming (Aspen Custom Modeling).

Figure 8: Schematic diagram of Multistage Flash Desalination with Recycle Brine.
[Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]
2.5.1 Operation of system

2.5.1.1 Operation of system
This thesis is about the study of efficiency of the multistage flash desalination with recycle brine plant to give a good production by adjusting the internal design of the system. It is good to understand the process that is happening around the system first and comes up with a good mathematical model, which is later on, will be used in the study. The operation of the multistage flash desalination with recycle brine is described below:

The operation is started from the feed seawater stream introduced to the heat-rejection section. This feed seawater stream flows through the condenser tubes where its temperature will increase by the latent heat released from the water vapor produced in the flash stage chamber. [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]

The feed seawater is mixed of two streams, the first one is the feed seawater ($M_f$) and the second one is cooling seawater ($M_{cw}$). At the end of the condenser of heat–rejection section, the stream is divided into three streams. [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]

i. Part of cooling seawater ($M_{cw}$) is recycled back to the input stream to mixed with feed seawater.

ii. Part cooling seawater ($M_{cw}$) is rejected to the sea.

iii. (Deaerated feed seawater ($M_f$) is mixed with the brine of the last stage of heat-rejection section.

1. The input stream to the condenser of the heat-recovery section is coming from the brine recycle stream ($M_r$) of the last stage (heat-rejection section). Same heating process happened to the temperature of brine recycle stream ($M_r$) as it flows through the condenser tubes along each of the stages. [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]

2. At the end of the condenser tube in the heat-recovery section, the brine recycle stream ($M_r$) is then entered to the brine heater. The function of this brine heater is to heat up the temperature of brine recycled stream ($M_r$) to its maximum temperature, which is called Top Brine Temperature ($T_o$). [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]

3. Then the brine that comes out from the brine heater enters the first flash stage chamber of heat-recovery section all the way to the last flash stage chamber of heat-rejection section. In each flash stage chamber, flashing process occurs due to low saturation temperature and pressure of the flash stage chamber. [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]

4. The condensation of the flashed off vapor is happening on the outside of the condenser in each of the stages and collected in a tray across the stages. This distillate product stream ($M_d$)
is withdrawn from the last stage of the heat-rejection section. [Hisham T. El-Dessouky & Hisham M. Ettouney, 2002]

![Diagram of the model variables in the flash stage chamber](image)

Figure 9: Schematic of the model variables in the flash stage chamber [Hisham T. El-Dessouky & Hisham M. Ettouney, 2002]

2.6 The development of Mathematical Model
2.6.1 Introduction

In every process system there are chemical and physical processes that are happening. In order to design, optimize and control these processes, the process model of the system needs to be developed beforehand. This process model can be used to manage and analyze any risk or hazard that can happen when the system is being implemented in the future. Every model that has been developed has its own reason and goal, which the developer wants to achieve from the process. [Hala Faisal Al-Fulaij, 2011]

In this thesis, the study is more to analyze the existent process model that has been developed by other researchers instead of building the model. The process model that has been used in this thesis is the one that has been introduced by [El-Dessouky & Ettouney, 2002]. This section will review the mathematical model equations and how the mathematical model has been developed. The evaluation of the model equation and outcomes from the study will be presented including the performance, strength and weakness. [Hala Faisal Al-Fulaij, 2011]
2.6.2 Mathematical Model

A simple mathematical model of a system can be a good starting point to understand and get quick estimation of the certain information of the process such as:

- Heat transfer area
- Performance ratio
- Temperature
- Flow rate
- Salinity

Even though the models can give quick estimation on the main features of the system but must be awarded that the calculated variables value and result gained from the model is not actually or accurately shows the actual behavior of the real system because the model created is based on some assumptions in order to make the model equation less complicated and easy to understand. [Hala Faisal Al-Fulaij, 2011]

Once the simple model has been developed and tested, the correlation of physical properties can be added to the model so that more accurate prediction on the performance chart as well as other operating characteristics. Calculating the mass and energy balance equations solves this model. [Hala Faisal Al-Fulaij, 2011]

2.6.3 Assumptions

The assumptions that been used to develop the mathematical model equations of multistage flash desalination with recirculating brine are as follows: [Hala Faisal Al-Fulaij, 2011]

1. **Negligible effect of the distillate salinity:** The average of distillate salinity is below 20 ppm while the feed seawater and brine salinity are varies from 40 000 to 70 000 ppm. This value is too small to give any affect to the distillate product, so the product is assume salt free.

2. **No heat losses:** Based on research done by (Abdel-Jabbar, Qiblawy, Mjalli, & Ettouny, 2007), the heat losses of the total input heat in the real system is only up to 5%. This small value is because the ratio of the multistage flash desalination plants surface volume is small. The other reason of this small heat losses is because the heat transfer to surrounding is too low as the ambient temperature is almost similar to the temperature of the low temperature stage.

3. Same vapour enthalpy below and above the demister in each of the flash stage chamber.

4. Neglected effect of non-condensable gases on the mass and energy balances.

5. Constant brine flow rate and brine holdup.
6. The heat transfer area in each section (heat-recovery and heat-rejection) is constant. But to design a multistage flash desalination plant with constant stage temperature difference for the whole system is basically not economical.

In this model, the correlations are used to calculate or estimate the other parameter such as:

- Boiling point elevation (BPE)
- Non-equilibrium allowance (NEA)
- Discharge coefficient (Cd)
- Overall heat transfer coefficient (U)

### 2.7 Material Balances

**Overall material balance**

\[ M_f = M_d + M_b \]

**Salt balance**

\[ X_f M_f = X_b M_b \]

**Total feed flow rate in terms of distillate flow rate**

\[ M_f = \frac{X_b}{X_b - X_f} M_d \]

### 2.7.1 Temperature Profiles of Stages and Condenser

The temperature distribution in the multistage flash desalination of recycle brine is divided into four temperature terms:

1. Steam, \( T_s \)
2. Brine leaving preheater (Top Brine Temperature), \( T_o \)
3. Brine leaving last stage, \( T_n \)
4. Intake seawater, \( T_{cw} \)

The temperature profile is assumed linear in stages and condenser.

**Temperature drop per stage**

\[ \Delta T = (T_o - T_n)/n \]

\[ T_1 = T_o - \Delta T \]

\[ T_2 = T_1 - \Delta T \]

So temperature at stage \( i \),

\[ T_i = T_o - i\Delta T \]
The recycle seawater flow into condenser of heat recovery is equal to \( T_n \) and it is increasing by \( \Delta T_r \) in the condenser of each unit. [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002] This increasing temperature is equal to the decreasing in the brine temperature in each stage, \( \Delta T \). [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]

### 2.7.2 Energy balance on stage \( i \),

\[
D_i C_p T_{vi} + B_i C_p T_i - D_{i+1} C_p T_{vi+1} - B_{i+1} C_p T_{i+1} = M_r C_p (T_{ri} - T_{ri+1})
\]

Assumptions:

- Temperature different \((T_i - T_{vi})\) is negligible on the energy balance because the value is too small. [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]
- The sum of \((D_i + B_i)\) in each stage is equal to \( M_r \). [Hisham T.El-Dessouky, 2002]

So

\[
M_r C_p T_i - M_r C_p T_{i+1} = M_r C_p (T_{ri} - T_{ri+1})
\]

\[
T_i - T_{i+1} = T_{ri} - T_{ri+1}
\]

Or

\[
\Delta T_i - \Delta T_{ri}
\]

**Seawater temperature (leaves condenser of 1st stage)**

\[ T_{r1} = T_n + (n - j) \Delta T \]

**Seawater temperature (leaves condenser of 2nd stage)**

\[ T_{r2} = T_{r1} - \Delta T \]

Substitute \( T_{r1} \)

\[ T_{r2} = T_n + (n - j) \Delta T - \Delta T \]

So temperature in stage \( i \),

\[ T_{ri} = T_n + (n - j) \Delta T - (i - 1)\Delta T \]

### 2.7.3 Stage energy balance

Temperature drops of the seawater in the condenser of the heat rejection section.

