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Modelling and Optimizing Single and Multiple Effect Evaporators Using Aspen Custom Modeler (ACM)

Thesis report

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ABSTRACT

The Modelling and Optimizing Single and Multiple Effect Evaporators Using Aspen Custom Modeler (ACM) are carried out to understand the developed model equations written for a double effect evaporator and be able to develop similar programs for both single effect and multiple effect evaporators. The case study was taken from the examples provided by Aspen Customer Modeller (ACM), a part of ASPEN software package.

The case study involves the double effect evaporator used to concentrate glycol from a dilute aqueous solution of 3.5 w% of glycol. The steady state model with the cost model to operate the double effect evaporator was obtained from ACM. These models were tested by performing steady and optimization simulations in MATLAB and ACM software.

To perform the simulation for single and multiple effect evaporator systems, a deeper understanding of process model is essentially required before applying the process model in MATLAB and ACM. A study on the process model was carried out using Excel spreadsheet. The single effect evaporator system is not a complex system investigated compared with the double effect evaporator system. Therefore, the steady state model for a single effect evaporator system was developed first before proceeding with double effect evaporator.

At the same time, sensitivity analysis of the single and multiple effect evaporators were performed and compared. Sensitivity analysis was performed to examine the limitations of process variables such as steam conditions and steam valve coefficients against concentration of product, mass flowrate of liquid, mass flowrate of steam, temperature liquid, and temperature chest.

As for the relationship between mass flowrate of steam against concentration of liquid out of evaporator, the increase in mass flowrate of steam affects the concentration of product. For the second case, sensitivity analysis was carried out to investigate the relationship between steam valve coefficients out of evaporator against concentration of liquid out. For single effect evaporator at the beginning of the process, the concentration of liquid increased then did not change and remained constant after a certain limit. As a conclusion for the result, to operate single effect evaporator, the steam valve coefficient for this process has a limit. For double effect evaporator, the concentration of liquid keep increased against steam valve coefficients out of evaporator.

Overall, most of the main objectives of this thesis were achieved with very satisfying results. However due to unforeseen circumstances and time constraints, optimization was not fully investigated.

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Abbreviations

Greek Letters

ΔP	Pressure different
λ	Latent heat

Model Subscripts

A_{tf}	Heat transfer Area
EV	Evaporator
F	Feeder
g	Glycol
H	Enthalpy
H_{tf}	Heat transfer Coefficient
i	In
KV	Valve Coefficient
l	Liquid
M	Mass Fraction
M_{hold}	Liquid Hold-up
o	Out
P	Pressure
PP	Pump
SM	Steamer
st/s	Steam
T	Temperature
V	Valve
vp	Vapour
w	Water
X	Concentration

Steam Flow Subscripts

Abbreviations	**Description**
Steam Flow	
H_{i_EVst}	Enthalpy steam in of Evaporator 1
H_{i_EVst1}	Enthalpy steam in of Evaporator 2
H_{i_Vst}	Enthalpy steam in of steam valve
H_{o_EVst}	Enthalpy steam out of Evaporator 1
H_{o_SMst}	Enthalpy steam out of steamer
H_{o_Vst}	Enthalpy steam out of steam valve
M_{i_EVst}	Mass steam in of Evaporator 1
M_{i_EVst1}	Mass steam in of Evaporator 2
M_{i_Vst}	Mass steam in of steam valve
M_{o_EVst}	Mass steam out of Evaporator 1
M_{o_SMst}	Mass steam out of steamer
M_{o_Vst}	Mass steam out of steam valve
P_{i_EVst}	Pressure steam in of Evaporator 1
P_{i_EVst1}	Pressure steam in of Evaporator 2
P_{i_Vst}	Pressure steam in of steam valve
P_{o_EVst}	Pressure steam out of Evaporator 1
P_{o_SMst}	Pressure steam out of steamer
P_{o_Vst}	Pressure steam out of steam valve
T_{i_EVst}	Temperature steam in of Evaporator 1
T_{i_EVst1}	Temperature steam in of Evaporator 2
T_{i_Vst}	Temperature steam in of steam valve
T_{o_EVst}	Temperature steam out of Evaporator 1
T_{o_SMst}	Temperature steam out of steamer
T_{o_Vst}	Temperature steam out of steam valve

Liquid Flow Subscripts

Abbreviations	**Description**
Liquid Flow	
H_{i_EVl} / H_{o_EVl}	Enthalpy liquid in/out of Evaporator 1
H_{i_EVl1} / H_{o_EVl1}	Enthalpy liquid in/out of Evaporator 2
H_{i_PPl} / H_{o_PPl}	Enthalpy liquid in/out of liquid Pump 1
H_{i_PPl1} / H_{o_PPl1}	Enthalpy liquid in/out of liquid Pump 2
H_{i_PPl2} / H_{o_PPl2}	Enthalpy liquid in/out of liquid Pump 3
H_{i_Vl} / H_{o_Vl}	Enthalpy liquid in/out of liquid Valve 1
H_{i_Vl1} / H_{o_Vl1}	Enthalpy liquid in/out of liquid Valve 2
H_{i_Vl2} / H_{o_Vl2}	Enthalpy liquid in/out of liquid Valve 3
H_{o_Fl}	Enthalpy liquid out of feeder
M_{i_EVg} / M_{o_EVg}	Mass Glycol in/out of Evaporator 1
M_{i_EVg1} / M_{o_EVg1}	Mass Glycol in/out of Evaporator 2
M_{i_EVl} / M_{o_EVl}	Total Mass liquid in/out of Evaporator 1
M_{i_EVl1} / M_{o_EVl1}	Total Mass liquid in/out of Evaporator 2
M_{i_EVw} / M_{o_EVw}	Mass Water in/out of Evaporator 1
M_{i_EVw1} / M_{o_EVw1}	Mass Water in/out of Evaporator 2
M_{i_PPg} / M_{o_PPg}	Mass Glycol in/out of liquid Pump 1
M_{i_PPg1} / M_{o_PPg1}	Mass Glycol in/out of liquid Pump 2
M_{i_PPg2} / M_{o_PPg2}	Mass Glycol in/out of liquid Pump 3
M_{i_PPl} / M_{o_PPl}	Total Mass liquid in/out of liquid Pump 1
M_{i_PPl1} / M_{o_PPl1}	Total Mass liquid in/out of liquid Pump 2
M_{i_PPl2} / M_{o_PPl2}	Total Mass liquid in/out of liquid Pump 3
M_{i_PPw} / M_{o_PPw}	Mass Water in/out of liquid Pump 1
M_{i_PPw1} / M_{o_PPw1}	Mass Water in/out of liquid Pump 2
M_{i_PPw2} / M_{o_PPw2}	Mass Water in/out of liquid Pump 3
M_{i_Vg} / M_{o_Vg}	Mass Glycol in/out of liquid Valve 1
M_{i_Vg1} / M_{o_Vg1}	Mass Glycol in/out of liquid Valve 2
M_{i_Vg2} / M_{o_Vg2}	Mass Glycol in/out of liquid Valve 3
M_{i_Vl} / M_{o_Vl}	Total Mass liquid in/out of liquid Valve 1
M_{i_Vl1} / M_{o_Vl1}	Total Mass liquid in/out of liquid Valve 2
M_{i_Vl2} / M_{o_Vl2}	Total Mass liquid in/out of liquid Valve 3
M_{i_Vw} / M_{o_Vw}	Mass Water in/out of liquid Valve 1
M_{i_Vw1} / M_{o_Vw1}	Mass Water in/out of liquid Valve 2

M_{i_Vw2} / M_{o_Vw2}	Mass Water in/out of liquid Valve 3
M_{o_Fg}	Mass Glycol out of feeder
M_{o_Fl}	Total Mass liquid out of feeder
M_{o_Fw}	Mass Water out of feeder
P_{i_EVl} / P_{o_EVl}	Pressure liquid in/out of Evaporator 1
P_{i_EVl1} / P_{o_EVl1}	Pressure liquid in/out of Evaporator 2
P_{i_PPl} / P_{o_PPl}	Pressure liquid in/out of liquid Pump 1
P_{i_PPl1}/ P_{o_PPl1}	Pressure liquid in/out of liquid Pump 2
P_{i_PPl2}/ P_{o_PPl2}	Pressure liquid in/out of liquid Pump 3
P_{i_Vl} / P_{o_Vl}	Pressure liquid in/out of liquid Valve 1
P_{i_Vl1} / P_{o_Vl1}	Pressure liquid in/out of liquid Valve 2
P_{i_Vl2} / P_{o_Vl2}	Pressure liquid in/out of liquid Valve 3
P_{o_Fl}	Pressure liquid out of feeder
T_{i_EVl} / T_{o_EVl}	Temperature liquid in/out of Evaporator 1
T_{i_EVl1} / $_{To\_EVl1}$	Temperature liquid in/out of Evaporator 2
T_{i_PPl} / T_{o_PPl}	Temperature liquid in/out of liquid Pump 1
T_{i_PPl1} / T_{o_PPl1}	Temperature liquid in/out of liquid Pump 2
T_{i_PPl2} / T_{o_PPl2}	Temperature liquid in/out of liquid Pump3
T_{i_Vl} / T_{o_Vl}	Temperature liquid in/out of liquid Valve 1
T_{i_Vl1} / T_{o_Vl1}	Temperature liquid in/out of liquid Valve 2
T_{i_Vl2} / T_{o_Vl2}	Temperature liquid in/out of liquid Valve 3
T_{o_Fl}	Temperature liquid out of feeder
X_{Fo}	Concentration liquid out of Feeder
X_{i_EVl} / X_{o_EVl}	Concentration liquid in/out of Evaporator 1
X_{i_EVl1} / X_{o_EVl1}	Concentration liquid in/out of Evaporator 2
X_{i_PPl} / X_{o_PPl}	Concentration liquid in/out of liquid Pump 1
$X_{i\_PPl\ 1}$/ X_{o_PPl1}	Concentration liquid in/out of liquid Pump 2
$X_{i\_PPl\ 2}$/ X_{o_PPl2}	Concentration liquid in/out of liquid Pump 3
X_{i_Vl} / X_{o_Vl}	Concentration liquid in/out of liquid Valve 1
X_{i_Vl1} / X_{o_Vl1}	Concentration liquid in/out of liquid Valve 2
X_{i_Vl2} / X_{o_Vl2}	Concentration liquid in/out of liquid Valve 3

1.0 Introduction

Traditionally when producing gas offshore, glycol is used as a hydrate inhibitor because it lowers the freezing point of water and thus prevents hydrate formation in flow lines (Richard I. Evans 1999). Glycol recovery systems generally leave a large portion of glycol in the brine stream that is lost during disposal. Additionally, some glycol is lost along with the vapour phase (Richard I. Evans 1999). As a result fresh glycol must be purchased and transported to the offshore platform to make up for the losses. A few other solutions considered for recovering glycol from the brine streams were distillation and evaporation (Richard I. Evans 1999).

This project will take the case study in the examples provided by Aspen Modeler Customer (ACM), in which a double effect evaporator is used to concentrate a diluted glycol solution. Additionally, this project involves developing and testing the models of single and multiple effect evaporators to produce a more concentrated glycol solution. The project report will cover:

Section 1: Introduction

This section introduces the major aim of the project and the layout of thesis.

Section 2: Literature Review and Project Background

This section briefly presents the available methods for recovering glycol and the software packages used to develop the models of the process to recover glycol.

Section 3: Research Objective and Scope

The scope and aim of the project are defined.

Section 4: Case Study Description and Model Development

This section describes the case study and the model equations of single effect and multiple effect evaporators, a mimic of an industrial process used to recover glycol.

Section 5: Research Methods

This section describes the method of applying, testing, and evaluating of the model equation of the single effect and multiple effect evaporators using the software tools.

Section 6: Result and Discussion

Results presented in Section 6 of steady state simulations and optimisations are presented, compared and discussed.

Section 7: Conclusion and Future Work

This section summarises the report and explains the future work suggested for future students.

2.0 Literature Review

A literature review is carried out to gain more background knowledge for this project. This section will investigate the available processes in the industry for glycol recovery and the software packages used for developing the process to be used in the case study of this project.

Glycol is a chemical component that has two hydroxyl (-OH) ions attached to different carbon atoms. According to most journal articles, ethylene glycol ($C_2H_2O_2$) is preferred over other types of glycol in evaporating systems (Kakimoto 2002). Ethylene glycol is commercially used as the coolant because it has higher boiling point as compared to water. This chemical is also used in the production of textiles (Broz 1975).

2.1 Available Method for Recovering Glycol

Two methods found in the literature to recover glycol are: (Richard I. Evans 1999).

1. Distillation columns

2. Evaporators

2.1.1 Glycol recovery using distillation column

Figure 1 shows the glycol recovery process which primarily consists of a distillation column to distil water off a diluted glycol solution.

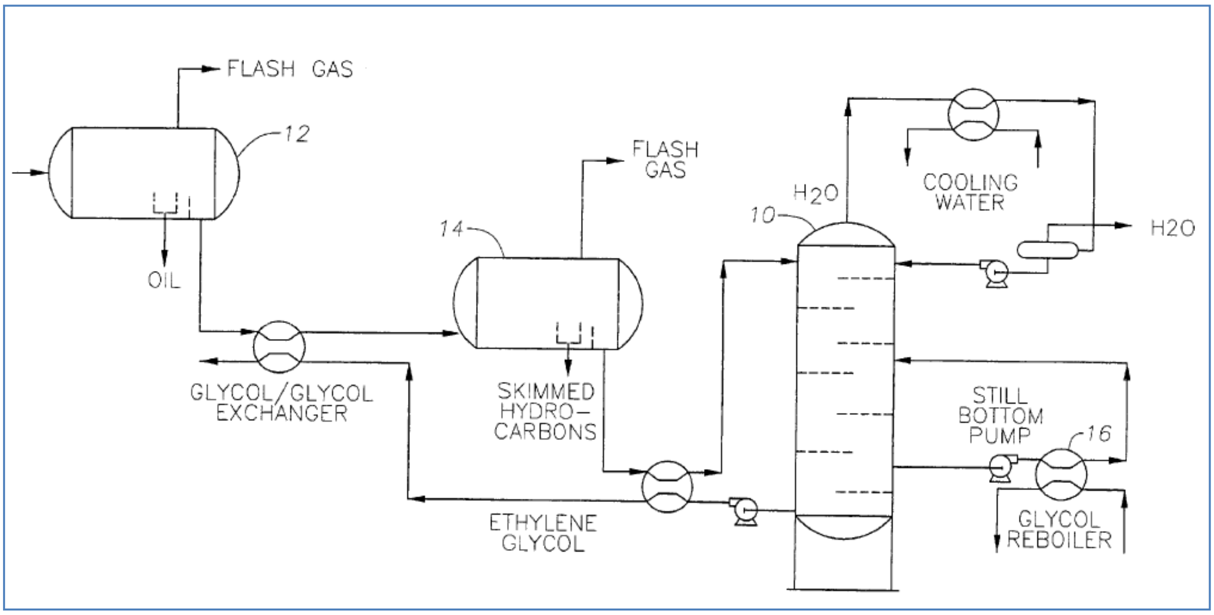


Figure 1: Glycol recovery using distillation column (Richard I. Evans 1999).