\[
D_i C_p T_{vi} + B_i C_p T_i - D_{i+1} C_p T_{vi+1} - B_{i+1} C_p T_{i+1} = (M_f + M_{cw}) C_p (T_{fi} - T_{fj+1})
\]

Assumptions:

- Temperature different \((T_i - T_{vi})\) is negligible on the energy balance because the value is too small. [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]
Temperature profile is assumed linear. [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]

\[ M_r C_p T_i - M_r C_p T_{i+1} = (M_f + M_{cw}) C_p (T_{ji} - T_{ji+1}) \]

\[ (T_{ji} - T_{ji+1}) = (T_i - T_{i+1}) (M_r / (M_f + M_{cw})) \]

\[ \Delta T_{ji} = (T_n + T_{cw}) / j \]

Seawater temperature (leaves condenser of last stage)

\[ T_{jn} = T_{cw} + (\Delta T_{ji}) \]

Temperature of seawater at rejection section

\[ T_{ji} = T_{cw} + (n - i + 1)(\Delta T_{ji}) \]

2.7.4 Stage Material and Salt Balance

“Flashing vapour formed in each stage can be calculated by studying the energy conservation that happened within stage. The latent consumed by the flashing is equal to the decrease in the brine sensible heat”. [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]

\[ D_1 = y M_r \]

\[ y = C_p \Delta T / \lambda_{av} \]

\[ T_{av} = (T_o + T_n) / 2 \]

Distillate formed at 2\textsuperscript{nd} stage

\[ D_1 = y (M_r - D_1) \]

Substitute \( D_1 \)

\[ D_2 = y (M_r - y M_r) \]

\[ D_2 = M_r y (1 - y) \]

Distillate formed at 3\textsuperscript{rd} stage

\[ D_3 = M_r y (1 - y)^2 \]

General formula for \( D_i \)

\[ D_i = M_r y (1 - y)^{(i-1)} \]

Total distillate flow rate

\[ D_1 + D_2 = M_r (y + y (1 - y)) \]
\[ D_1 + D_2 = M_r \left( 1 - (1 - y)^2 \right) \]

Addition of \(D_3\) will make:
\[ D_1 + D_2 + D_3 = M_r \left( 1 - (1 - y)^3 \right) \]

So
\[ M_d = M_r(1 - (1 - y)^3) \]

**Salt concentration in recycle stream, \(X_r\)**

\[ X_r M_r + M_b X_b = X_f M_f + (M_r M_d) X_n \]
\[ X_r = (X_f M_f + (M_r M_d) X_n - M_b X_b) / M_r \]

Assumption:

- \( X_n = X_b \)

\[ X_r = (X_f M_f + (M_r M_d) X_b - M_b X_b) / M_r \]

Since
\[ M_f = M_d + M_b \]
\[ X_r = (X_f M_f + (M_r M_d) X_b - M_b X_b) / M_r \]
\[ X_r = ((X_f X_b) M_f + (M_r X_b)) / M_r \]

**Flow rate of the brine stream leaving stage \(i\),**

\[ B_i = M_r - \sum_{k=1}^{i} D_k \]

**Salt concentration in the brine stream leaving stage \(i\),**

\[ X_i = \frac{M_r - \sum_{k=1}^{i} D_k}{B_i} \]

Need to determine cooling water flow rate, \(M_{cw}\)

- Required to obtain specific cooling water flow rate, \(sM_{cw}\), which affect process economics. [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]
- \(T_{cw}\), as ref temperature in energy balance. [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]
\[ M_s \lambda_s = M_{cw} C_p (T_n - T_{cw}) + M_b C_p (T_n - T_{cw}) + M_d C_p (T_n - T_{cw}) \]
\[ M_{cw} = \frac{(M_s \lambda_s - M_f C_p (T_n - T_{cw}))}{(C_p (T_n - T_{cw}))} \]

2.7.5 Heat Transfer Area for Brine

The purpose of the brine heater is to heat up the coming flow seawater from the output condenser. The temperature is called top brine temperature.

\[ M_s \lambda_s = M_r C_p (T_o - T_{f1}) \]
\[ M_s = \frac{M_r C_p (T_o - T_{f1})}{\lambda_s} \]

**Area of brine heater, \( A_b \)**

\[ A_b = \frac{M_s \lambda_s}{U_b (LMTD)_b} \]
\[ (LMTD)_b = (T_s - T_o) - (T_s - T_{f1})/\ln((T_s - T_o)/(T_s - T_{f1})) \]

\[ U_b = 1.7194 + 3.2063 \times 10^{-3} T_s + 1.5971 \times 10^{-5} T_s^2 - 1.9918 \times 10^{-7} T_s^3 \]

2.7.6 Heat Transfer Area for Condenser (Heat recovery section)

The assumption for heat transfer area of the condenser in both heat recovery section and heat rejection section is equal for each of the stage.

\[ A_r = \frac{M_r C_p (T_{r1} - T_{r2})}{(U_r (LMTD)_r)} \]
\[ U_r = 1.7194 + 3.2063 \times 10^{-3} T_{v1} + 1.5971 \times 10^{-5} T_{v2}^2 - 1.9918 \times 10^{-7} T_{v3}^3 \]

\[ T_{v1} = T_1 - BPE_1 - NEA_1 - \Delta T_{d1} \]
\[ (LMTD)_r = (T_{v1} - T_{r1}) - (T_{v1} - T_{r2})/\ln((T_{v1} - T_{r1})/(T_{v1} - T_{r2})) \]

BPE = Boiling Point Elevation
NEA = Non-equilibrium allowance
Tv = Condensing vapour
\( \Delta T_{d1} \) = Temperature drop in demister
Ur = Condenser Overall heat transfer coefficient

The correlation equation for BPE, NEA and $\Delta T_{d1}$ can be found in the appendix section.

### 2.7.7 Heat Transfer Area for Condenser (Heat rejection section)

$$A_r = (M_f - M_r)C_p(T_{jn} - T_{aw})/(U_j(LMTD)_j)$$

$$U_j = 1.7194 + 3.2063 \times 10^{-3}T_{vn} + 1.5971 \times 10^{-5}T_{vn}^2 - 1.9918 \times 10^{-7}T_{vn}^3$$

$$T_{vn} = T_n - BPE_n - NEA_n - \Delta T_{dn}$$

$$(LMTD)_j = (T_{vn} - T_{cw}) - (T_{vn} - T_{jn})/\ln((T_{vn} - T_{rn})/(T_{vn} - T_{jn}))$$

Total Heat transfer area for condensers in both heat recovery section and heat rejection section.

$$A_c = (n - j)A_r + (j)A_j$$

### 2.7.8 Dimensions of the Flash Stage Chamber

The dimensions of the stage that need to calculated are as follows: [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]

- Height of brine pool
- Width of stage
- Gate height
- Length of stage

It is important to calculate the stage dimensions because as the height of brine pool must be sufficient enough to prevent any vapour from passing through between stages. The dimensions of the stages is set equal for the whole system. [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]

#### 2.7.8.1 Gate height

$$GH_i = \left( M_r - \sum_{j=1}^{i-1} D_j \right) (2p_{bj} \Delta P_i)^{(-0.5)}/(C_dW)$$

In this configuration the gate height is always set 0.2 higher than brine pool height.

$$H_i = 0.2 + GH_i$$

$$\Delta P_i = P_i - P_{i+1}$$

$$W = M_r/V_b$$
\[ P_i = \text{Pressure in stage 1} \]
\[ P_{i+1} = \text{Pressure in stage } i+1 \]
\[ V_b = \text{Brine mass velocity/chamber} \]

### 2.7.8.2 Length of stage

\[ L = \frac{D_n}{(p_{vn}V_{vn}W)} \]

### 2.7.8.3 Cross section area of flash stage chamber

\[ A_s = LW \]

### 2.7.9 System Performance

To evaluate the system performance, there are few variables that theoretically give big influence to the production of distillate water. The variables are as follows:

- **Thermal performance ratio**
  \[ PR = \frac{M_d}{M_s} \]

- **Specific heat transfer area**
  \[ sA = \frac{(A_b + A_c)}{M_d} \]

- **Specific cooling water flowrate**
  \[ sM_c = \frac{M_{cw}}{M_d} \]
3. Research methods

This research study is based on the case study proposed by [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002], the specification of the multistage flash desalination system was taken from the case study.