A natural gas stream containing glycol and sea water was introduced into a series of separator vessels (12 and 14) where the pressure was reduced to flash off the natural gas. The water/glycol was then introduced into the distillation column where it was heated by the reboiler. This steam boiler is used to drive the water overhead and concentrate the glycol. The major weakness of this distillation process is often due to formation of precipitation of the salt that can foul and plug the recovery system (Richard I. Evans 1999).

2.1.2 Glycol recovery using multiple effect evaporators in series

An example of a multiple effect evaporator is shown in Figure 2.

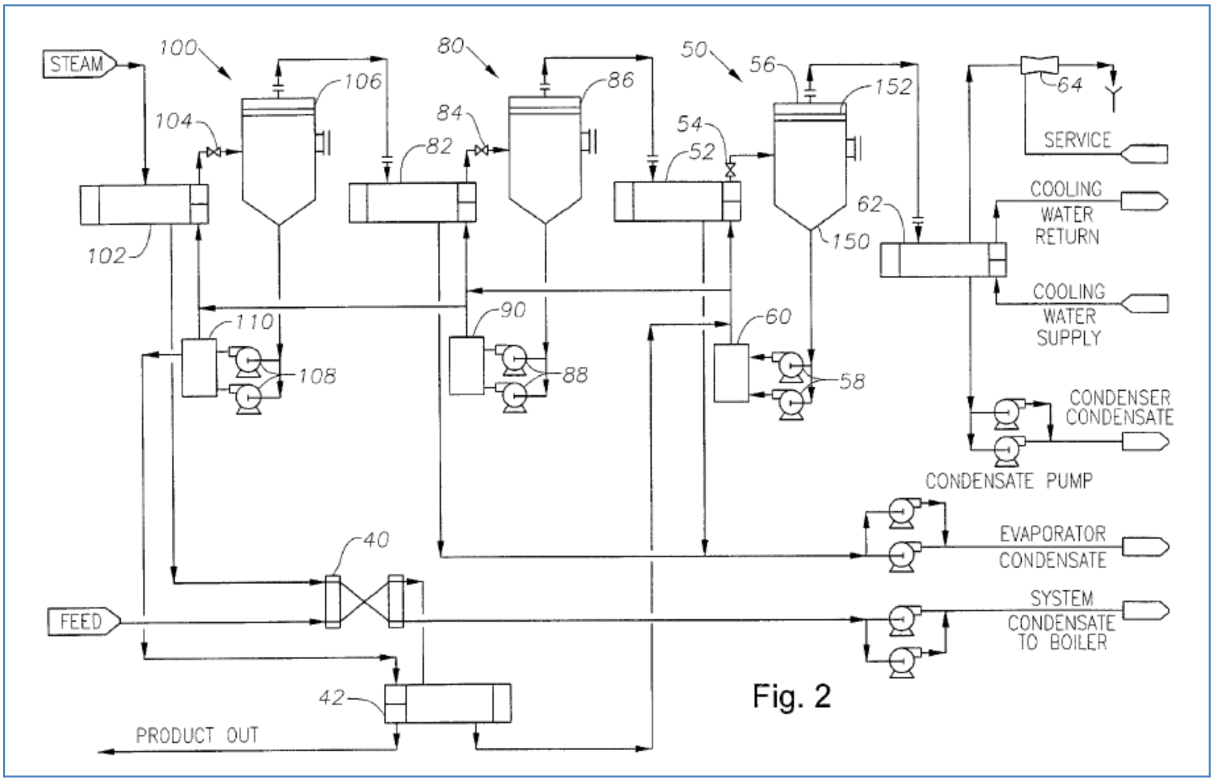


Fig. 2

Figure 2: Glycol recovery using three effect evaporators in series (Richard I. Evans 1999).

Figure 2 shows a three effect evaporator in series. Each effect of the evaporator system is comprised of an evaporator, a separator vessel, product pumps, and a solid removal system. These evaporators remove salt and other solids as well as excess water and leaving a glycol stream that can be reused as hydrate inhibitor (Richard I. Evans 1999).

In the first evaporation system the preheated stream is introduced into a suppressed boiling point evaporator where it is heated under a constant pressure. The stream pressure is then dropped to cause a portion of the water for vaporizing or flashing. The flashing stream is then introduced into a separator vessel in which the water vapour is separated from the remaining liquid stream. The water vapour is removed from the separator and condensed. The remaining liquid glycol/brine stream is then pumped from the separator vessel through a solid removal system where precipitated salts and solid are removed. These processes are repeated twice in the second and the third evaporation systems. Each time these steps are performed, the remaining liquid stream becomes more concentrated with glycol (Dunning 2000).

To maximize the energy efficiency of the process, heat energy from the water vapour generated in the third evaporator process is used to supply heat for the second evaporator process, and the heat energy from the second evaporator process is used to heat the first evaporator process (Richard I. Evans 1999).

The energy consumption of the overall system is reduced by about 50% if the vapour produced by the first effect evaporator is used as heating steam in the second effect evaporator (Gunajit and Surajit 2010). The single effect evaporator system has limited industrial application. This is because the amount of water produced is less than the amount of heating steam. However to gain understanding of the evaporator effect, the single effect evaporator system is usually studied first before further investigation is applied to the multiple effect evaporator system.

2.2 Software Overview

The EXCEL, MATLAB and ACM are the software programs that are used in this thesis. These softwares have different capabilities, for example MATLAB is able to perform real-time simulation based on coding while ACM is able to perform real-time simulation based on graphics.

A case study involving a double effect evaporator to concentrate an aqueous glycol solution was given by ACM which is an Aspen technology simulation tool for creating rigorous process models and for applying these process models to simulate the processes. ACM has a wide range of capabilities, including steady state simulation, dynamic simulation, and optimization (Tremblay and Feers 2015).

In this thesis, MATLAB and Microsoft Excel is used to investigate and familiar with steady state model, optimization, and dynamics model before applying the process model in the ACM software. MATLAB stand for MATrix LABoratory is a high-performance language for technical computing and easy-to-use environment where problems and solutions are expressed in familiar mathematical notation (Houcque 2005). MATLAB is not only able to performed math and computation, it also able to performed modelling and simulation (Houcque 2005). Microsoft Excel is a spreadsheet program included in the Microsoft Office. Spreadsheets present tables of values arranged in rows and columns that can be manipulated mathematically using both basic and complex arithmetic operations and functions.

3.0 Project Objective and Scope

This project will take the case study in the examples provided by ACM, in which a double effect evaporator is used to concentrate a diluted glycol solution. The method used in the case study is similar to that used in the industry to recover glycol as shown in Figure 2 in Method for Recovering Glycol section. The purpose of recovery glycol is to produce more glycol solution, this process able to prevent from purchase the additional glycol. The main objective of the project is to understand the developed model equations written for a double effect evaporator and be able to develop similar programs for a single effect and triple effect evaporators. In addition to these technical objectives, the project has the following learning objectives:

(i) to apply and practice the knowledge and skills that have been gained at Murdoch University over the past three years;
(ii) to gain experience in project research, implementation and testing;
(iii) to develop knowledge and skills in project planning and scheduling, research, presentation and documentation.

The following tasks are prepared to accomplish the research objective.

i. As the solver in ACM can simultaneously solve all of the model equations, it is not necessary to write these equations in sequence. This is an advantage of using ACM for model development but it is difficult to understand a model equation written in ACM and to modify the program for other applications. This is because the example program shown the model equation not in sequences. Therefore the first and most important task is to develop and test the model equations of the double effect evaporator in EXCEL and in MATLAB using the sequential modular technique. EXCEL is used to check all mathematical equation while MATLAB requires rearranging all mathematical equations in a particular order so that the unknowns can be sequentially solved.
ii. After the model of the double effect evaporator is tested and thoroughly understood in EXCEL and MATLAB, similar programs are developed in ACM for a single effect and double effect evaporators.
iii. Steady state simulations are performed for three programs of single, double and triple effect evaporators. Sensitivity analyses are performed at the same time to understand the limitations of process variables such as steam conditions and operating temperatures and concentration in each evaporator.
iv. The cost objective function given for the double effect evaporator is studied and modified to apply to the models of the single and triple effect evaporators.
v. Optimizations are performed for three systems of single, double and triple effect evaporators.

vi. Dynamic models are developed in ACM for dynamic simulations and for control system designs in the future.

The above objective is ambitious but it can and will be a layout for another project to accomplish all the tasks that might not be completed in this project.

4.0 Case Study Description and Model Development

The case study taken from ACM was originally developed for the double effect evaporator. To understand the mathematical equations used in modeling more easily, this section will present the development of a single effect evaporator first followed by the adaptation of the single effect model into the multiple effects evaporator models.

4.1 Single Effect Evaporator

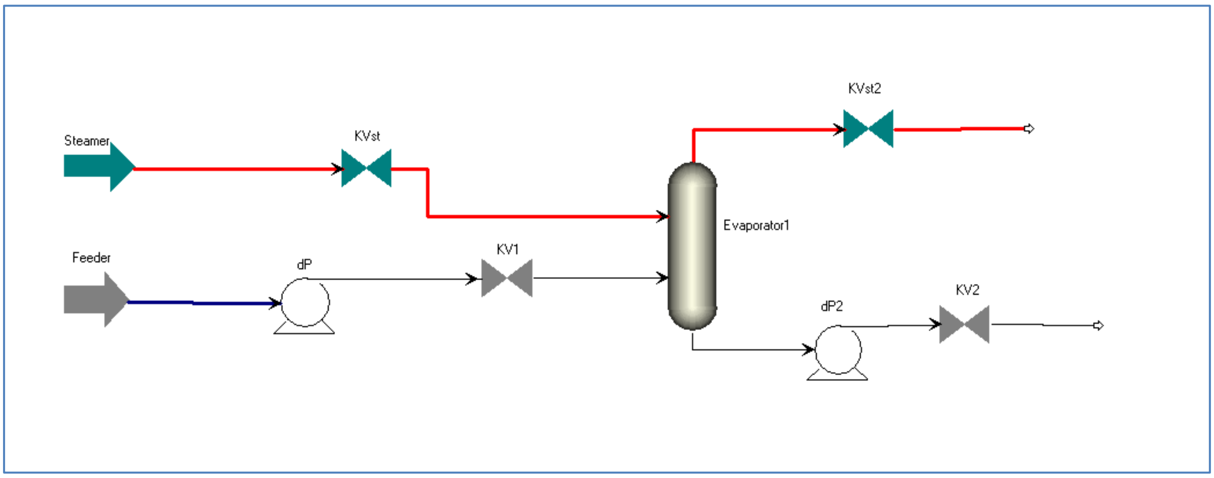


Figure 3: Flow diagram of single effect evaporator

Figure 3 shows the flow diagram of a single evaporator. Saturated steam provided by the steamer is available at 105°C. The corresponding saturation pressure is obtained from the below correlation (E1), which gives the same result as would be shown in any saturated steam table.

$$P_{o\_SMst} = 0.1333*10^{\left(7.9668-\frac{166821}{T_{o\_SMst}+228}\right)}, \qquad \text{(E1)}$$

In Equation E1, P and T are pressure and temperature, respectively. The full abbreviations with subscripts can be found in the list of abbreviations.

From the steamer the saturated steam passes a steam valve, which is described by Equation E2, where m stands for mass flowrate and KV is the valve coefficient, which is initially set at 46.36 $\frac{m^3}{h}$.

$$m_{i\_Vst} = m_{o\_Vst} = \sqrt{KV_{st} * (P_{i\_Vst} - P_{o\_Vst})} \tag{E2}$$

The feed, which is a diluted aqueous solution of 3.5 w% glycol, is introduced to the feeder through a pump and a liquid valve. The feed is maintained at 100 kPa and sub-cooled to 88°C. The relationship between the saturation pressure and temperature of a glycol solution is obtained from the correlation (E3). The model of the liquid pump and the liquid valve are shown in Equations E4 and E5.

$$P_{li} = 0.1333 * \left\{ \frac{\frac{(1-X_i)}{MW_w}}{\frac{(1-X_i)}{MW_w} + \frac{X_i}{MW_g}} \right\} 10^{\left(7.96681 - \frac{166821}{T_i + 228}\right)} \tag{E3}$$

$$\Delta P = P_{o\_PPl} - P_{i\_PPl} \tag{E4}$$

$$m_{i\_Vl} = m_{o\_Vl} = \sqrt{KV1 * (P_{i\_Vl} - P_{o\_Vl})} \tag{E5}$$

In Equation E3, X stands for glycol mass fraction and MW is molar mass. In this case study molar masses of glycol and water are 62.00 $\frac{g}{mol}$ and 18.02 $\frac{g}{mol}$ respectively. The liquid valve has the same model as the steam valve (E2) but the valve coefficient is set at 185$\frac{m^3}{h}$.

Around the evaporator the total mass and glycol balances are shown in Equations E6 and E7. The energy balances are shown in Equations E8 and E9.

$$M_{li} - M_{lo} - M_{vpo} = 0 \tag{E6}$$

$$X_i M_{li} - X_o M_{lo} = 0 \tag{E7}$$

$$M_{li}(\hat{H}_{li} - \hat{H}_{lo}) - M_{vpo}(\hat{H}_{vo} - \hat{H}_{lo}) + M_{st}\lambda = 0 \tag{E8}$$

$$\lambda M_{st} - H_{tf} * A_{tf} * \Delta T = 0 \tag{E9}$$

In the above equations λ is the heat of condensation of steam, which is assumed to be a constant value at 2080.8 $\frac{kJ}{kg}$. The heat transfer area A_{tf} and overall heat transfer coefficient H_{tf} are given as 145 m^2 and 80 $\frac{kJ}{h.K}$ respectively. The temperature difference is between the heating medium and the operating temperature in the evaporator, e.g. $\Delta T = (T_s - T)$.

Specific enthalpies of liquid glycol solutions and water vapour or steam are calculated in the following equations, where the reference temperature is taken as $T_{ref} = 60°C$; heat capacities of glycol and water are 2.4 $\frac{kJ}{kg°C}$ and 4.183 $\frac{kJ}{kg°C}$ respectively.

$$\hat{H}_{lo} = \hat{H}_{o\_Fl} = (T_{o\_Fl} - T_{ref}) * \{(1 - X_{Fo})C_{pw} + X_{Fo}C_{pg}\} \tag{E10}$$

$$\hat{H}_{o\_Vst} = (T_{o\_Vst} - T_{ref}) * C_{pw} + \lambda \tag{E11}$$

The vapour leaving the evaporator goes through the vapour valve, which has the valve coefficient initially set at 521.33$\frac{m^3}{h}$. The model of this valve is shown in Equation E12. It is noted that the difference in pressure is between the inlet liquid and the outlet vapour. In the double effect evaporator the vapour leaving the first effect will be used to heat the second effect.

$$m_{vpo} = \sqrt{Kv_{vpo} * (P_{li} - P_{vpo})} \tag{E12}$$

The liquid coming out of the single effect evaporator is the product. In the double effect evaporator the more concentrated solution coming out from the first effect will be introduced to the second effect for further water evaporation.