3.1 Simulation of Multistage Flash Desalination with Recirculating Brine Plant

In this section the method of applying, testing and evaluating of the model equations of the multistage flash desalination using the software tools will be discussed. The software that is used to simulate the model equation is Aspen Custom Modeler package.

As discussed in the previous section, modeling is a mathematically description of industrial process by a set of equations. The concept used for simulation technique is just by entering the independent process variables value into the software. The objectives of constructing modeling and the simulation are to improve and optimize the existed model equations so that a better understanding on the working principles of the process and a better control of the process can be achieved.

In Aspen Custom Modeler, the real plant has been constructed so that the reading of each of the part in the multistage flash desalination plant can be monitor and check. Figure 11 shows the construction of heat recovery section for the multistage flash desalination plant. This figure represents the real system that can be seen in Figure 12.

Figure 10: Heat Recovery Section of Multistage Flash Desalination Plant with Recycle Brine (Aspen Custom Modeler)
Each of the columns shown in the Figure 11 is the representation of the flash stage chamber of the multistage flash desalination plant, Figure 10. The arrows with numbering mark is the flow of each variable that is available in the plant. This physical interconnections of the flow can be characterized as temperature, salt concentration, pressure and flowrate. These variables are important to calculate other specifications characteristic.
The value of process variables in each of the column can be seen in form of table. The values of the variables in the table can be altered and fixed depending on the requirement and condition of the system. Example of Variables Table can be seen in Table 3.

### Table 3: Table of Variables of stage 1 of heat recovery section

<table>
<thead>
<tr>
<th>Component List</th>
<th>Value</th>
<th>Spec</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cp</strong></td>
<td>4.18</td>
<td>Free</td>
<td>kJ/kg*degree_c</td>
<td></td>
</tr>
<tr>
<td>In_Stage1_Brine.Brine_conc</td>
<td>42000</td>
<td>Free</td>
<td>ppm</td>
<td>Input Brine Concentration</td>
</tr>
<tr>
<td>In_Stage1_Brine.Brine_flow</td>
<td>1000</td>
<td>Free</td>
<td>kg/hr</td>
<td>Input Brine Flow</td>
</tr>
<tr>
<td>In_Stage1_Brine.Brine_temp</td>
<td>25</td>
<td>Free</td>
<td>C</td>
<td>Input Brine temperature</td>
</tr>
<tr>
<td>In_Stage1_Brine.Brine.ComponentList</td>
<td>Default</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In_Stage1_seawater.ComponentList</td>
<td>Default</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In_Stage1_seawater.Recy_Conc</td>
<td>42000</td>
<td>Free</td>
<td>ppm</td>
<td>Input Recycle Seawater Concentration</td>
</tr>
<tr>
<td>In_Stage1_seawater.Recy_Flow</td>
<td>1000</td>
<td>Free</td>
<td>kg/hr</td>
<td>Input Recycle Seawater flow</td>
</tr>
<tr>
<td>In_Stage1_seawater.Recy_Temp</td>
<td>25</td>
<td>Free</td>
<td>C</td>
<td>Input Recycle Seawater temperature</td>
</tr>
<tr>
<td>Latent_av</td>
<td>1</td>
<td>Free</td>
<td></td>
<td>Latent heat average</td>
</tr>
<tr>
<td>Out_Stage1_Brine.Brine_conc</td>
<td>42000</td>
<td>Free</td>
<td>ppm</td>
<td>Output Brine Concentration</td>
</tr>
<tr>
<td>Out_Stage1_Brine.Brine_flow</td>
<td>1000</td>
<td>Free</td>
<td>kg/hr</td>
<td>Output Brine Flow</td>
</tr>
<tr>
<td>Out_Stage1_Brine.Brine_temp</td>
<td>25</td>
<td>Free</td>
<td>C</td>
<td>Output Brine temperature</td>
</tr>
<tr>
<td>Out_Stage1_Brine.Brine.ComponentList</td>
<td>Default</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Out_Stage1_Distl.ComponentList</td>
<td>Default</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Out_Stage1_Distl.Distl_conc</td>
<td>42000</td>
<td>Free</td>
<td>ppm</td>
<td>Output Distillate concentration</td>
</tr>
<tr>
<td>Out_Stage1_Distl.Distl_Flow</td>
<td>1000</td>
<td>Free</td>
<td>kg/hr</td>
<td>Output Distillate Flow</td>
</tr>
<tr>
<td>Out_Stage1_Distl.Distl_temp</td>
<td>25</td>
<td>Free</td>
<td>C</td>
<td>Output Distillate temperature</td>
</tr>
<tr>
<td>Out_Stage1_seawater.ComponentList</td>
<td>Default</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Out_Stage1_seawater.Recy_Conc</td>
<td>42000</td>
<td>Free</td>
<td>ppm</td>
<td>Output Recycle Seawater concentration</td>
</tr>
<tr>
<td>Out_Stage1_seawater.Recy_Flow</td>
<td>1000</td>
<td>Free</td>
<td>kg/hr</td>
<td>Output Recycle Seawater flow</td>
</tr>
<tr>
<td>Out_Stage1_seawater.Recy_Temp</td>
<td>25</td>
<td>Free</td>
<td>C</td>
<td>Output Recycle Seawater Temperature</td>
</tr>
</tbody>
</table>
The full design of the multistage flash desalination plant is shown in the flowsheet of the Aspen Custom Modeler. This simulation model of multistage flash desalination plant is made of three different sections with related mathematical model equations. The different sections are called:

- Brine Heater
- Heat recovery section
- Heat rejection section

*Figure 13: Full Simulation design of Multistage Flash Desalination with Recycle Brine (Aspen Custom Modeler)*
In each of the hierarchy block there are 4 flash stage chambers so that the test on different number of stages can be done easily just by adding and removing the hierarchy block. The concept of hierarchy is also used to make the flow sheet more neat and less crowded when the testing is required as a big number of stages.

3.2 Project Specification

Based on the case study discussed in the reference, there are a few variables that are given and fixed when the process is on running. The MSF system specification is as follows: [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]

- The system has 24 stages.
- It produces 7.2 million gallons per day (MGD) of product water.
- There are 21 stages in the recovery section.
- There are 3 stages in the rejection section.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake seawater temperature</td>
<td>$T_{cw}$</td>
<td>25</td>
<td>°C</td>
</tr>
<tr>
<td>Steam temperature</td>
<td>$T_s$</td>
<td>116</td>
<td>°C</td>
</tr>
<tr>
<td>Top brine temperature</td>
<td>$T_o$</td>
<td>106</td>
<td>°C</td>
</tr>
<tr>
<td>Brine temperature (Last Stage)</td>
<td>$T_n$</td>
<td>40</td>
<td>°C</td>
</tr>
<tr>
<td>Heat capacity of liquid streams</td>
<td>$C_p$</td>
<td>4.18</td>
<td>kJ/kg°C</td>
</tr>
<tr>
<td>Salinity of intake seawater</td>
<td>$X_f$</td>
<td>42000</td>
<td>ppm</td>
</tr>
<tr>
<td>Salinity of brine blow down</td>
<td>$X_b$</td>
<td>70000</td>
<td>ppm</td>
</tr>
<tr>
<td>Vapour velocity (last stage)</td>
<td>$V_{vn}$</td>
<td>6</td>
<td>m/s</td>
</tr>
<tr>
<td>Brine mass flow rate per stage length width</td>
<td>$V_b$</td>
<td>180</td>
<td>Kg/ms</td>
</tr>
<tr>
<td>Weir friction coefficient</td>
<td>$C_d$</td>
<td>0.5</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4: Variables Parameter [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]

Based on this specifications, the value of variables in the table of variables is updated according to the value stated in Table 5.
3.3 Simulation of Steady State condition using Aspen Custom Modeler

3.3.1 Description of Aspen Custom Modeler

By using Aspen Custom modeler it is easy to create a model of plant and process according to the desired design. This software is very flexible to customize and it can run in several modes like steady state and dynamic. This Aspen Custom Modeler is not only good at simulation but it can also provide other tasks such as generating custom graphical, estimating and optimization and interfacing results.

The manual on how to create model using Aspen Custom Modeler can be found in appendix section.

Table 5: Comparison between the reference data and Aspen Custom Modeler data

<table>
<thead>
<tr>
<th>Operating Parameters</th>
<th>[Hisham T.El-Dessouky &amp; Hisham M.Ettouney, 2002]</th>
<th>ACM data</th>
<th>Deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Stages</td>
<td>24</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>Mf (kg/s)</td>
<td>947</td>
<td>947.2</td>
<td>0.021114865</td>
</tr>
<tr>
<td>Tf (°C)</td>
<td>25</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>Ms (kg/s)</td>
<td>52.52</td>
<td>52.43</td>
<td>-0.171657448</td>
</tr>
<tr>
<td>Ts (°C)</td>
<td>116</td>
<td>116</td>
<td>0</td>
</tr>
<tr>
<td>Xf (ppm)</td>
<td>42000</td>
<td>42000</td>
<td>0</td>
</tr>
<tr>
<td>TBT (°C)</td>
<td>106</td>
<td>106</td>
<td>0</td>
</tr>
<tr>
<td>T_brine(1) (°C)</td>
<td>103.25</td>
<td>103.25</td>
<td>0</td>
</tr>
<tr>
<td>T_cond(1) (°C)</td>
<td>97.75</td>
<td>97.75</td>
<td>0</td>
</tr>
<tr>
<td>Md (kg/s)</td>
<td>378.8</td>
<td>378.8</td>
<td>0</td>
</tr>
<tr>
<td>T_vn (°C)</td>
<td>37</td>
<td>37.4</td>
<td>1.069518717</td>
</tr>
<tr>
<td>sA (m^2/(kg/s))</td>
<td>259.6</td>
<td>257.3</td>
<td>-0.893898173</td>
</tr>
<tr>
<td>X(1)</td>
<td>62474</td>
<td>62479.1</td>
<td>0.00816273</td>
</tr>
<tr>
<td>PR</td>
<td>7.21</td>
<td>7.23</td>
<td>0.276625173</td>
</tr>
</tbody>
</table>
Once the data of the plant specification has been put into the table of variables, a simulation was performed to obtain results from the table. The results gained is compared with the result from the reference to ensure that the operation of the flowsheet is according to the case study expectation. The evaluation data is shown in Table 6.

To evaluate the results, a stage profiles of the multistage flash desalination plant is created. In this stage profile, the values of important process variables in each of the flash stage chamber has been obtained from the simulation and presented in the table. The process variables included in the table are as follows:

- Distillate product flowrate, \( D \)
- Brine flowrate, \( B \)
- Temperature of brine, \( T_b \)
- Temperature of seawater at condenser, \( T_c \)
- Pressure at flash stage chamber, \( P \)
- Brine concentration, \( X \)
- Gate Height, \( GH \)
- Brine pool height, \( H \)

By creating this stage profiles, it is easier to check any changes to the process variables if changes is applied to one of the variables. The studies of efficiency of the model are mostly done on the effect of the number of stages, effect of the top brine temperature to any of the variable and variables that mostly affect the performance ratio of the system.

The stage profiles of the multistage flash desalination plant can be seen in Table 6.
Table 6: Stage profiles of the Multistage Flash Desalination Plant

<table>
<thead>
<tr>
<th>Stage/Unit</th>
<th>D</th>
<th>ΣD</th>
<th>B</th>
<th>T_b</th>
<th>T_c</th>
<th>T_vapor</th>
<th>P</th>
<th>X</th>
<th>GH</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg/s</td>
<td></td>
<td>ppm</td>
<td>°C</td>
<td>°C</td>
<td>°C</td>
<td>kPa</td>
<td>ppm</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>1</td>
<td>16.6972</td>
<td>16.6972</td>
<td>3367.92</td>
<td>103.25</td>
<td>97.75</td>
<td>103.338</td>
<td>113.624</td>
<td>62479.1</td>
<td>0.08496</td>
<td>0.28496</td>
</tr>
<tr>
<td>2</td>
<td>16.6148</td>
<td>33.312</td>
<td>3351.3</td>
<td>100.5</td>
<td>95</td>
<td>100.584</td>
<td>103.118</td>
<td>62788.9</td>
<td>0.08853</td>
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</tr>
<tr>
<td>3</td>
<td>16.5329</td>
<td>49.8449</td>
<td>3334.77</td>
<td>97.75</td>
<td>92.25</td>
<td>97.8291</td>
<td>93.4295</td>
<td>63100.2</td>
<td>0.09232</td>
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<tr>
<td>4</td>
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<td>66.2962</td>
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<td>94.5086</td>
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<td>82.6664</td>
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<td>86.75</td>
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<td>98.9558</td>
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<td>70.25</td>
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<td>0.33341</td>
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<td>67.5</td>
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<td>67.5</td>
<td>62</td>
<td>67.5019</td>
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<td>0.35572</td>
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<td>42.75</td>
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<td>49.2959</td>
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<td>3035.69</td>
<td>45.5</td>
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<td>3020.72</td>
<td>42.75</td>
<td>35</td>
<td>42.6883</td>
<td>43.7131</td>
<td>69645.7</td>
<td>0.27488</td>
<td>0.47488</td>
</tr>
<tr>
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<td>378.7998</td>
<td>3005.82</td>
<td>40</td>
<td>30</td>
<td>39.9336</td>
<td>40.9858</td>
<td>70000</td>
<td>0.27488</td>
<td>0.47488</td>
</tr>
</tbody>
</table>
4. Results and Discussion

4.1 Results from Aspen Custom Modeler

4.1.1 The effect of number of stages

Based on Figure 14: The increasing number of flash stage chamber will cause the performance ratio of the system to increase. The increase of top brine temperature has effects on the system performance ratio but the temperature drops per stages will decrease as the number of stages increases. The flashing range is depended on the top brine temperature, the higher the top brine temperature the higher the production of distillate water per unit mass of heating steam. [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]

Based on Figure 15: It is noted that, the calculations for total production rate has been kept on constant. As the number of stages increases, the specific heat transfer area also increases but for the top brine temperature, the lower the value of top brine temperature, the higher the specific heat transfers area. When the operation of the system is at low top brine temperature, it will reduce the heat transfer coefficient. [Hisham T.El-Dessouky & Hisham M.Ettouney, 2002]
**Figure 15:** Effect of number of stages to the specific heat transfer area

**Figure 16:** Effect of number of stages to the specific flowrate of cooling seawater
Based on Figure 15: The changing in top brine temperature has almost no effect to the specific cooling water flow rate but when the number of stages increases, the specific flow rate cooling seawater is increased. This could be the reason for the results obtained in Figure 15, where to keep the constant production of distillate product, the system need to use a small amount of heating steam. As the amount of heating steam is reduced, the amount of heat energy added to the system will decrease and causes the removal of heat energy removed by the cooling seawater to decrease. [Hisham T.EL-Dessouky & Hisham M.Ettouney, 2002]

Based on Figure 16: The specific flow rate of recirculating brine is decreasing as the temperature of the top brine increases. This will cause the increasing in the system efficiency.

4.1.2 The effect of Top Brine Temperature

![Top Brine Temperature vs Performance Ratio](image)

*Figure 17: Effect of Top Brine temperature to the performance ratio*

Based on Figure 17: The increase top brine temperature and number of stages slightly increases the performance ratio of the system. The range of top brine temperature is tested from 90°C to 110°C while the number of stages is changing from 18, 22 to 27. The system must use higher top brine temperature in order to get good production of distillate water.
4.2 Discussion on the role of variables to the system and its effect on the system.