4.2 Multiple Effect Evaporators

All model equations developed for the single effect evaporator can be used for the double and triple effect evaporators. However saturated steam is only used in the first effect. The second and all of the following effects are heated by the vapour coming out from the upstream effect. Further detail of the multiple effect evaporators are shown in the following sections.

4.2.1 Double Effect Evaporator

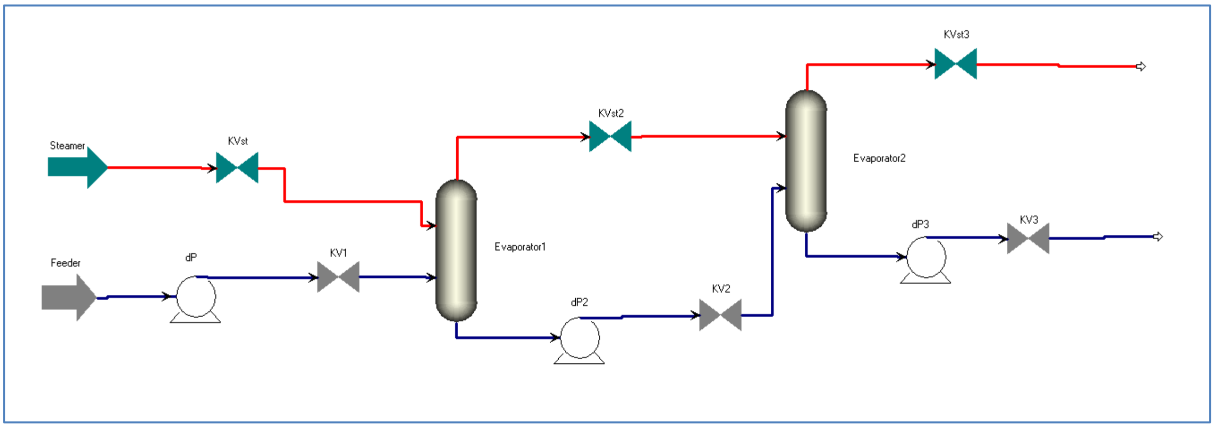


Figure 4: Flow diagram of double effect evaporator

Figure 4 shows the flow diagram of a double effect evaporator. The first effect is similar to the single effect shown in Section 4.1. The second effect is the adaptation of the single effect model into the multiple effect evaporator models. The second effect is heated by the vapour coming out from the first effect. At the same time, the concentrated solution coming out from the first effect will be introduced to the second effect. Since the second effect model is an adaptation of single effect model, all the mathematical equations used in modeling this section is similar to the single effect model.

4.3 Operation of the system

This case study is about the study of knowledge of the different effect of evaporator to concentrate a diluted glycol solution by adjusting the internal design of the system. It is good to understand the process that is happening around the system first then come up with an investigation of a mathematical model, which has been discussed in section 4.1, and it will be used in the study. The operation of the system is described below:

1) A 4.095 $\frac{kg}{kg}$ of glycol (M_{o_Fg}) and 112.898 $\frac{kg}{kg}$ of water (M_{o_Fw}) solution is feed into the first tank through liquid pump and liquid valve.
2) Inside the evaporator tank a glycol and water concentration is heated by 42.653 $\frac{kg}{kg}$ of steam (M_{o_SMst}).
3) The liquid coming out of the single effect evaporator is a product for single effect.
4) In the double effect evaporator the glycol becomes more concentrated, while the vapour from the first effect is used to heat the second evaporator which is 42.071$\frac{kg}{kg}$. The remaining glycol and water concentration after the second stage is more concentrated which is 4.095 $\frac{kg}{kg}$ and 27.390 $\frac{kg}{kg}$.
5) The liquid coming out of the double effect evaporator is a product for double effect.

4.4 Process Variable and Constrains

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 mixture 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 double effect evaporator system all the process variables that contribute to the process have been highlighted.

For modelling and optimizing Single and multiple effects Evaporator project is using the same process variable from the double effect evaporator example program. This case study consists of steady state model, optimization model, and dynamics model.

5.0 Research Methods

In this section the method of applying, testing, and evaluating of the model equation of the single and multiple effect evaporators using the software tools will be discussed. The flow chart below shows the case study methodology. The projects have been carried out using following step:

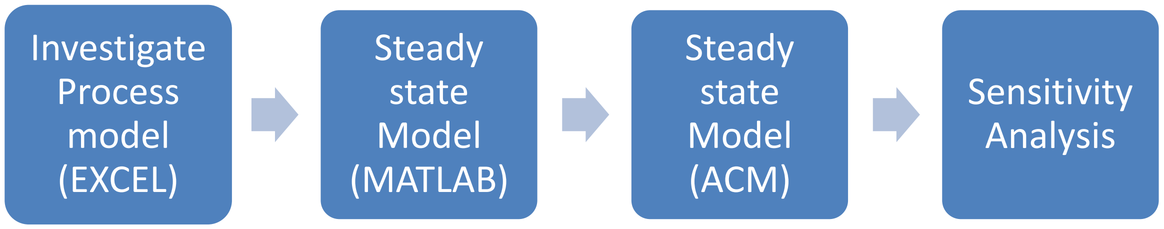


Figure 5: Research Methods

5.1 Development and testing the model equations

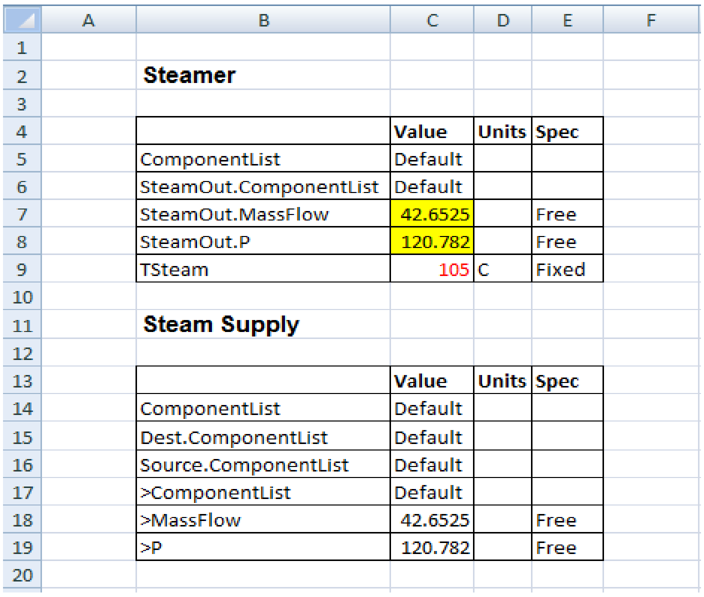
This section describes the procedure to develop and test the model equations of the double effect evaporator in EXCEL and in MATLAB using the sequential modular technique. This requires rearranging all mathematical equations in a particular order so that the model equations are able to understand.

5.1.1 Collecting Data

The value or parameter obtained from simulation of steady state in the double effect evaporator example program is recorded in Excel spreadsheet. From the recorded data, fixed and calculated values for all process variable and constrains are easier to be collected.

Figure 6 shows the example of recorded data in Excel spreadsheet for steamer and steam supply model. From the figure below it is easier to identify which one is fixed or calculation value. At the same time it is easier to understand the overall process because all process model value is on one screen. In this case study, fixed value indicates a given or constant value for the process; while for free value is values that are obtained from calculation for every process model equation. All recorded values are presented in Appendix A.

Figure 6 also shows the Steamer model, where temperature steam out of steamer (To_SMst) is fixed value but pressure steam out of steamer (Po_SMst) and mass steam out of steamer (Mo_SMst) is calculated value from the model equation.



Steamer

	Value	Units	Spec
ComponentList	Default		
SteamOut.ComponentList	Default		
SteamOut.MassFlow	42.6525		Free
SteamOut.P	120.782		Free
TSteam	105	C	Fixed

Steam Supply

	Value	Units	Spec
ComponentList	Default		
Dest.ComponentList	Default		
Source.ComponentList	Default		
>ComponentList	Default		
>MassFlow	42.6525		Free
>P	120.782		Free

Figure 6: Example Data in Excel spread sheet

From the recorded data, double effect evaporator example program have a few fixed value. All fixed values are listed below:

Liquid Properties

Table 1: Liquid Properties

Properties	Specific heat (C_p), $\frac{kJ}{kg^\circ C}$	Molar Mass , $\frac{g}{mol}$
Glycol	2.40	18.02
Water	4.18	62.00

Physical Properties

Table 2: Physical Properties

	Single Evaporator	Double Evaporator
Heat Transfer Area (A_{tf},A_{tf1},A_{tf2}), m^2	168	145
Heat Transfer Coefficient (H_{tf},H_{tf1},H_{tf2}), $\frac{kJ}{h.K}$	150	80
Water latent heat at 160°C (λ), $\frac{kJ}{kg}$	2080.8	2080.8
Liquid Hold-up (M_{hold} ,M_{hold1} ,M_{hold2}) , kg	3300	2500

Valve Properties

Table 3: Valve Properties

	Single Evaporator	Double Evaporator
Steam Valve Coefficient (Kv_{st}), $\frac{m^3}{h}$	46.361	-
Steam Valve Coefficient after evaporator (KV_{apv} , KV_{apv1}), $\frac{m^3}{h}$	521.33	703.35
Liquid Valve Coefficient (KV1,KV2,KV3), $\frac{m^3}{h}$	185	Calculate

Pump Properties

Table 4: Pump Properties

	Single Evaporator (In)	**Single Evaporator (Out) / Double Evaporator (In)**	**Double Evaporator (Out)**
Pressure differences across the pump (dP,dP1,dP2), kPa	44.27	10.00	90.30

Fixed Properties

Table 5: Other Fixed Properties

	Single Evaporator	**Double Evaporator**
Concentration liquid out (X_{o_EVl} , X_{o_EVl1}), $\frac{kg}{kg}$	0.05465	0.13005

- ✓ Mass Glycol out of feeder (Mo_Fg) = 0.035 $\frac{kg}{kg}$
- ✓ Temperature of the steam out of steamer (To_SMst) = 105ºC
- ✓ Temperature of the liquid out of Feeder (To_Fl) = 88ºC
- ✓ Pressure liquid out of Feeder (Po_Fl) = 100 kPa
- ✓ Pressure liquid out of liquid valve 2 (Po_Vl2) = 120 kPa
- ✓ Pressure steam out of Evaporator 1 (Po_Evst1) = 45 kPa

From the data collected from double effect example program there are a few unknown values required before starting the process. All the process variable is able to calculate if the process does not have any unknown.

Unknowns

- ✓ Feed flowrate (Mo_Fl) , kg/h
- ✓ Steam flowrate (Mo_SMst), kg/h
- ✓ Product flowrate (Mo_EVl) , kg/h

Total liquid mass flowrate (Mo_EVl) can be calculated using the equation below:

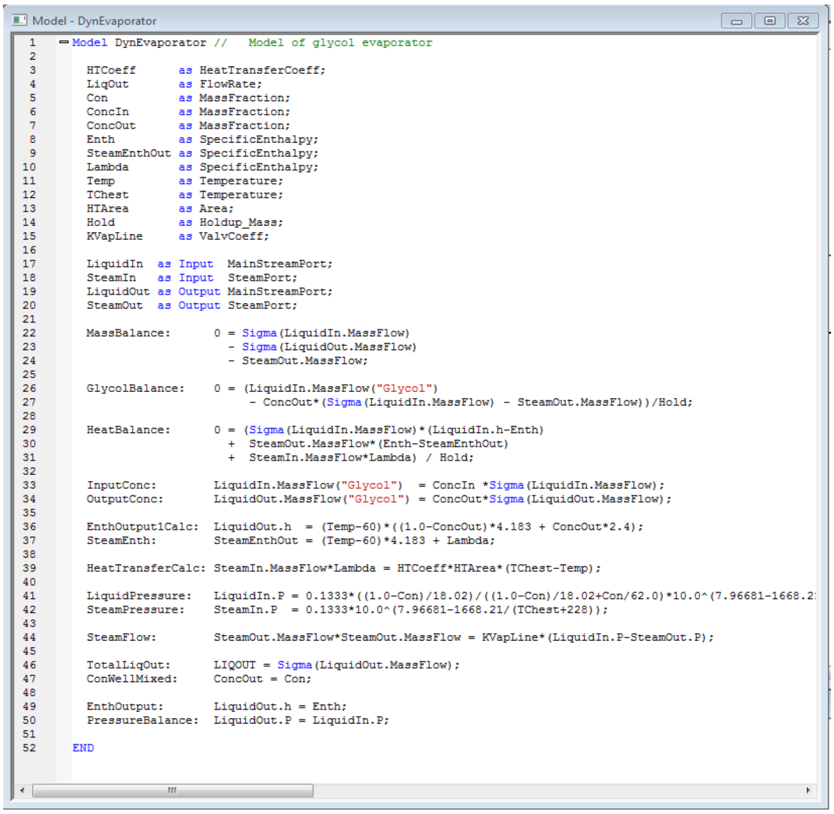
$$M_{o\_EVl} = \left(\frac{X_{Fo}}{X_{o\_EVl}} \right) * M_{i\_EVl} \tag{E13}$$

In conclusion, there is only one unknown to be specified. Either Feed flowrate is given or the mass of water evaporated. At this stage we assume both unknowns is given. Hence the steady state simulation using MATLAB can be performed.

5.1.2 Investigating the Model Equations

The modeling is a mathematical description of industrial process using a set of equations.The objectives of constructing modeling and the simulation are to improve and optimize the existing model equations so that we can get a better understanding on the working principles of the process and can get a better control of the process. In ACM, the real plant has been constructed so that we can monitor and check the reading of each of the part in the evaporator plant.

The double effect evaporator example program includes models for the steamer, feeder, pump, steam valve, main valve, and evaporator. Figure 7 shows the evaporator model and other models are given in Appendix B. This entire model is checked to obtain all mass balance equation, energy balance equation and other equations. All equations are used to calculate the free value in process flow as explained in Section 5.1.1. After identifying all equations from double evaporator example program, all equations are then checked before testing the steady state model in MATLAB and ACM. The model equation has been checked and explained in Section 4.1 and the detail model equation is shown in Appendix D.

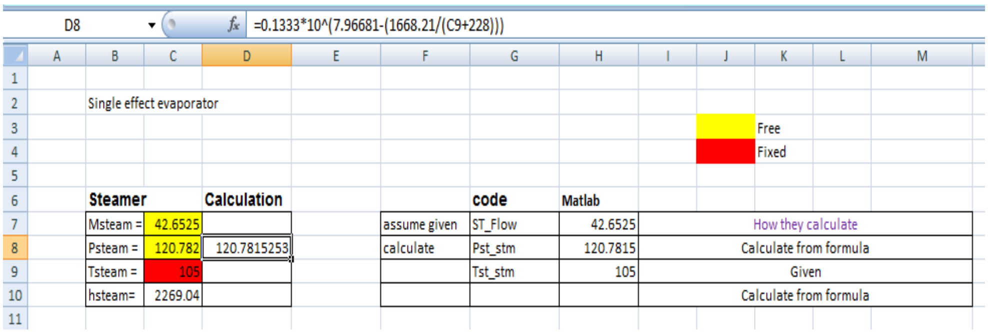


```
Model DynEvaporator //   Model of glycol evaporator

  HTCoeff      as HeatTransferCoeff;
  LiqOut       as FlowRate;
  Con          as MassFraction;
  ConcIn       as MassFraction;
  ConcOut      as MassFraction;
  Enth         as SpecificEnthalpy;
  SteamEnthOut as SpecificEnthalpy;
  Lambda       as SpecificEnthalpy;
  Temp         as Temperature;
  TChest       as Temperature;
  HTArea       as Area;
  Hold         as Holdup_Mass;
  KVapLine     as ValvCoeff;

  LiquidIn  as Input  MainStreamPort;
  SteamIn   as Input  SteamPort;
  LiquidOut as Output MainStreamPort;
  SteamOut  as Output SteamPort;

  MassBalance:      0 = Sigma(LiquidIn.MassFlow)
                      - Sigma(LiquidOut.MassFlow)
                      - SteamOut.MassFlow;

  GlycolBalance:    0 = (LiquidIn.MassFlow("Glycol")
                         - ConcOut*(Sigma(LiquidIn.MassFlow) - SteamOut.MassFlow))/Hold;

  HeatBalance:      0 = (Sigma(LiquidIn.MassFlow)*(LiquidIn.h-Enth)
                      +  SteamOut.MassFlow*(Enth-SteamEnthOut)
                      +  SteamIn.MassFlow*Lambda) / Hold;

  InputConc:        LiquidIn.MassFlow("Glycol")  = ConcIn *Sigma(LiquidIn.MassFlow);
  OutputConc:       LiquidOut.MassFlow("Glycol") = ConcOut*Sigma(LiquidOut.MassFlow);

  EnthOutput1Calc:  LiquidOut.h  = (Temp-60)*((1.0-ConcOut)*4.183 + ConcOut*2.4);
  SteamEnth:        SteamEnthOut = (Temp-60)*4.183 + Lambda;

  HeatTransferCalc: SteamIn.MassFlow*Lambda = HTCoeff*HTArea*(TChest-Temp);

  LiquidPressure:   LiquidIn.P = 0.1333*((1.0-Con)/18.02)/((1.0-Con)/18.02+Con/62.0)*10.0^(7.96681-1668.2
  SteamPressure:    SteamIn.P  = 0.1333*10.0^(7.96681-1668.21/(TChest+228));

  SteamFlow:        SteamOut.MassFlow*SteamOut.MassFlow = KVapLine*(LiquidIn.P-SteamOut.P);

  TotalLiqOut:      LIQOUT = Sigma(LiquidOut.MassFlow);
  ConWellMixed:     ConcOut = Con;

  EnthOutput:       LiquidOut.h = Enth;
  PressureBalance:  LiquidOut.P = LiquidIn.P;

END
```

Figure 7: Evaporator Model

5.1.3 Investigate Steady State Model in Excel Spread sheet

All equations collected from the example program are recalculated in Excel spreadsheet to ensure that the same value is achieved and the model equations are correctly used. Figure 8 shows the pressure steam out of steamer is calculated using equation E1 (see section 4.1). For the steamer, feeder, pump, steam valve and evaporator model checking is shown in appendix C. The single effect and double effect evaporator of the overall process has been checked and displayed in Appendix G.



D8 =0.1333*10^(7.96681-(1668.21/(C9+228)))

	A	B	C	D	E	F	G	H	I	J	K	L	M
1													
2		Single effect evaporator											
3										🟨	Free		
4										🟥	Fixed		
5													
6		**Steamer**		**Calculation**			**code**	**Matlab**					
7		Msteam =	42.6525			assume given	ST_Flow	42.6525	How they calculate				
8		Psteam =	120.782	120.7815253		calculate	Pst_stm	120.7815	Calculate from formula				
9		Tsteam =	105				Tst_stm	105	Given				
10		hsteam=	2269.04						Calculate from formula				
11													

Figure 8: Checking Steady state model in Excel spread sheet

5.1.4 Investigate Steady State Model in MATLAB

This section describes the model equations of the double effect evaporator in MATLAB using the sequential modular technique. This requires rearranging all mathematical equations in a particular order so that the unknowns can be sequentially solved.

The reference values for process variable is shown in Table 6.This value are used at the beginning of the process as an input to the single and multiple effect evaporator process.

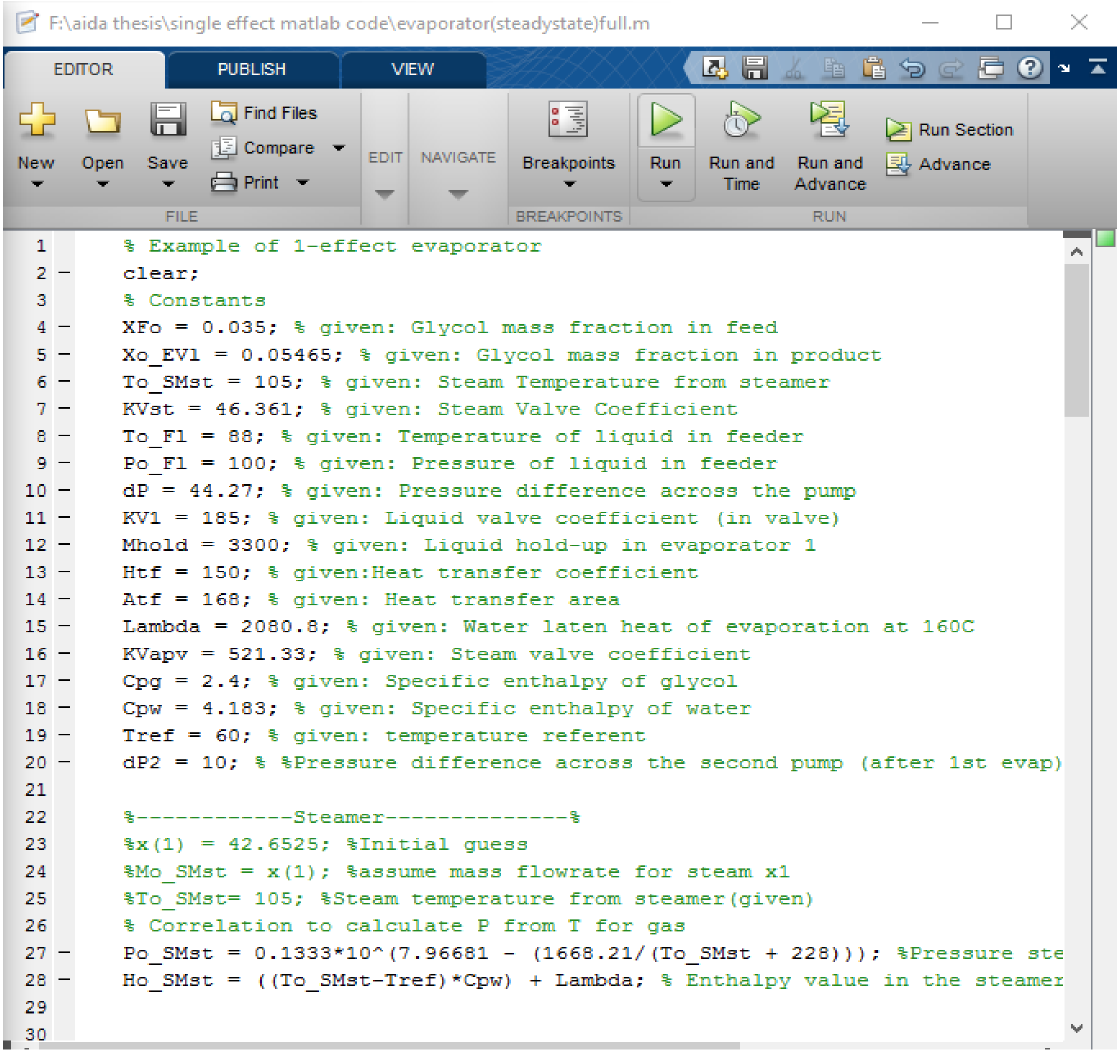
Table 6: Input Process Variables

INPUT Evaporator process	**Operating Value**
STEAMER	
To_SMst (Given)	105 °C
Po_SMst (Calculate)	120.782 kPa
Ho_SMst (Calculate)	2269.04 $\frac{kJ}{h.K}$
Mo_SMst (Assume)	42.6525 $\frac{kg}{kg}$
FEEDER	
T0_Fl (Given)	88 °C
Po_Fl (Given)	100 kPa
Ho_Fl (Calculate)	115.377 $\frac{kJ}{h.K}$
Mo_Fl (Assume)	116.993 $\frac{kg}{kg}$
Mo_Fg (Calculate)	4.09476 $\frac{kg}{kg}$
Mo_Fw (Calculate)	112.898 $\frac{kg}{kg}$
XFo (Given)	0.035 $\frac{kg}{kg}$

From table 1, the two unknowns which is mass flowrate of steam (Mo_SMst) and mass flowrate of total liquid (Mo_Fl) assumed is given to this process. The variable which declared as Given means the value that provided by double effect evaporator case study. For calculated variable, is a value that obtained from mathematical model equations.

5.1.4.1 Single Effect Evaporator MATLAB

From Process model equation, steady state model for single effect evaporator have been developed using MATLAB in sequence order. After checking the process model equation, the development of steady state model for single effect evaporator becomes easier. Figure 9 shows all constant value needed to be declared first so that MATLAB is able to perform simulation. The overall steady state model program for single effect evaporator is shown in Appendix E.



```
% Example of 1-effect evaporator
clear;
% Constants
XFo = 0.035; % given: Glycol mass fraction in feed
Xo_EV1 = 0.05465; % given: Glycol mass fraction in product
To_SMst = 105; % given: Steam Temperature from steamer
KVst = 46.361; % given: Steam Valve Coefficient
To_F1 = 88; % given: Temperature of liquid in feeder
Po_F1 = 100; % given: Pressure of liquid in feeder
dP = 44.27; % given: Pressure difference across the pump
KV1 = 185; % given: Liquid valve coefficient (in valve)
Mhold = 3300; % given: Liquid hold-up in evaporator 1
Htf = 150; % given:Heat transfer coefficient
Atf = 168; % given: Heat transfer area
Lambda = 2080.8; % given: Water laten heat of evaporation at 160C
KVapv = 521.33; % given: Steam valve coefficient
Cpg = 2.4; % given: Specific enthalpy of glycol
Cpw = 4.183; % given: Specific enthalpy of water
Tref = 60; % given: temperature referent
dP2 = 10; % %Pressure difference across the second pump (after 1st evap)

%------------Steamer--------------%
%x(1) = 42.6525; %Initial guess
%Mo_SMst = x(1); %assume mass flowrate for steam x1
%To_SMst= 105; %Steam temperature from steamer(given)
% Correlation to calculate P from T for gas
Po_SMst = 0.1333*10^(7.96681 - (1668.21/(To_SMst + 228))); %Pressure ste
Ho_SMst = ((To_SMst-Tref)*Cpw) + Lambda; % Enthalpy value in the steamer
```

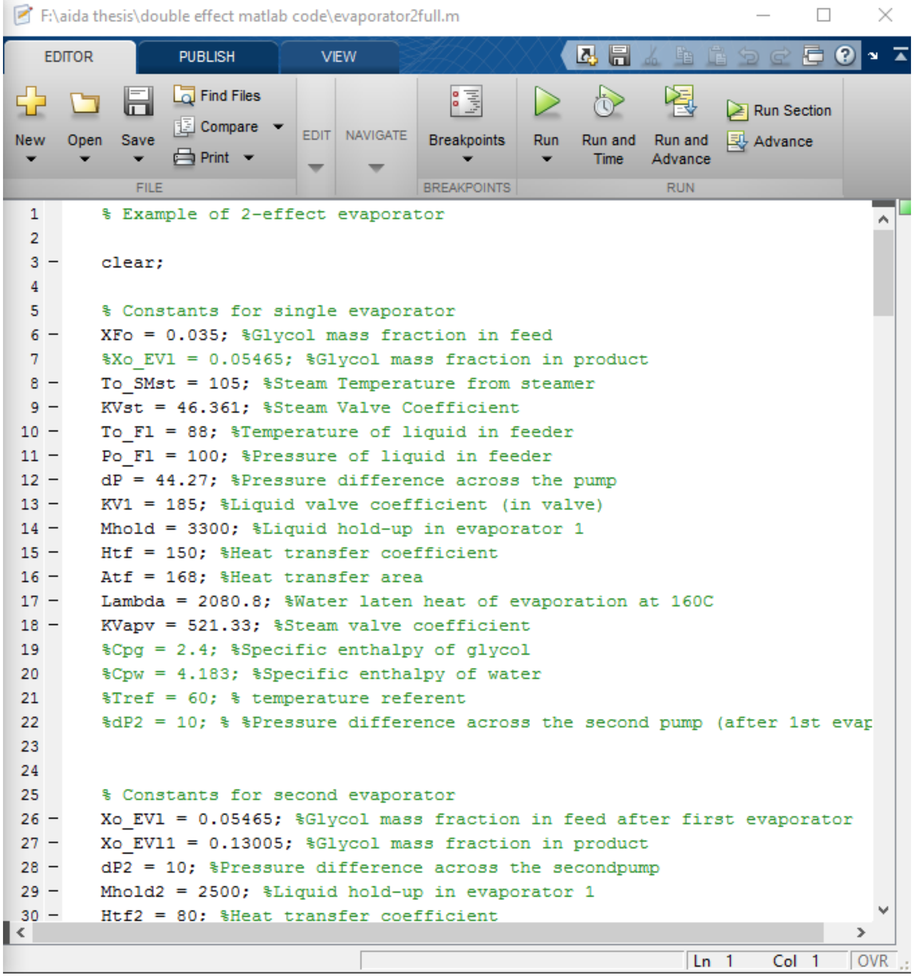
Figure 9: MATLAB example code for Single Effect Evaporator program

5.1.4.2 Double Effect Evaporator MATLAB

The steady state model for double effect evaporator has been developed using MATLAB. Since this is a complicated system, the program becomes more complicated to write as compared to single effect evaporator program. All the mathematical equations used in modelling this section are similar with the single effect model.

The overall steady state model program for double effect evaporator is shown in Appendix F. All constants and process variables need to be declared prior to performing a simulation as shown in Figure 10 in order for MATLAB to be able to perform simulation.