4.2.1 Top Brine Temperature

The top brine temperature is the most important variable that can extremely affect the performance ratio (PR) of a multistage flash desalination plant. Performance ratio is the ratio between total flow rates of product produced (located at the end of the flash stage chamber) to the flow rate of steam used on the brine heater section. There is limitation on raising the top brine temperature to a certain value due to scaling issues. As the solution to increase the top brine temperature to a desired value, some chemicals need to be added to the feed seawater as pretreatment before it enters the multistage flash desalination system. The upper limit temperature of top brine temperature can be from 90 °C to 121 °C depending on the type of chemical used. In general, top brine temperature used in industry only up to 110 °C. Top brine temperature must be operated in certain limit, if the temperature value used is below the limit it will cause an incomplete extraction of non-condensable gases due to insufficient pressure different to the vent condenser. This condition may lead to instability and corrosion problem. Usually this top brine temperature is fixed for the entire process. [Khawla AbdulMohsen Al-Shayji, 1998]

The changes in temperature of brine at the last flash stage chamber will affect the inter-stage temperature differences and directly causes the changes in pressure in each of the flash stage
chamber. As a result from the changes of those two variables will cause changes to the brine flow along the inter-stage. The only solution to fix back the brine flow to its original condition is by adjusting the orifices. Manually changing the brine flow from the source (adjusting the pump) is not the solution because other variable will be affected by these changes such as the output of evaporator. [Khawla AbdulMohsen Al-Shayji, 1998]

4.2.2 Feed Seawater Flow rates
The flow of feed seawater into the system is depending on the ambient temperature, if the ambient temperature decreases the flow of seawater also needs to be reduced. This is to maintain the output temperature of seawater at the rejection section. [ETD] There is a minimum requirement for the velocity and temperature of the seawater before it can enters heat-rejection section. So in winter seasons, part of reject cooling water coming out from heat-rejection section is recycled back to mix the feed seawater stream. The limitation of the velocities is as follows: [Khawla AbdulMohsen Al-Shayji, 1998]

Table 7: The limitation of the velocities

<table>
<thead>
<tr>
<th>Velocities of seawater</th>
<th>Restricted by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower limit</td>
<td>Requirement of specific rate of evaporation in the heat-rejection section</td>
</tr>
<tr>
<td>Upper limit</td>
<td>Capability of the supply pump.</td>
</tr>
</tbody>
</table>

4.2.3 Recirculating Brine Flowrate
Another important variable after top brine temperature is recirculating brine flow rate. This variable can give a big impact on the system performance ratio. As the recirculating brine increases, the production of distillate product also increases. The changes happen in recirculating brine flow rate can also influence the brine flow inside the condenser tube. [Khawla AbdulMohsen Al-Shayji, 1998]

Changes in flow rate can directly affect the production of distillate water and the thermal efficiency. The degree of fouling to occur is depending on the recirculating brine flow rate. If the value of recirculating brine flow rate is decreasing, there will be a decrease in scouring of deposits in the tube surfaces and the potential of fouling to occur is high. [Khawla AbdulMohsen Al-Shayji, 1998]

The recirculating brine flow rate also have the upper limit and lower limit for the system. The stability and efficiency of this multistage flash desalination system with recirculating brine will be disturbed if the flow of recirculating brine is too slow but if the flow of recirculating brine is too fast, flooding can happen in the system and might contaminate the product. [ETD] But if the flow of recirculating brine...
is too fast, flooding can happen in the system and might contaminating the product. When the distillate product has been contaminated by floods, the salinity of the product will increase and it will take a long period of time to reduce it back the salinity percentage to an acceptable value. [Khawla AbdulMohsen Al-Shayji, 1998]

4.2.4 Inlet and Outlet Temperature of Cooling-Seawater

Flash range is the difference between cooling-seawater inlet temperature to the heat-rejection section and the top brine temperature. This flash range is very important as it determines the efficiency of the multistage flash desalination plant. The higher the seawater temperatures, the smaller the flash ranges. This condition will be used to determine the design of heat transfer area and the recirculating brine. Thermodynamic of the evaporator will change if the temperature of seawater is too low. As the saturation pressure is decreasing, the evaporator pressure also decreases. As the effect from these changes, the pressure drops between stages will also drop. [Khawla AbdulMohsen Al-Shayji, 1998]

This cooling-seawater is recycled back to mix with the inlet feed seawater only when the ambient temperature is too low especially during the winter season. The purpose of recycling cooling water is to raise the inlet seawater temperature. Depending on the recycled seawater flow to keep inlet seawater temperature constant might not be possible as the temperature will always drop during winter season. [Khawla AbdulMohsen Al-Shayji, 1998]

4.2.5 Orifice Height (The inter-stage Brine Transfer Design)

The orifice height in every multistage flash desalination plant plays an important role. Every efficient orifice height should be able to give a smooth brine flow, mixing up the brine by turbulence which also will reduce the unsteady-state losses and provide smooth vapor flow through the demister by avoiding the brine from splashing on the demister. The configuration of the orifice could cause many problems in the multistage flash desalination plant such as: [Khawla AbdulMohsen Al-Shayji, 1998]

Table 8: Problem and Cause in the configuration of the orifice

<table>
<thead>
<tr>
<th>Problem</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapor blowing-through into subsequent stages</td>
<td>Over-sized orifices</td>
</tr>
<tr>
<td>High brine level</td>
<td>Under-sized orifices</td>
</tr>
<tr>
<td>Instability</td>
<td>Improper brine-level setting</td>
</tr>
</tbody>
</table>
4.2.6 Flash Stage Chamber

In every flash stage chamber, there are some parts that are commonly found in every multistage flash desalination plant. Each of the part has its own function that plays an important role to provide good operation and maintaining the flashing performance. As shown in Figure 8, each of the flash stage chamber should consist of: [Hala Faisal Al-Fulaij, 2011]

1. **The Demister**

   The flashed vapour that formed in the flash stage chamber has entrained brine droplets in it and this can cause the salinity of distillate product to increase and make it less quality than expected. So it is important to eliminate or at least minimize the effect of this entrained brine droplets from affect the distillate product. The demister is specifically designed to overcome this problem. [Hala Faisal Al-Fulaij, 2011]

2. **The Condenser or preheater tubes (Tube Bundles)**

   The condensation of flashed off vapour is happening on the outer surface of the condenser or preheater. The brine that flow through the condenser tube receives the latent heat that is released from the condensation process. This is called heat energy recovery and it is important for the whole plant so it can maintain the system performance at its very best. While designing this condenser or preheater, the engineer should take consideration of the heat transfer area of the condenser as it plays an important role in controlling: [Hala Faisal Al-Fulaij, 2011]

   - the temperature of the brine that flows into the brine heater
   - the condensation temperature of the vapour
   - the pressure inside the flash stage chamber

   Too high heat transfer area will increase the potential of fouling process to happen due to decreasing in brine recycle velocity in the condenser tube. Nevertheless, the heat transfer area is too small it will cause high velocity of brine and low energy recovery. [Hala Faisal Al-Fulaij, 2011]

3. **Distillate tray**

   This is where the product of distillate water is collected throughout the entire plant. The final product is located at the last stage of flash chamber. The location of distillate tray is located under the condenser tube. [Hala Faisal Al-Fulaij, 2011]

4. **Ventilation System**

   The seawater contains air and dissolved gas such as oxygen, nitrogen and carbon dioxide. These gases are needed to be removed before the seawater enters the flash stage chamber. These gases could affect the heat transfer rate around the condenser due to the low thermal connectivity of the gases.
The existent of carbon dioxide and oxygen in the plant are also very dangerous as these gases could promote corrosion in any location in the system. So a device called deaerator is implemented in the plant to remove all of these gases. There is ventilation system, which is located at the coolest point of each of the flashing stage chamber which functions to venting all the unnecessary gases out from the plant. [Hala Faisal Al-Fulaij, 2011]

![Schematic Diagram of Flash Stage Chamber](image)