The simulation result of double effect evaporator from MATLAB is similar with EXCEL value. All process variables from MATLAB have been compared with simulation result using ACM.



```
% Example of 2-effect evaporator

clear;

% Constants for single evaporator
XFo = 0.035; %Glycol mass fraction in feed
%Xo_EV1 = 0.05465; %Glycol mass fraction in product
To_SMst = 105; %Steam Temperature from steamer
KVst = 46.361; %Steam Valve Coefficient
To_F1 = 88; %Temperature of liquid in feeder
Po_F1 = 100; %Pressure of liquid in feeder
dP = 44.27; %Pressure difference across the pump
KV1 = 185; %Liquid valve coefficient (in valve)
Mhold = 3300; %Liquid hold-up in evaporator 1
Htf = 150; %Heat transfer coefficient
Atf = 168; %Heat transfer area
Lambda = 2080.8; %Water laten heat of evaporation at 160C
KVapv = 521.33; %Steam valve coefficient
%Cpg = 2.4; %Specific enthalpy of glycol
%Cpw = 4.183; %Specific enthalpy of water
%Tref = 60; % temperature referent
%dP2 = 10; % %Pressure difference across the second pump (after 1st evap


% Constants for second evaporator
Xo_EV1 = 0.05465; %Glycol mass fraction in feed after first evaporator
Xo_EV11 = 0.13005; %Glycol mass fraction in product
dP2 = 10; %Pressure difference across the secondpump
Mhold2 = 2500; %Liquid hold-up in evaporator 1
Htf2 = 80; %Heat transfer coefficient
```

Figure 10: MATLAB example program for Double effect evaporator program

5.2 Simulation of Steady State condition using Aspen Custom Modeler

After the model of the double effect evaporator is tested and thoroughly understood in EXCEL and MATLAB, similar programs are developed in ACM for a single effect and double effect evaporators. From MATLAB simulation, all mathematical equation has been checked and fully understands.

In ACM, 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, optimization, and dynamic. This ACM is not only good at simulations but it can also provide other tasks such as generating custom graphical and interfacing results.

In ACM, the real plant has been constructed so that we can monitor and check the reading of each of the part in the single and multiple effect evaporator plant. The construction of single and double effect evaporator as showed in figure 3 and 4.

The steady state simulations are performed for single and double evaporators. Sensitivity analyses are performed at the same time to understand the limitations of process variables such as steam conditions, operating temperatures and pressures in each evaporator. Sensitivity result is discussed in the next section.

6.0 Results

As discussed in section 3.0, the main objectives of this project were to understand the developed model equations written for a double effect evaporator and be able to develop similar programs for a single effect and triple effect evaporators. To test out the model equations, the steady state simulations were performed for three programs of single and multiple effect evaporators. Sensitivity analyses were performed at the same time to learn the limitations of process variables such as steam conditions with respect to concentration of liquid, operating temperatures with respect to mass flowrate of steam and concentration of product with respect to steam valve coefficient in each evaporator.

6.1 Reference Steady state run

By using computer based simulation technique, ACM and MATLAB, the efficiency of the mathematical model equation was being evaluated and presented for single and multiple effect evaporators. Table 7 shows the reference value for steady state simulation of single and multiple effect evaporators. This simulation was performed in ACM and it based on the initial variable as discussed in section 5.2.

Table 7: Reference value of steady state simulation

	In to First Evaporator	**Out of First Evaporator/ In of Second Evaporator**	**Out of the Second Evaporator**
Mass Flowrate of Total liquid , $\frac{kg}{kg}$	116.993	74.922	31.4851
Mass Flowrate of Glycol, $\frac{kg}{kg}$	4.09476	4.09476	4.09476
Mass Flowrate of Water, $\frac{kg}{kg}$	112.898	70.8272	27.3903
Concentration of Liquid, $\frac{kg}{kg}$	0.035 (Fixed)	0.0546536	0.130054
Mass Flowrate of Steam, $\frac{kg}{kg}$	42.6526	42.0711	43.4369

Based on Table 7, the increasing number of effect will cause the concentration of liquid to increase, and opposite to the mass flowrate of total liquid and water. This is because the water lost along with the vapour phase becoming a vapour. Besides that, the concentration of liquid become more concentrated.

6.2 Sensitivity Analysis

Sensitivity analysis was performed in ACM to investigate the limitations of process variables such as steam conditions and steam valve coefficient against concentration of product, mass flowrate of liquid, mass flowrate of steam and temperature.

The initial variable (see section 5.1.4) had been varying to investigate the limitation of mass flowrate of steam and steam valve coefficient for single and double effect evaporators. The sensitivity analysis was performed for two cases which were varying the mass flowrate of steam coming in of evaporator and the steam valve coefficient out of the evaporator. All recorded results is presented in Appendix H and Appendix I.

6.2.1 Sensitivity Analysis: Mass flowrate of steam (In of evaporator)

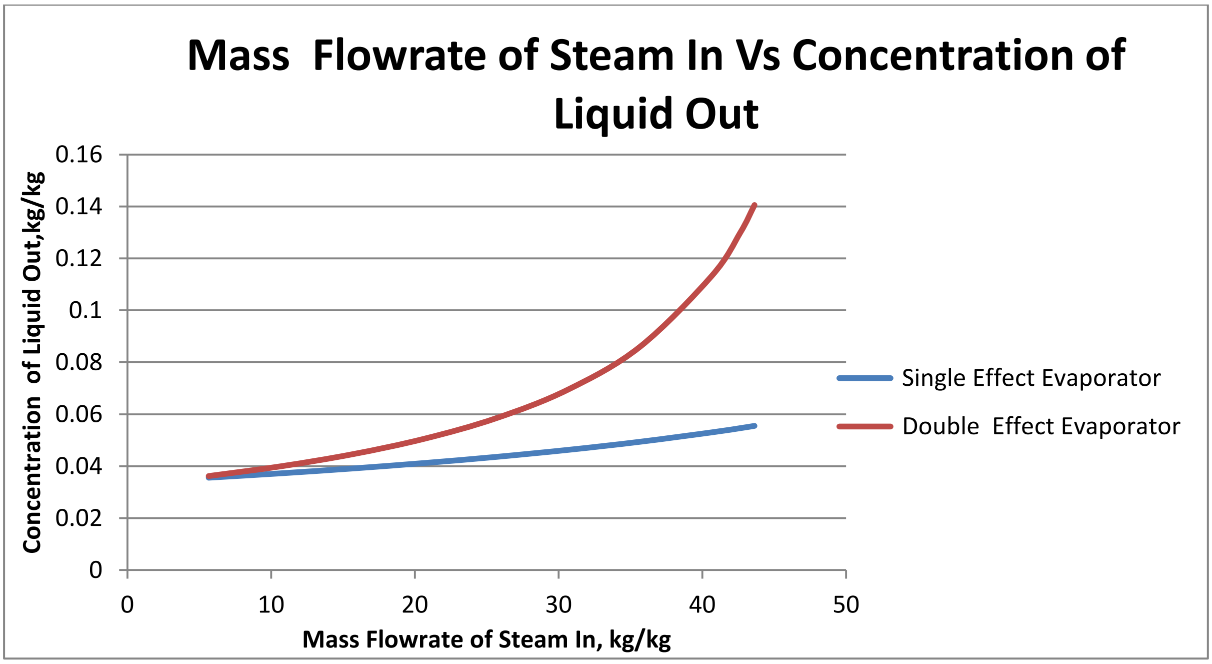


Figure 11: Mass Flowrate of Steam In Vs Concentration of Liquid Out

Figure 11 shows the relationship between mass flowrate of steam flow to the first effect against concentration of liquid out. The saturated steam is only used in the first effect. The second and the double effects are heated by the vapour coming out from the single effect. The requirements of steam in each effect, for a single effect evaporator concentrating from 0.035 $\frac{kg}{kg}$ up to 0.055 $\frac{kg}{kg}$ and for a double effect evaporator concentrating from 0.035 $\frac{kg}{kg}$ up to 0.14 $\frac{kg}{kg}$. Therefore, it can be seen clearly from the figure 11 that the concentration product for double effect evaporator increased exponentially compared with concentration product for single effect evaporator. This is because, the concentration continues to demonstrate certain limitation due to the high energy consumption. Conclusively, the increase of mass flowrate of steam affects the concentration of product.

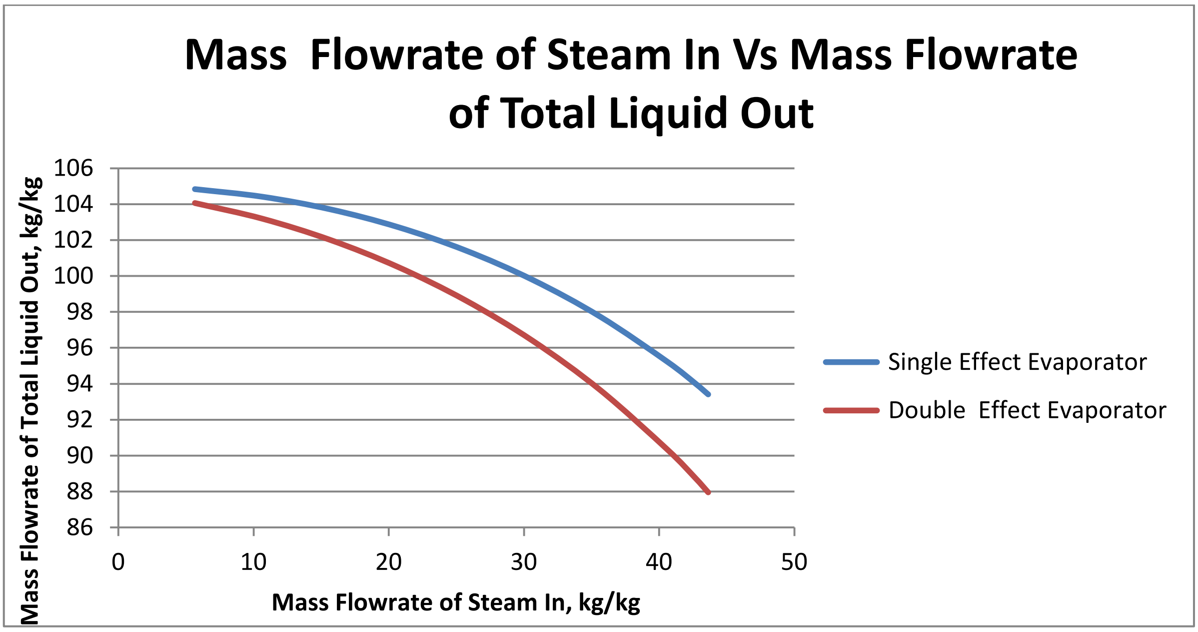


Figure 12: Mass Flowrate of Steam In Vs Mass Flowrate of Total Liquid Out

Figure 12 shows the relationship between mass flowrate of steam against mass flowrate of total liquid out of evaporator. It can be observed that the mass flowrate of steam affected the mass flowrate of total liquid out of evaporator; whereby increasing the mass flowrate of steam would decrease the mass flowrate of total liquid. The mass flowrate of total liquid for second effect lost more compare with single effect evaporator. The mass flowrate of total liquid lost and became vapour.

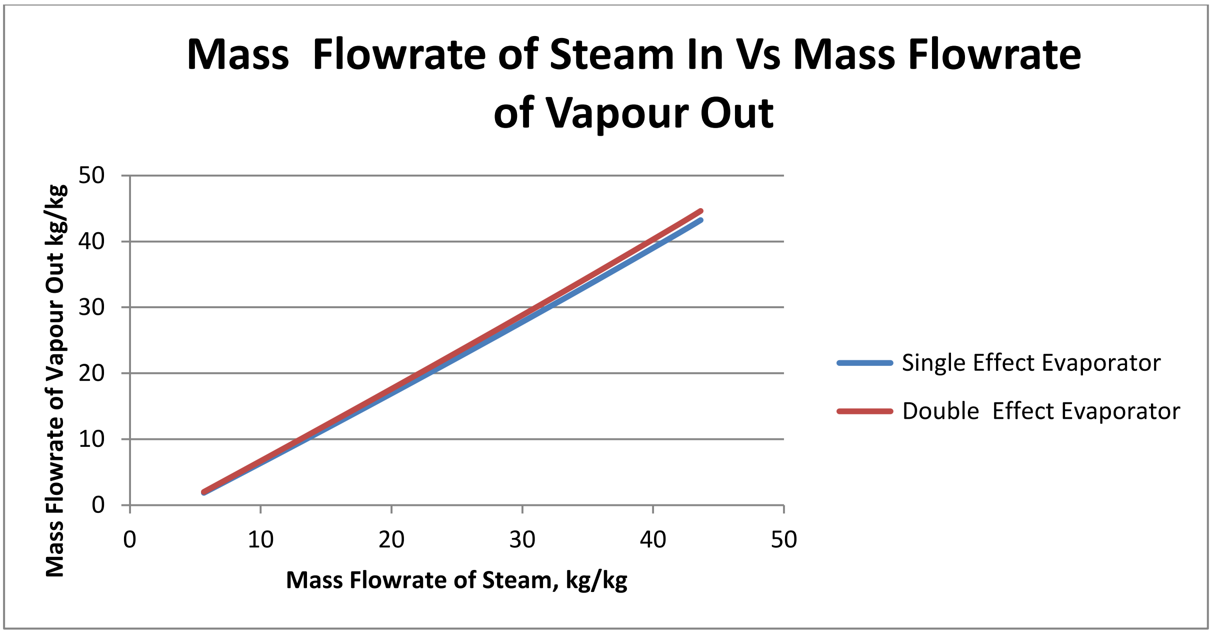


Figure 13: Mass Flowrate of Steam In Vs Mass Flowrate of Vapour Out

Figure 13 displays the relationship between mass flowrate of steam against mass flowrate of vapour out of evaporator. It can be seen clearly from Figure 13 that the mass flowrate of steam affected the mass flowrate of vapour out of evaporator; whereby increasing the mass flowrate of steam would increase the mass flowrate of vapour. There is no difference between the two systems because in the second evaporator, the steam in the second effect is the vapour from the first effect and that will condense at approximately the same temperature as it boiled.

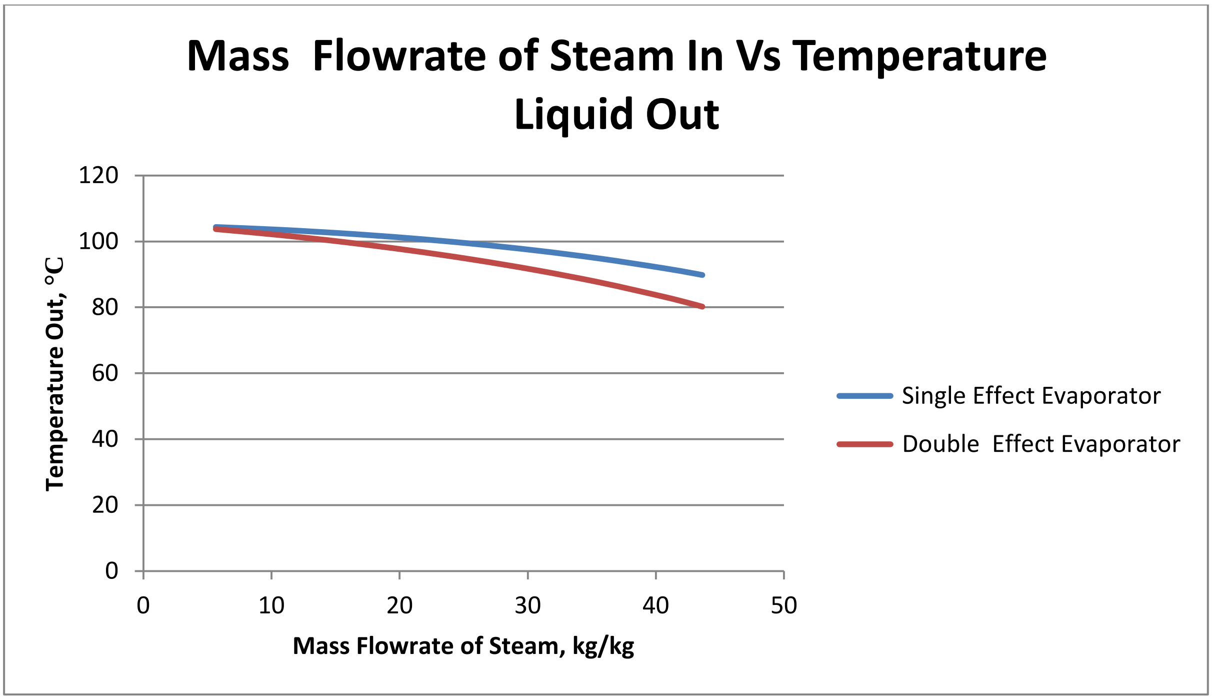


Figure 14: Mass Flowrate of Steam In Vs Temperature Liquid Out

Figure 14 represents the relationship between mass flowrate of steam against temperature liquid out of evaporator. Therefore, it shows a single effect evaporator temperature decreased from 103ºC down to 89ºC and for a double effect evaporator temperature from 103 ºC down to 80 ºC**.** This means the increase of mass flowrate of steam affects the temperature of liquid.