**Figure 19: Schematic Diagram of Flash Stage Chamber [12345]**

### 4.2.7 Performance of the Multistage Flash Desalination System

To evaluate the performance ratio of the system, first the variables that mostly give big impacts to the production has been determined. The process efficiency is the measurement of thermal performance ratio. Where the higher the ratio, the larger the rate of production per heating steam flowrate. The variables that affect the production of distillate are as follows [Hisham T.El-Dessouky and Hisham M.Ettouney, 2002]

- Specific heat transfer area, Temperature profiles (feed seawater flow and flashing brine) and Thermal performance ratio

Besides thermal performance ratio, the specific heat transfer area also gives impacts to the systems performance. As the testing range of specific heat transfer area is done between 200 to 300 m^2/(kg/s). In order to maintain the rate production at constant value the heating steam flowrate need to be increased. [Hisham T.El-Dessouky and Hisham M.Ettouney, 2002]
4.3 Introduction of Internal Design (Demister)
As mentioned in the previous section, the function of demister is to remove or at least reduce the effect of entrained liquid in the flashing vapour so that it will not affect the salinity of the distillate product. There are various types of demister like vane pack, coalesce and mesh. The types of demister that is referred in this thesis are the wire mesh type demister. Most of the demister installation are horizontally against the vertical movement of flashing vapour. The performance of wire mesh demister is depending on the: [Obeid F, Janajreh I, Chaouki Ghenai, 2014]

- Vapour Velocity
- Packing density
- Wire diameter
- Thickness

4.3.1 Experiment on the effect of demister
The experiment on the demister has been done in terms of the effect of the demister when the system is run with or without the demister. Theoretically, when there is no demister in the system as what been done in the previous section, the velocity of vapour formed in the flash stage chamber is fast as there is no resistance. By adding the demister, there should be reducing in vapour velocity and this could affect the distillate product. This entire hypothesis should be answered in the discussion side.

The specification of the demister was introduced by the [Hisham T.El-Dessouky and Hisham M.Ettouney, 2002].

*Table 9: Demister Specification Range (Experiments)*

<table>
<thead>
<tr>
<th>Experimental Variable</th>
<th>Range of testing</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top brine temperature, TBT</td>
<td>100 – 106</td>
<td>°C</td>
</tr>
<tr>
<td>Vapour Velocity, V</td>
<td>0.98 – 7.5</td>
<td>m/s</td>
</tr>
<tr>
<td>Demister Pressure Drop, Pp</td>
<td>80.317 – 208.16</td>
<td>Kg/m^2</td>
</tr>
<tr>
<td>Mesh Pad Thickness, L</td>
<td>100 – 200</td>
<td>mm</td>
</tr>
<tr>
<td>Wire Diameter, δw</td>
<td>0.2 – 32</td>
<td>mm</td>
</tr>
<tr>
<td>Diameter of entrained droplets, dd</td>
<td>1 - 5</td>
<td>mm</td>
</tr>
</tbody>
</table>
In the previous section, the effects of temperature dropping in the demister for condensing vapour temperature, $T_v$, at flash stage chamber is assumed negligible but for this experiment, the value of temperature in the demister is taken into account so that the changing in variables can be observed. The equation is as follow:

**Condensing Vapour Temperature at Stage 1**

$$T_{v1} = T_1 - BPE_1 - NEA_1 - \Delta T_{d1}$$

4.3.2 Result of demister effect.

The test of demister performance has been done on the pressure drop around the demister by the effect of changing in the vapour velocity. The pressure drop is increasing as the vapour velocity is increasing. But for this experiment the performance of demister only been tested on these two variables. For more details performance of demister the other elements of demister should be consider like the length of wire mesh, the condition of the demister (wet or dry), demister thickness and other.

As there is pressure drop in each of the stages, it has caused the drop in the heat transfers area in the system. Figure 20 shows the effect of demister to the heat transfer area in each of the stages as the system run with and without demister.
4.3.3 The effect of demister to the System

![Graph showing the effect of demister on heat transfer area]

*Figure 20: The Effect of demister on the heat transfer area*
5. Conclusion

This major part of this thesis was mostly focusing in the programming part. At first the mathematical model equations for the multistage flash desalination with recycle brine are taken and studied from the reference. Some assumptions that introduced by reference has been taken into consideration as the model was been transferred into the Aspen Custom Modeler. Some major assumptions are as follows:

- Salt free in the distillate product
- No heat loss from the plant
- Negligible effect of superheating and subcooling to the energy balance

In term of programming, it was quite challenging to understand how the software working. This is because lack in knowledge and zero experience. But problem on the software understanding was slowly been solved by study the manual handbook and working with some examples. By putting the equations alone will not make the programming work as what is desired. The variables like temperature, flow rate, latent heat and concentration need to be defined properly. There are special commands like every other programming software so that the equation that been put can be connected to other variables or equations.

Simulation by Aspen Custom Modeler is so simple. The value of each variables that been defined in the programming will pop up in the table of variables. This value can be change into any value that is desired. Once the value is selected, then simulation can be done in four different modes which are Steady State, Dynamic, Initialization and Optimization.

Based on the study on the relationship between the operational variables, the variables that mostly affect the efficiency of the multistage flash desalination system are the top brine temperature and number of stages. As the value of top brine temperature is increasing, there will be increasing in the performance ratio. Even though there is decreasing in the specific condensing area, but it not give a big effect on the energy balance. When the number of stages is increasing, the pressure drop in each stage will reduce as there is reduction in condenser and energy losses in flashing stage, but the thermal performance is increasing. This condition will cause increasing in the system performance.
6. Future Works

This scopes of this thesis only covers the efficiency of the mathematical model of the multistage flash desalination with the recycle brine, this mathematical model was developed by [Hisham T. El-Dessouky & Hisham M. Ettouney, 2002]. The performance results gained are limited to the concept of the model when it has been developed and the assumptions which have been made.

There are some suggestions for the future work.

1. Steady state is based on simplified physio-chemical representation of the process, but to get better information on the system a detailed model is preferred. A simulation could be done with the same concept as what has been done in this thesis to the dynamic model of multistage flash desalination with recycling brine. Then the comparison between steady state and dynamic model can be done in terms of desalination efficiency. [Said Alforjani R. Said, 2012]. Non-condensable gases like \( N_2, CO_2 \) and \( O_2 \) are serious problem for multistage flash desalination plant. But for this thesis, the effect of non-condensable gases is assumed negligible to the mass and energy balance of the system. These gases were present in the multistage flash desalination plant, it would cause:
   - Decrease in system efficiency
   - Reduction of performance
   - Increasing in cost especially thermal desalination units.

Therefore by including in the model equation the correlations representing the effect of non-condensable gases to the mass and energy balances, the study of efficiency of mathematical model equation for multistage flash desalination plant could be more accurate. [Said Alforjani R. Said, 2012]

2. The study also can be widen by studying the fouling factor of calcium carbonate. A steady state model of multistage flash desalination plant can be developed by varying calcium carbonate fouling in the heat rejection section, heat recovery section and brine heater. [Said Alforjani R. Said, 2012]

3. In term of internal design effect to the system efficiency, the part that covered in this thesis is only on the demister effect. There are more variables to be considered while do testing on this design as the result gained is not really showing the ability of this demister on system efficiency. [Said Alforjani R. Said, 2012]
7. Bibliography

8. Appendix A: Aspen Custom Modeler (Flowsheet)

*Figure 21: Flowsheet of Multistage Flash Desalination - Hierarchy Expanded for Recovery Section (Aspen)*
Figure 22: Flowsheet of Multistage Flash Desalination - Hierarchy Expanded for Rejection Section (Aspen)
Figure 23: Heat Rejection Section of Multistage Flash Desalination with recycle brine (Aspen Custom Modeler)
Figure 24: Aspen Custom Modeler File Directory
### Figure 25: Table of Variable for Heat Recovery Section of Multistage Flash Desalination (Aspen Custom Modeler)

<table>
<thead>
<tr>
<th>Component/Variable</th>
<th>Value</th>
<th>Units</th>
<th>Spec</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cp</td>
<td>4.18</td>
<td>kg/mole*degree_C</td>
<td>Fixed</td>
<td></td>
</tr>
<tr>
<td>In_Stag1_Brine</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In_Stag1_Brconc</td>
<td>62105.7</td>
<td>ppm</td>
<td>Fixed</td>
<td></td>
</tr>
<tr>
<td>In_Stag1_BrineF0</td>
<td>3384.3</td>
<td>kg/s</td>
<td>Fixed</td>
<td></td>
</tr>
<tr>
<td>In_Stag1_BrineF1</td>
<td>105.0</td>
<td>C</td>
<td>Free</td>
<td></td>
</tr>
<tr>
<td>In_Stag1_seawater</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In_Stag1_seawaterReyConc</td>
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<td>ppm</td>
<td>Free</td>
<td></td>
</tr>
<tr>
<td>In_Stag1_seawaterReyF0</td>
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<td>Free</td>
<td></td>
</tr>
<tr>
<td>In_Stag1_seawaterReyF1</td>
<td>95.0</td>
<td>C</td>
<td>Free</td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>3.9</td>
<td></td>
<td>Free</td>
<td>Need to be updated every time</td>
</tr>
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<td>Latent</td>
<td>2330.1</td>
<td></td>
<td>Fixed</td>
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</tr>
<tr>
<td>M_d</td>
<td>376.8</td>
<td>kg/s</td>
<td>Fixed</td>
<td>Flow rate of final product</td>
</tr>
<tr>
<td>M_r</td>
<td>3384.3</td>
<td>kg/s</td>
<td>Free</td>
<td>Flow rate of return flashed brine</td>
</tr>
<tr>
<td>N</td>
<td>24.8</td>
<td></td>
<td>Free</td>
<td>No of stages</td>
</tr>
<tr>
<td>Out_Stag1_Brine</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Out_Stag1_Brconc</td>
<td>62105.7</td>
<td>ppm</td>
<td>Free</td>
<td></td>
</tr>
<tr>
<td>Out_Stag1_BrineF0</td>
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<td>kg/s</td>
<td>Free</td>
<td></td>
</tr>
<tr>
<td>Out_Stag1_BrineF1</td>
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<td>C</td>
<td>Free</td>
<td></td>
</tr>
<tr>
<td>Out_Stag1_BrineRey</td>
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<td>Out_Stag1_seawater_reconc</td>
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<td>ppm</td>
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<tr>
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<td>kg/s</td>
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<td>Out_Stag1_seawaterReyF1</td>
<td>97.75</td>
<td>C</td>
<td>Free</td>
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</tr>
<tr>
<td>Qdtst1</td>
<td>16.697</td>
<td>kg/s</td>
<td>Free</td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>103.25</td>
<td>C</td>
<td>Free</td>
<td>Temperature of Brine at stage 1</td>
</tr>
<tr>
<td>T2</td>
<td>100.5</td>
<td>C</td>
<td>Free</td>
<td>Temperature of Brine at stage 2</td>
</tr>
<tr>
<td>TAv</td>
<td>73.0</td>
<td>C</td>
<td>Free</td>
<td>Average Temperature (Degree C)</td>
</tr>
<tr>
<td>T3</td>
<td>40.0</td>
<td>C</td>
<td>Fixed</td>
<td>Temperature Brine last stage (Degree C)</td>
</tr>
<tr>
<td>T11</td>
<td>106.0</td>
<td>C</td>
<td>Fixed</td>
<td>Top Brine Temperature (Degree C)</td>
</tr>
<tr>
<td>T12</td>
<td>97.75</td>
<td>C</td>
<td>Free</td>
<td>Temperature of seawater leaving condenser at stage 1</td>
</tr>
<tr>
<td>T12</td>
<td>95.0</td>
<td>C</td>
<td>Free</td>
<td>Temperature of seawater leaving condenser at stage 2</td>
</tr>
<tr>
<td>T12</td>
<td>2.75</td>
<td>C</td>
<td>Free</td>
<td>Temperature Drop at stage</td>
</tr>
<tr>
<td>x</td>
<td>0.0493328</td>
<td></td>
<td>Free</td>
<td>Specific rate of sensible heat and latent heat</td>
</tr>
</tbody>
</table>
**Figure 26: Table of Variable for Heat Rejection Section of Multistage Flash Desalination (Aspen Custom Modeler)**

<table>
<thead>
<tr>
<th>Component/AllVariables</th>
<th>Value</th>
<th>Units</th>
<th>Spec</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cp</td>
<td>4.16</td>
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<td>Fixed</td>
<td>Stage no rejection section</td>
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<tr>
<td>b Last RefIn_Brine_conc</td>
<td>24.0</td>
<td>ppm</td>
<td>Free</td>
<td></td>
</tr>
<tr>
<td>p Last RefIn_Brine_flow</td>
<td>0.21657</td>
<td>kg/m</td>
<td>Free</td>
<td></td>
</tr>
<tr>
<td>b Last RefIn_Brine_Temp</td>
<td>42.75</td>
<td>°C</td>
<td>Free</td>
<td></td>
</tr>
<tr>
<td>h Last RefIn_BrineComponentList</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>b Last RecySeawater_ComponentList</td>
<td>Default</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b Last RecySeawater_ReFeed_Conc</td>
<td>42900.0</td>
<td>ppm</td>
<td>Fixed</td>
<td></td>
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<tr>
<td>p Last RecySeawater_ReFeed_Flow</td>
<td>947.0</td>
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<td>h Last RecySeawaterComponentList</td>
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<td>ppm</td>
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<td>Fixed</td>
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<td>°C</td>
<td>Free</td>
<td></td>
</tr>
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<td>iTemp</td>
<td>25.0</td>
<td>°C</td>
<td>Fixed</td>
<td>Temperature of inlet feed of stage Last</td>
</tr>
<tr>
<td>j</td>
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<td>Fixed</td>
<td>No of rejection sections</td>
</tr>
<tr>
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<td>Fixed</td>
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<td>kg/s</td>
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<td>Flow rate of return flashing brine</td>
</tr>
<tr>
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<td>ppm</td>
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<td>Free</td>
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<td>Free</td>
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<td>Free</td>
<td></td>
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<tr>
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<td>ppm</td>
<td>Free</td>
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</tr>
<tr>
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<td>kg/m</td>
<td>Free</td>
<td></td>
</tr>
<tr>
<td>Out Last_Rein_SeaWater_Feed_Temp</td>
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<td>°C</td>
<td>Free</td>
<td>out datilate at first of rejection section</td>
</tr>
<tr>
<td>T_dv</td>
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<td>kg/s</td>
<td>Free</td>
<td></td>
</tr>
<tr>
<td>T_cv</td>
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<td>°C</td>
<td>Free</td>
<td>Average Temperature (Degree C)</td>
</tr>
<tr>
<td>T_Ilast</td>
<td>25.0</td>
<td>°C</td>
<td>Fixed</td>
<td>Temperature of intake seawater</td>
</tr>
<tr>
<td>T_last</td>
<td>30.0</td>
<td>°C</td>
<td>Fixed</td>
<td>Temperature of seawater leaving last condenser</td>
</tr>
<tr>
<td>T_Reject</td>
<td>40.0</td>
<td>°C</td>
<td>Fixed</td>
<td>Temperature of brine at stage Last</td>
</tr>
<tr>
<td>T_Reject_D Sultan_Temp</td>
<td>40.0</td>
<td>°C</td>
<td>Fixed</td>
<td>Temperature of mixture in last stage (Degree C)</td>
</tr>
<tr>
<td>T_Reject</td>
<td>106.0</td>
<td>°C</td>
<td>Fixed</td>
<td>Top Brine Temperature (Degree C)</td>
</tr>
<tr>
<td>TDS_Reject</td>
<td>2.75</td>
<td>°C</td>
<td>Fixed</td>
<td>Top Brine Temperature (Degree C)</td>
</tr>
<tr>
<td>TDS_Reject</td>
<td>5.0</td>
<td>°C</td>
<td>Free</td>
<td>Temperature drop at stage</td>
</tr>
<tr>
<td>TDS_Reject</td>
<td>2.75</td>
<td>°C</td>
<td>Fixed</td>
<td>Temperature drop at stages in rejection sections</td>
</tr>
<tr>
<td>X_b</td>
<td>719900.0</td>
<td>ppm</td>
<td>Fixed</td>
<td>Brine concentration (fixed)</td>
</tr>
<tr>
<td>X_r</td>
<td>62.1857</td>
<td>ppm</td>
<td>Free</td>
<td>Recycle brine concentration</td>
</tr>
<tr>
<td>y</td>
<td>0.00493526</td>
<td>%</td>
<td>Free</td>
<td>Specific ratio of sensible heat and latent heat</td>
</tr>
</tbody>
</table>
9. Appendix B: Aspen Custom Modeler (Code)

```plaintext
// Model - Brine Heater
n as Real30 (description:"No of stages", value:24, spec:Fixed);
M_A as Flow_rate (description:"Flow rate of final product", value:379.8, spec:Fixed);
T_0 as temperature (description:"Top Brine Temperature (Degree C)", value:60, spec:Fixed);
T_L as temperature (description:"Temperature Brine last stage (Degree C)", value:60, spec:Fixed);
Q as heatCapacity (value:4.18, spec:Fixed);
Latent_t as Real30 (description:"Latent heat from correlation, table", spec:fixed);
T_IN as temperature (description:"Temperature Drop at stage ", spec:fixed);
T_AV as temperature (description:"Average Temperature (Degree C)", spec:fixed);
y as ratio (description:"Specific ratio of sensible heat and latent heat", spec:fixed);
T_L as temperature (description:"Temperature of steam (Degree C)", value:116, spec:fixed);

// Latent heat correlation

Temp_steam as temperature (description:"Temperature of steam", value:116, spec:fixed);
Latent_s as Real30 (description:"Latent heat of steam", spec:fixed);

Latent_t = 2501.987149 - ( ( 2.4070649734947 * ( T_ST ) ) + ( ( 1.39211710^-3 ) * ( T_ST ) ) ) - ( ( 0.563310^-3 ) * ( T_ST ) ) ;
Latent_av = 2501.987149 - ( ( 2.4070649734947 ) *( Temp_steam ) + ( ( 1.39211710^-3 ) * ( Temp_steam ) ) ) - ( ( 0.563310^-3 ) * ( Temp_steam ) ) ;

// the calculated value might be different from references, but already confirmed that calculated value is correct... just proceed...

// 1. Temperature Drop in each stage
TDD_Each = ( T_0 - T_N ) / n ;

// 2. Average Temperature
T_AV = ( T_0 + T_N ) / 2 ;

// 3. Specific ratio of sensible heat and latent heat
y = CP*TDD_Each/Latent_av ;

// Flow rate of return flashing brine M_r
M_r as Flow_rate (description:"Flow rate of return flashing brine", spec:Fixed);
M_r = M_0 / ( 1 - ( y ) ) ;

// Input/Output variables
In_Brige as Input BrineStream ;
Out_Brige as Output BrineStream ;
```