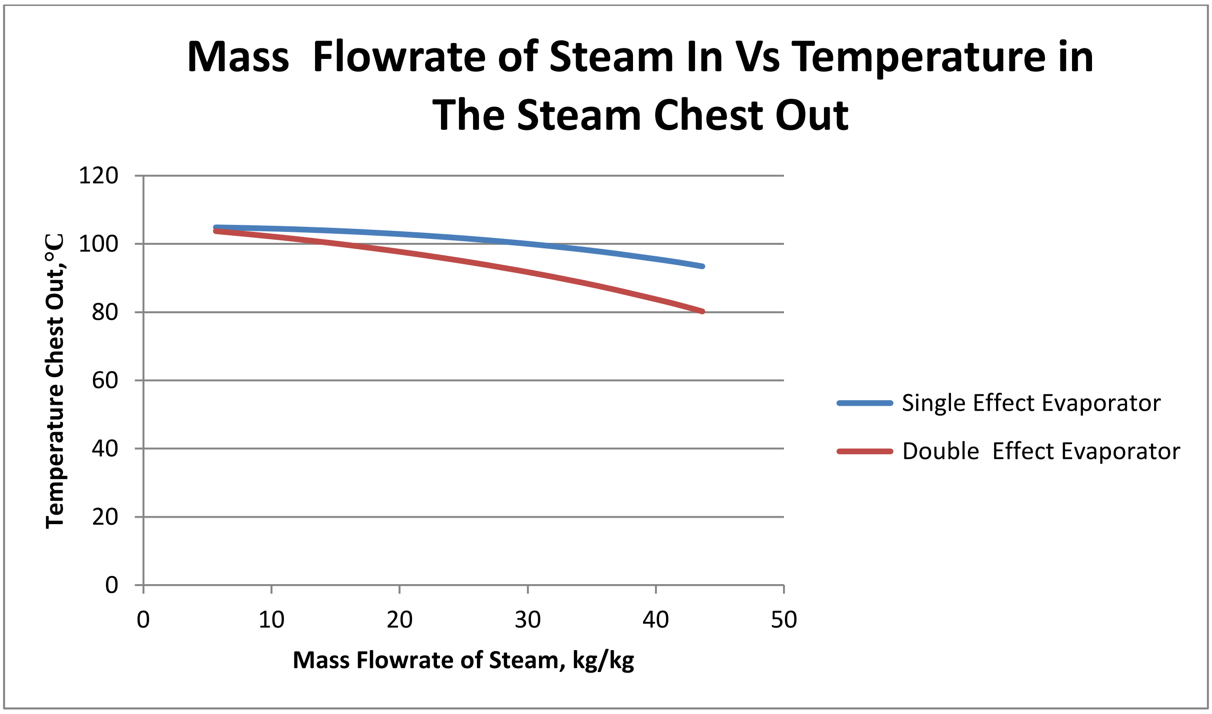


Figure 15: Mass Flowrate of Steam In Vs Temperature in The Steam Chest Out

Based on figure 15, the increased mass flowrate of steam slightly decreased the temperature in the steam chest. The range of mass flowrate of steam was tested from $5\frac{kg}{kg}$ to $43\frac{kg}{kg}$ while the temperature chest changed from 103 ºC to 93 ºC for single effect evaporator and 80 ºC for double effect evaporator. The temperature out for two effect system drops to lower value because the steam provided by the evaporation in the first effect will boil off liquid in the second effect, the boiling temperature in the second effect must be lower and so that effect must be under lower pressure.

6.2.2 Sensitivity Analysis: Steam Valve coefficient (Out of evaporator)

For this case, the sensitivity analysis was carried out to investigate the limitation of steam valve coefficient out of evaporator by varying this valve.

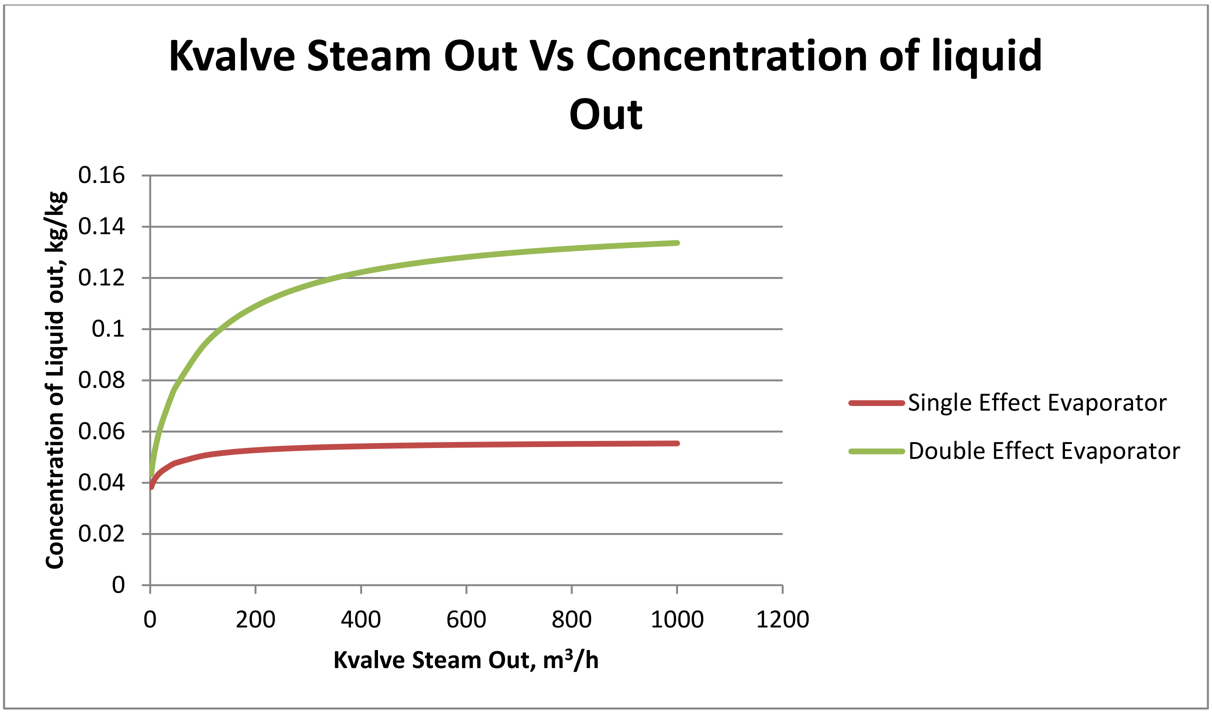


Figure 16: Kvalve Steam Out Vs Concentration of liquid Out

Figure 16 exhibits the relationship between steam valve coefficients (Kvalve) out of evaporator against concentration of liquid out. The steam valve coefficients out of evaporator locate after each effect evaporators and it used to control steam out of evaporator. The steam valve coefficient for both evaporators affected the concentration, for a single effect evaporator concentrating from 0.04 $\frac{kg}{kg}$ up to 0.013 $\frac{kg}{kg}$ and for a double effect evaporator concentrating from 0.04 $\frac{kg}{kg}$ up to 0.055 $\frac{kg}{kg}$. Therefore, it is clear from the Figure 16 that the concentration of product for double effect evaporator increased exponentially. For single effect evaporator at the beginning the concentration increased then it did not change and remained constant. This means the limit for steam valve coefficient to operate a single effect evaporator lies between 2$\frac{m^3}{h}$ and 200$\frac{m^3}{h}$. The simple systems such as single effect evaporator only used a small range of valve coefficient for reduce the operating cost.

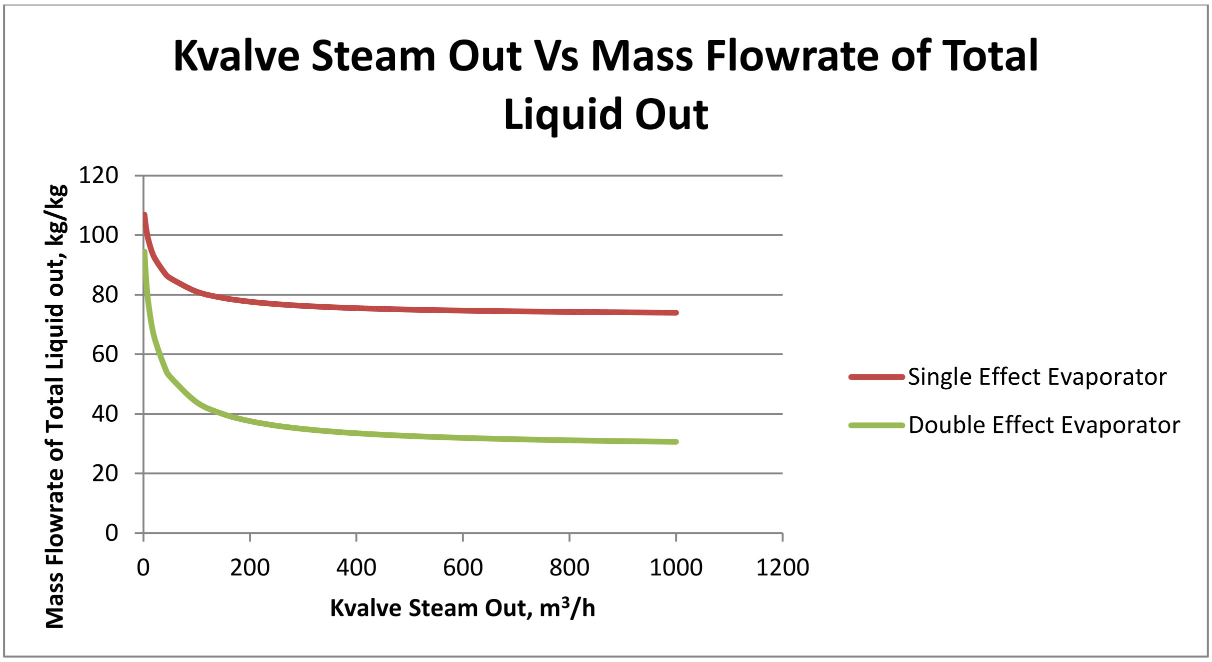


Figure 17: Kvalve Steam Out Vs Mass Flowrate of Total Liquid Out

Figure 17 shows the relationship between steam valve coefficients out of evaporator against mass flowrate of total liquid out of evaporator. It can be seen clearly from Figure 17 that the steam valve coefficients affected the mass flowrate of total liquid out of evaporator; whereby increasing the steam valve coefficients would decrease the mass flowrate of total liquid. The mass flowrate of total liquid lost and became vapour. For double effect evaporator, the mass flowrate of total liquid out evaporator loss was greater compared with single effect evaporator. For single effect evaporators at the beginning, the mass flowrate of total liquid decreased rapidly then it did not change much. This means the limit for steam valve coefficient to operate a single effect evaporator is between $2\frac{m^3}{h}$ to $200\frac{m^3}{h}$. This is because; the more complex a system such as double effect evaporator used a large range of valve coefficient for concentrate more liquid.

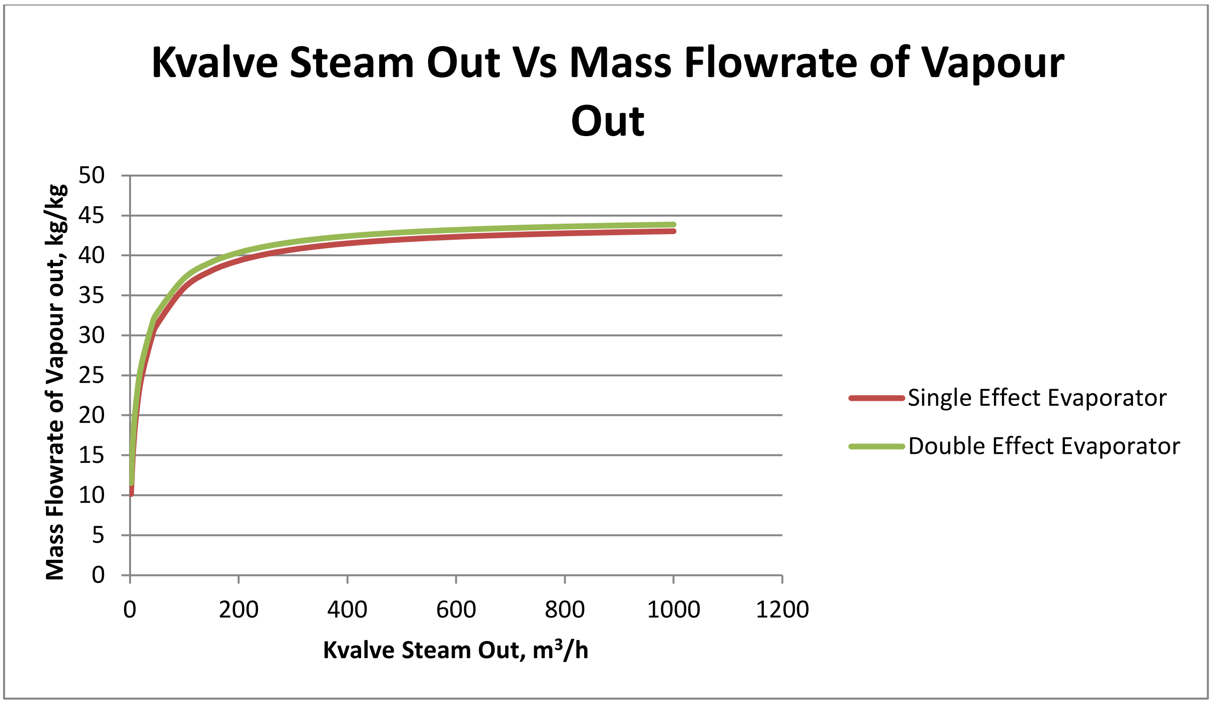


Figure 18: Kvalve Steam Out Vs Mass Flowrate of Vapour Out

Figure 18 represents the relationship between steam valve coefficients out of evaporator against mass flowrate of vapour out of evaporator. It can be observed that the steam valve coefficients affected the mass flowrate of vapour out of evaporator; whereby increasing the mass flowrate of steam would increase the mass flowrate of vapour. There is no difference between the two systems because in the second evaporator, the steam in the second effect is the vapour from the first effect and that will condense at approximately the same temperature as it boiled.