Figure 27: Brine Heater Coding Part 1 (Aspen Custom Modeler)
Figure 28: Brine Heater Coding Part 2 (Aspen Custom Modeler)
Figure 29: Heat Recovery Section Coding Part 1 (Aspen Custom Modeler)
Figure 30: Heat Recovery Section Coding Part 2 (Aspen Custom Modeler)
Figure 31: Heat Recovery Section Coding Part 3 (Aspen Custom Modeler)
Figure 32: Heat Rejection Section Coding Part 1 (Aspen Custom Modeler)
Figure 33: Heat Rejection Section Coding Part 2 (Aspen Custom Modeler)
<table>
<thead>
<tr>
<th>Constraints - Flowsheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONSTRAINTS</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>// CORRELATIONS</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>// Boiling Point Elevation (BPE)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>BPE_1 as Temperature (description:&quot;Boiling Point Elevation&quot;, specFree);</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>H_1 as RealNo (description:&quot;Correlation for boiling point elevation (from tables eqn)&quot;, specFree);</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>C_1 as RealNo (description:&quot;Correlation for boiling point elevation (from tables eqn)&quot;, specFree);</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>BPE_1 = RealNo.0.001* (B_1 + RealNo.0.001* (C_1)) * 10^-3;</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>// SPECIFIC VOLUME IF Saturated Water Vapor</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>// Density of vapour, p_vap, by correlatin for the specific volume of saturated water vapor (pg 546)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>T_v as temperature.abs (description:&quot;Given value&quot;, value:647.286, specified);</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>V_v as vol massa (description:&quot;Vapor specific volume &quot;, specFree);</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>f_A_1 as RealNo (description:&quot;Given value&quot;, value:83.6212088, specified);</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>f_A_2 as RealNo (description:&quot;Given value&quot;, value:6.662163390, specified);</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>f_A_3 as RealNo (description:&quot;Given value&quot;, value:0.004296364, specified);</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>f_A_4 as RealNo (description:&quot;Given value&quot;, value:5.04185*10^-56, specified);</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>f_A_5 as RealNo (description:&quot;Given value&quot;, value:3.14255*10^-99, specified);</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>f_A_6 as RealNo (description:&quot;Given value&quot;, value:2.32701*10^-12, specified);</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>f_A_7 as RealNo (description:&quot;Total of f values &quot;, specFree);</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>T_value1 as Temperature (description:&quot;Desired Temperature 1&quot;, value: 1, specified);</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>T_value2 as Temperature (description:&quot;Desired Temperature 2&quot;, value: 1, specified);</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>f_A_i as RealNo (description:&quot;Desired stage no.&quot;, value: 1, specified);</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>// f_i = f_i + f_i + f_i + f_i + f_i + f_i + f_i;</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>// Vapor = V_v^((T_v/(T_value + 273.15)-1)) * exp((sum of) f_A_i * ((T_value + 273.15)^(-1 - 1))), real equation</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>f_A_1 = ((f_A1^-((T_value + 273.15)^(-1 - 1))) + (f_A2^-((T_value + 273.15)^(-2 - 1))) + (f_A3^-((T_value + 273.15)^(-3 - 1))) + (f_A4^-((T_value + 273.15)^(-4 - 1)))</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Vapor = V_v^((T_v/(T_value + 273.15)-1)) * exp(f_A_i);</td>
</tr>
</tbody>
</table>

Figure 34: Physical Properties Correlation Coding Part 1 (Aspen Custom Modeler)
Figure 35: Physical Properties Correlation Coding Part 2 (Aspen Custom Modeler)
Figure 36: Physical Properties Correlation Coding Part 3 (Aspen Custom Modeler)
Figure 37: Physical Properties Correlation Coding Part 4 (Aspen Custom Modeler)
Figure 38: Physical Properties Correlation Coding Part 5 (Aspen Custom Modeler)
Figure 39: Physical Properties Correlation Coding Part 6 (Aspen Custom Modeler)
10. Appendix C: Correlation (Demister)

This is correlation for the pressure drop happening around demister. [Hisham T.El-Dessouky, 2002]

\[
\Delta P_p = 3.88178(P_p)^{0.375798}(V)^{0.81317}(\delta_w)^{-1.56114147}
\]

\( \Delta P_p \) = Demister Pressure Drop

V = Vapour Velocity

\( \delta_w \) = Wire Diameter

The pressure drop in Connecting Lines

\[
\Delta P = \frac{0.0001306M^2L(1 + \frac{3.6}{\delta_i})}{p_v\delta_i^5}
\]

\( M^2 \) = Mass flow rate of vapour stream

L = Tube length

\( \delta_i \) = Tube inner diameter

\( p_v \) = Vapour Density

\( \Delta P \) = Pressure drop

The Gravitational Pressure Drop

\[
\Delta P = (p_v\alpha + (1 - \alpha)p_l)g L(\theta)
\]

\[
\alpha = \frac{1}{1 + \frac{1-x}{x}\left(\frac{P_v}{P_l}\right)^{0.5}}
\]

X = Vapour mass fraction

\( P_v \) = Density of vapour

\( P_l \) = Liquid streams at saturation condition