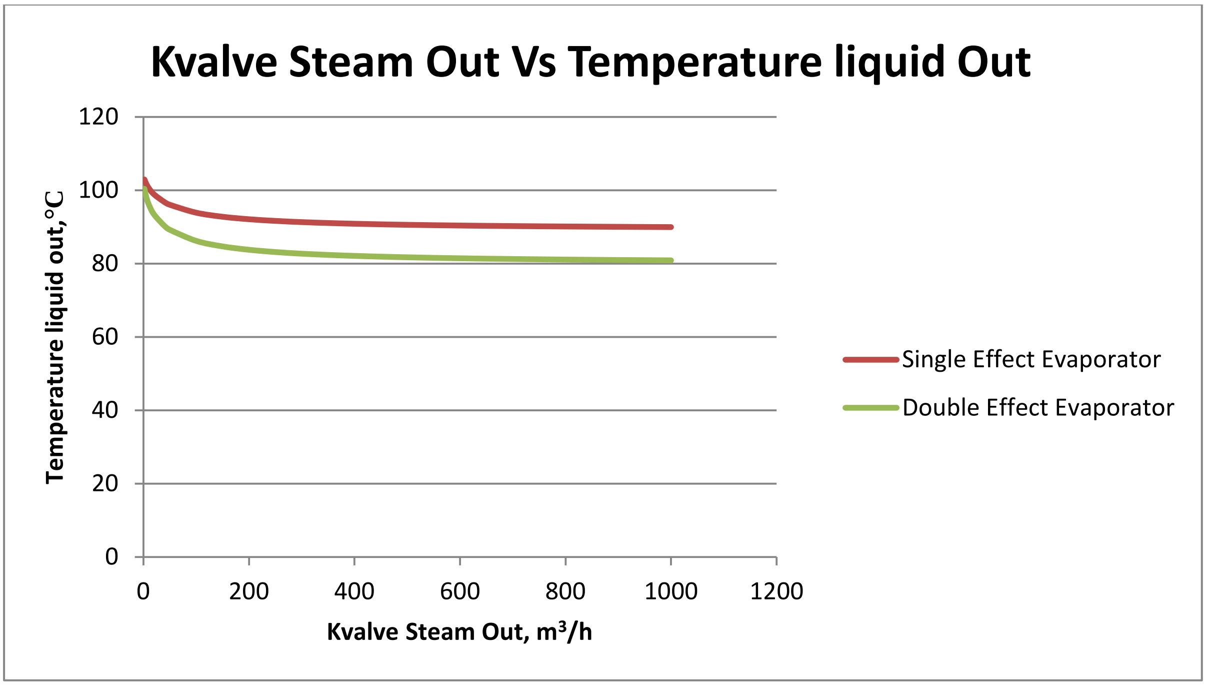


Figure 19: Kvalve Steam Out Vs Temperature liquid Out

Figure 19 shows the relationship between steam valve coefficients out of evaporator against temperature liquid out of evaporator. Therefore, it can be seen from Figure 19 that a single effect evaporator temperature decreased from 105ºC down to 90ºC and for a double effect evaporator temperature from 105 ºC down to 81 ºC**.** It is obvious that a temperature of liquid remained constant after point 200$\frac{m^3}{h}$. This means the increase in steam valve coefficients affected the temperature of liquid at point 5$\frac{m^3}{h}$ to 200$\frac{m^3}{h}$; beyond this point, the steam valve coefficient did not affect the temperature of liquid. This because, a small range of valve coefficient is able to reduce the temperature liquid out of both effect.

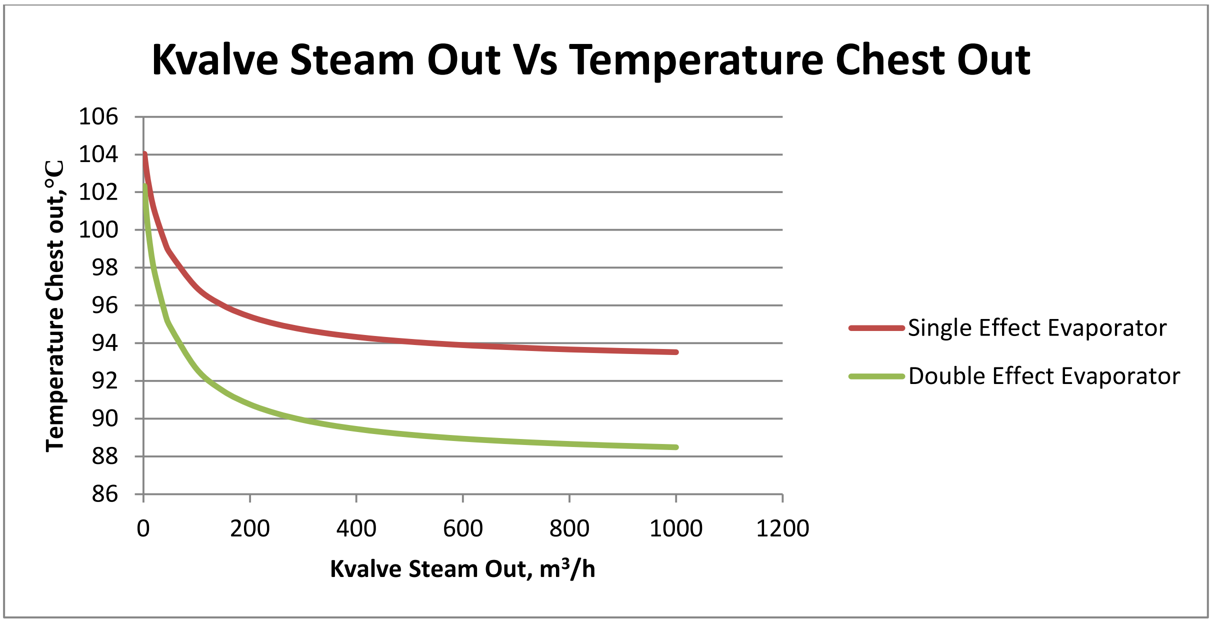


Figure 20: Kvalve Steam Out Vs Temperature Chest Out

Based on Figure 20, the increase in mass flowrate of steam slightly decreased the temperature chest. The range of steam valve coefficients was varying while the temperature chest was changing from 104 ºC to 93 ºC for single effect evaporator and 88 ºC for double effect evaporator. Similar with previous graph, a small range of valve coefficient is able to reduce the temperature liquid out of both effects.

7.0 Conclusion

This section discusses the achievements and efforts made throughout this project. The aims will be reviewed again, and achievements will be presented.

In the literature review section, this report has briefly present the available methods for recovering glycol and the software packages used to develop the models of the process to recover glycol. The two methods found in the literature to recover glycol are Distillation columns and Evaporators Effect. This case study is similar to second method, which is recovering glycol using evaporator effect.

The EXCEL, MATLAB, and ACM are software used to develop single and double effect evaporator system. In this thesis, EXCEL software was used to investigate the mathematical model equation, while MATLAB and ACM software was used to develop the others steady state models which is single and multiple effect evaporators. As mention at the beginning, double effect evaporator case study was taken from ACM.

Investigating and understanding the developed model equations written for a double effect evaporator case study has been fully succeeded. All mathematical equations from Model of steamer, feeder, liquid pump, liquid valve and evaporator were checked one by one using EXCEL software. Then, a similar program had been developed to discover the capability of single and double effect evaporator system in MATLAB and ACM.

In MATLAB, the mathematical model equations had been rearranged in particular order to perform the simulation. So, all unknowns have calculated. This case study has two unknown and, this unknown was assumed from the execution of ASPEN.

In ACM, the steady state model had been developed for single effect evaporator and triple effect evaporator. Unfortunately, for triple effect evaporators were not fully functioning, thus further investigation needed to solve this issues. At the same time, sensitivity analysis was carried out to investigate the limitations of process variables such as steam conditions and steam valve coefficient against concentration of product, mass flowrate of liquid, mass flowrate of steam, temperature liquid, and temperature chest. For this thesis pressure have a correlation with temperature, so when temperature changed the pressure also changed.

Based on sensitivity analysis results, it is to conclude that the double effect evaporator concentrate more product compared to single effect evaporator and more economic. The double effect evaporator has a large limit for steam valve coefficient compared with single effect evaporator. This analysis will used to compare with others effect soon.

This project is a privilege for the researcher to gain valuable knowledge in exploring the software and mathematical equation for different effect of evaporator system.

7.1 Future Work

This section discusses possible future directions that can be undertaken by future students working on this project.

This thesis covers the understanding of mathematical model of single and multiple effect evaporators with the model developed by ASPEN technology. It has been discussing the developed steady state model for single and double effect in MATLAB and ACM and sensitivity analysis result. There are some suggestions that can be made for future work. They are:

1) Develop steady state model for triple effect evaporator using MATLAB and ACM,

To investigate the capability of different effect evaporator, it is useful to compare this project with different effect evaporators, such as triple and fourth effect. In section 2.1.2., they used three effect evaporators for the recovery of glycol solution.

2) Investigate and develop optimization model using MATLAB and ACM.

The cost objective function given for the double effect evaporator needs to be studied further and modified before applying to the models of the single and triple effect evaporators. Optimization simulations need to be performed for three programs of single, double and triple effect evaporators.

3) Develop Dynamic models in MATLAB then in ACM

Develop Dynamic models in MATLAB then in ACM for dynamic simulations and control system designs in the future.

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Appendices

Appendix A (steady State Variable)

Steamer

	Value	Units	Spec
ComponentList	Default		
SteamOut.ComponentList	Default		
SteamOut.MassFlow	42.6525		Free
SteamOut.P	120.782		Free
TSteam	105	C	Fixed

Steam Supply

	Value	Units	Spec
ComponentList	Default		
Dest.ComponentList	Default		
Source.ComponentList	Default		
>ComponentList	Default		
>MassFlow	42.6525		Free
>P	120.782		Free

Feeder

	Value	Units	Spec
ComponentList	Default		
LiquidOut.ComponentList	Default		
LiquidOut.h	115.377		Free
LiquidOut.MassFlow("Glycol")	4.09476		Free
LiquidOut.MassFlow("Water")	112.898		Free
LiquidOut.P	100		Fixed
TempOut	88	C	Fixed
TotalFlow	116.993		Free
X	0.035	kg/kg	Fixed

Liquor

	Value	Units	Spec
ComponentList	Default		
Dest.ComponentList	Default		
Source.ComponentList	Default		
>ComponentList	Default		
>h	115.377		Free
>MassFlow("Glycol")	4.09476		Free
>MassFlow("Water")	112.898		Free

Steam supply

	Value	**Units**	**Spec**
>>ComponentList	Default		
>>MassFlow	42.6525		Free
>>P	120.782		Free
ComponentList	Default		
Dest.ComponentList	Default		
Source.ComponentList	Default		

Steam line

	Value	**Units**	**Spec**
>>ComponentList	Default		
>>MassFlow	42.6525		Free
>>P	120.782		Free
ComponentList	Default		
Dest.ComponentList	Default		
Source.ComponentList	Default		

Liquor

	Value	**Units**	**Spec**
>>ComponentList	Default		
>>h	115.377		Free
>>MassFlow("Glycol")	4.09476		Free
>>MassFlow("Water")	112.898		Free
>>P	100		Fixed
ComponentList	Default		
Dest.ComponentList	Default		
Source.ComponentList	Default		

Liquor line

	Value	**Units**	**Spec**
>>ComponentList	Default		
>>h	115.377		Free
>>MassFlow("Glycol")	4.09476		Free
>>MassFlow("Water")	112.898		Free
>>P	100		Fixed
ComponentList	Default		
Dest.ComponentList	Default		
Source.ComponentList	Default		

Steam valve

	Value	Units	Spec
ComponentList	Default		
Input1.ComponentList	Default		
Input1.MassFlow	42.6525		Free
Input1.P	120.782		Free
KValve	46.361		Fixed
Output1.ComponentList	Default		
Output1.MassFlow	105		Free
Output1.P	81.5408		Free

Pump

	Value	Units	Spec
ComponentList	Default		
DelP	44.27		Fixed
Input1.ComponentList	Default		
Input1.h	115.377		Free
Input1.MassFlow("Glycol")	4.09476		Free
Input1.MassFlow("Water")	112.898		Free
Input1.P	100		Free
Output1.ComponentList	Default		
Output1.h	115.377		Free
Output1.MassFlow("Glycol")	4.09476		Free
Output1.MassFlow("Water")	112.898		Free
Output1.P	144.27		Free
TotFlow	116.993		Free

Valve

	Value	Units	Spec
ComponentList	Default		
Input1.ComponentList	Default		
Input1.h	115.377		Free
Input1.MassFlow("Glycol")	4.09476		Free
Input1.MassFlow("Water")	112.898		Free
Input1.P	144.27		Free
KValve	185		Fixed
Output1.ComponentList	Default		
Output1.h	115.377		Free
Output1.MassFlow("Glycol")	4.09476		Free
Output1.MassFlow("Water")	112.898		Free
Output1.P	70.2842		Free
TotFlow	116.993		Free

Evaporator 1

	Value	Units	Spec
ComponentList	Default		
Con	0.0546536	kg/kg	Free
ConcIn	0.035	kg/kg	Free
ConcOut	0.0546536	kg/kg	Free
Enth	124.65		Free
Hold	3300	kg	Fixed
HTArea	168	m2	Fixed
HTCoeff	150		Fixed
KVapLine	521.33		Fixed
Lambda	2080.8		Fixed
LiqOut	74.922		Free
LiquidIn.ComponentList	Default		
LiquidIn.h	115.377		Free
LiquidIn.MassFlow("Glycol")	4.09476		Free
LiquidIn.MassFlow("Water")	112.898		Free
LiquidIn.P	70.2842		Free
LiquidOut.ComponentList	Default		
LiquidOut.h	124.65		Free
LiquidOut.MassFlow("Glycol")	4.09476		Free
LiquidOut.MassFlow("Water")	70.8272		Free
LiquidOut.P	70.2842		Free
SteamEnthOut	2208.42		Free
SteamIn.ComponentList	Default		
SteamIn.MassFlow	105		Free
SteamIn.P	81.5408		Free
SteamOut.ComponentList	Default		
SteamOut.MassFlow	42.071		Free
SteamOut.P	66.8891		Free
TChest	94.0318	C	Free

Steam out

	Value	**Units**	**Spec**
ComponentList	Default		
Dest.ComponentList	Default		
Source.ComponentList	Default		
>ComponentList	Default		
>MassFlow	42.071		Free
>P	66.8891		Free

Liquid Out

	Value	**Units**	**Spec**
ComponentList	Default		
Dest.ComponentList	Default		
Source.ComponentList	Default		
>ComponentList	Default		
>h	124.65		Free
>MassFlow("Glycol")	4.09476		Free
>MassFlow("Water")	70.8272		Free
>P	70.2842		Free

Temp	90.5099	C	Free

Pump 2

	Value	Units	Spec
ComponentList	Default		
DelP	10		Fixed
Input1.ComponentList	Default		
Input1.h	124.65		Free
Input1.MassFlow("Glycol")	4.09476		Free
Input1.MassFlow("Water")	70.8272		Free
Input1.P	70.2842		Free
Output1.ComponentList	Default		
Output1.h	124.65		Free
Output1.MassFlow("Glycol")	4.09476		Free
Output1.MassFlow("Water")	70.8272		Free
Output1.P	80.2842		Free
TotFlow	74.922		Free

Valve

	Value	Units	Spec
ComponentList	Default		
Input1.ComponentList	Default		
Input1.h	124.65		Free
Input1.MassFlow("Glycol")	4.09476		Free
Input1.MassFlow("Water")	70.8272		Free
Input1.P	80.2842		Free
KValve	172.178		Free
Output1.ComponentList	Default		
Output1.h	124.65		Free
Output1.MassFlow("Glycol")	4.09476		Free
Output1.MassFlow("Water")	70.8272		Free
Output1.P	47.6825		Free
TotFlow	74.922		Free

Evaporator 2

	Value	Units	Spec
ComponentList	Default		
Con	0.130054	kg/kg	Free
ConcIn	0.0546536	kg/kg	Free
ConcOut	0.130054	kg/kg	Free
Enth	83.8625		Free
Hold	2500	kg	Fixed
HTArea	145	m2	Fixed
HTCoeff	80		Fixed
KVapLine	703.35		Fixed
Lambda	2080.8		Fixed
LiqOut	31.4851		Free
LiquidIn.ComponentList	Default		
LiquidIn.h	124.65		Free
LiquidIn.MassFlow("Glycol")	4.09476		Free
LiquidIn.MassFlow("Water")	70.8272		Free
LiquidIn.P	47.6825		Free
LiquidOut.ComponentList	Default		
LiquidOut.h	83.8625		Free
LiquidOut.MassFlow("Glycol")	4.09476		Free
LiquidOut.MassFlow("Water")	27.3903		Free
LiquidOut.P	47.6825		Free
SteamEnthOut	2169.58		Free
SteamIn.ComponentList	Default		
SteamIn.MassFlow	42.071		Free
SteamIn.P	66.8891		Free
SteamOut.ComponentList	Default		
SteamOut.MassFlow	43.4369		Free
SteamOut.P	45		Fixed
TChest	88.7717	C	Free

Steam out

	Value	Units	Spec
ComponentList	Default		
Dest.ComponentList	Default		
Source.ComponentList	Default		
>ComponentList	Default		
>MassFlow	43.4369		Free
>P	45		Fixed

Pump

	Value	Units	Spec
ComponentList	Default		
DelP	90.3		Fixed
Input1.ComponentList	Default		
Input1.h	83.8625		Free
Input1.MassFlow("Glycol")	4.09476		Free
Input1.MassFlow("Water")	27.3903		Free
Input1.P	47.6825		Free
Output1.ComponentList	Default		
Output1.h	83.8625		Free
Output1.MassFlow("Glycol")	4.09476		Free
Output1.MassFlow("Water")	27.3903		Free
Output1.P	137.983		Free
TotFlow	31.4851		Free

Temp	81.225	C	Free

Steam

	Value	Units	Spec
ComponentList	Default		
Dest.ComponentList	Default		
Source.ComponentList	Default		
>ComponentList	Default		
>MassFlow	43.4369		Free
>P	45		Fixed

Valve

	Value	**Units**	**Spec**
ComponentList	Default		
Dest.ComponentList	Default		
Source.ComponentList	Default		
>ComponentList	Default		
>h	83.8625		Free
>MassFlow("Glycol")	4.09476		Free
>MassFlow("Water")	27.3903		Free
>P	137.983		Free

Componentlist	Default		
Input1.ComponentList	Default		
Input1.h	83.8625		Free
Input1.MassFlow("Glycol")	4.09476		Free
Input1.MassFlow("water")27.3903			Free
Input1.P	137.983		Free
Kvalve	55.1262		Free

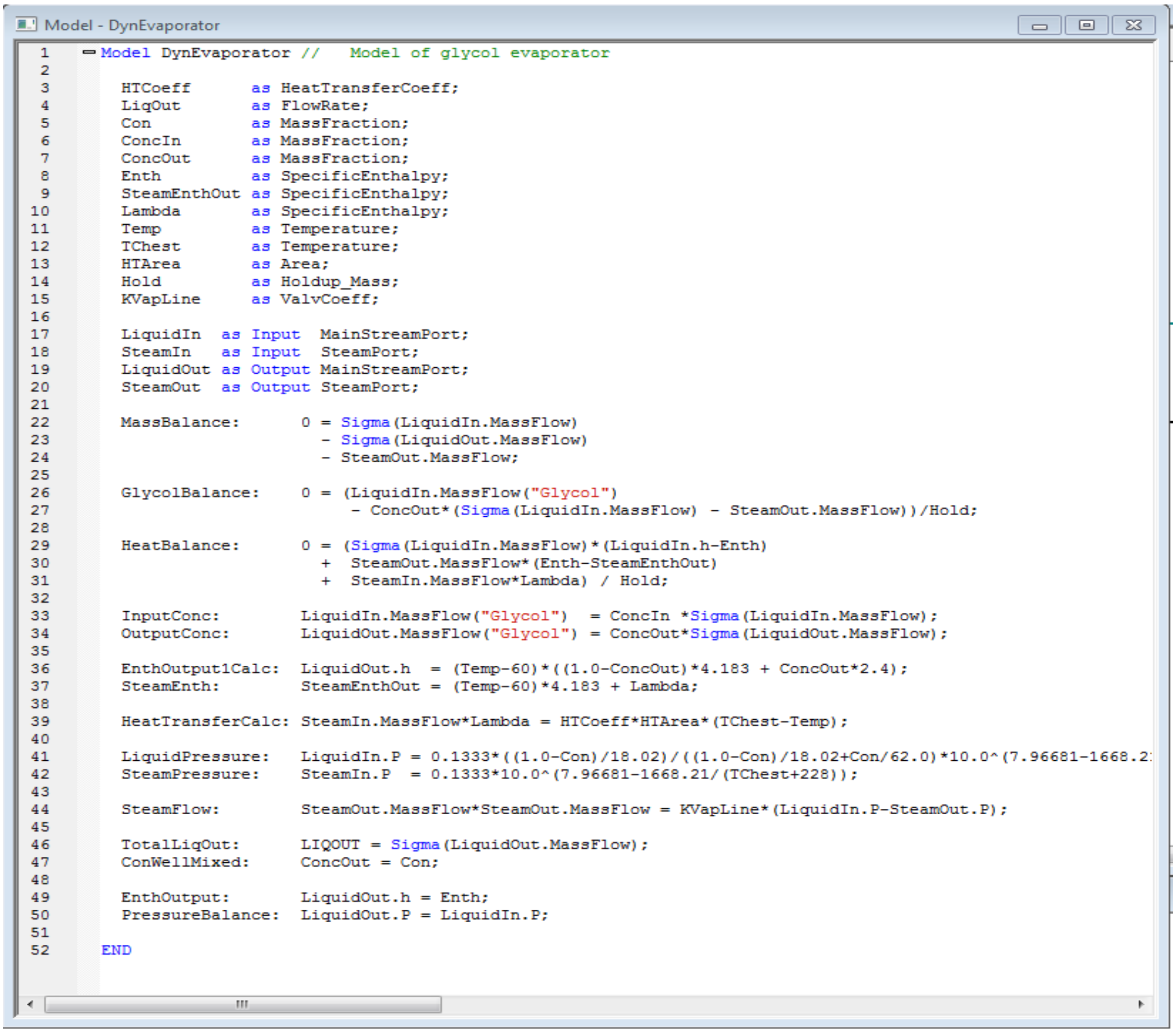
Concentrate

	Value	Units	Spec
ComponentList	Default		
Dest.ComponentList	Default		
Source.ComponentList	Default		
>ComponentList	Default		
>h	83.8625		Free
>MassFlow("Glycol")	4.09476		Free
>MassFlow("Water")	27.3903		Free
>P	120		Fixed

Output1.ComponentListDefault	Default		
Output1.h	83.8625		Free
output1.massFlow("Glycol")	4.09476		Free
output1.massFlow("Water")27.3903			Free
Output1.P	120		Fixed
TotFlow	31.4851		Free

Appendix B (ACM Model)

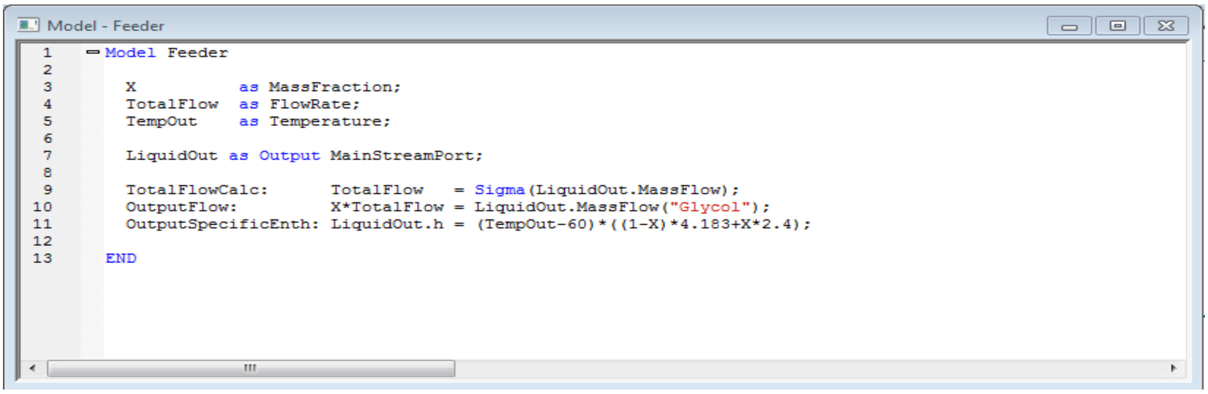
Model Evaporator



```
Model DynEvaporator //   Model of glycol evaporator

   HTCoeff      as HeatTransferCoeff;
   LiqOut       as FlowRate;
   Con          as MassFraction;
   ConcIn       as MassFraction;
   ConcOut      as MassFraction;
   Enth         as SpecificEnthalpy;
   SteamEnthOut as SpecificEnthalpy;
   Lambda       as SpecificEnthalpy;
   Temp         as Temperature;
   TChest       as Temperature;
   HTArea       as Area;
   Hold         as Holdup_Mass;
   KVapLine     as ValvCoeff;

   LiquidIn  as Input  MainStreamPort;
   SteamIn   as Input  SteamPort;
   LiquidOut as Output MainStreamPort;
   SteamOut  as Output SteamPort;

   MassBalance:      0 = Sigma(LiquidIn.MassFlow)
                       - Sigma(LiquidOut.MassFlow)
                       - SteamOut.MassFlow;

   GlycolBalance:    0 = (LiquidIn.MassFlow("Glycol")
                          - ConcOut*(Sigma(LiquidIn.MassFlow) - SteamOut.MassFlow))/Hold;

   HeatBalance:      0 = (Sigma(LiquidIn.MassFlow)*(LiquidIn.h-Enth)
                       +  SteamOut.MassFlow*(Enth-SteamEnthOut)
                       +  SteamIn.MassFlow*Lambda) / Hold;

   InputConc:        LiquidIn.MassFlow("Glycol")  = ConcIn *Sigma(LiquidIn.MassFlow);
   OutputConc:       LiquidOut.MassFlow("Glycol") = ConcOut*Sigma(LiquidOut.MassFlow);

   EnthOutput1Calc:  LiquidOut.h  = (Temp-60)*((1.0-ConcOut)*4.183 + ConcOut*2.4);
   SteamEnth:        SteamEnthOut = (Temp-60)*4.183 + Lambda;

   HeatTransferCalc: SteamIn.MassFlow*Lambda = HTCoeff*HTArea*(TChest-Temp);

   LiquidPressure:   LiquidIn.P = 0.1333*((1.0-Con)/18.02)/((1.0-Con)/18.02+Con/62.0)*10.0^(7.96681-1668.2
   SteamPressure:    SteamIn.P  = 0.1333*10.0^(7.96681-1668.21/(TChest+228));

   SteamFlow:        SteamOut.MassFlow*SteamOut.MassFlow = KVapLine*(LiquidIn.P-SteamOut.P);

   TotalLiqOut:      LIQOUT = Sigma(LiquidOut.MassFlow);
   ConWellMixed:     ConcOut = Con;

   EnthOutput:       LiquidOut.h = Enth;
   PressureBalance:  LiquidOut.P = LiquidIn.P;

 END
```

Figure 21: Model of Evaporator

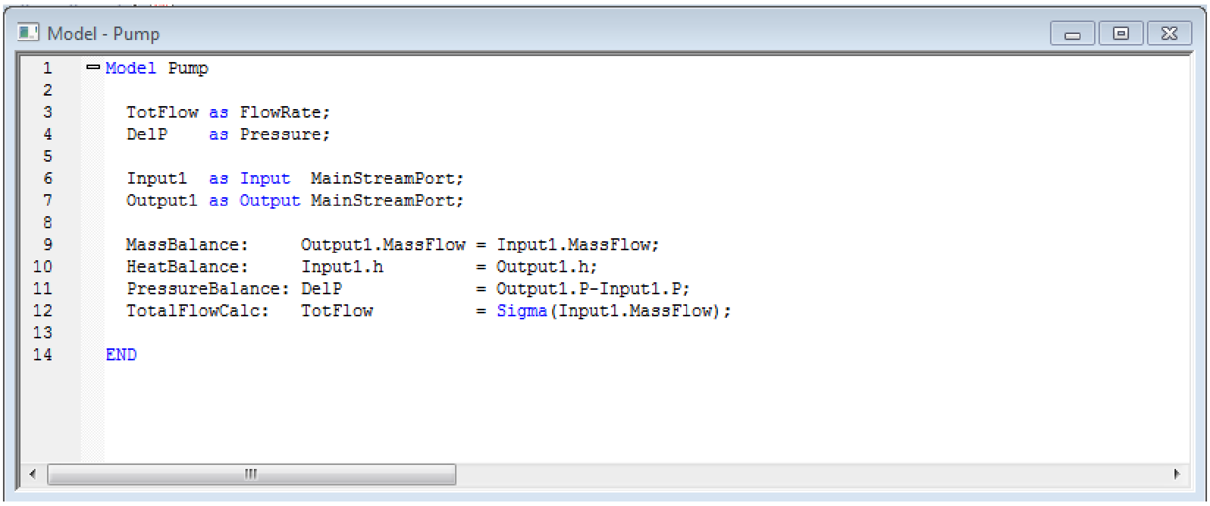
Model Feeder



```
Model Feeder

   X          as MassFraction;
   TotalFlow  as FlowRate;
   TempOut    as Temperature;

   LiquidOut as Output MainStreamPort;

   TotalFlowCalc:        TotalFlow   = Sigma(LiquidOut.MassFlow);
   OutputFlow:           X*TotalFlow = LiquidOut.MassFlow("Glycol");
   OutputSpecificEnth: LiquidOut.h = (TempOut-60)*((1-X)*4.183+X*2.4);

 END
```

Figure 22: Model of Feeder

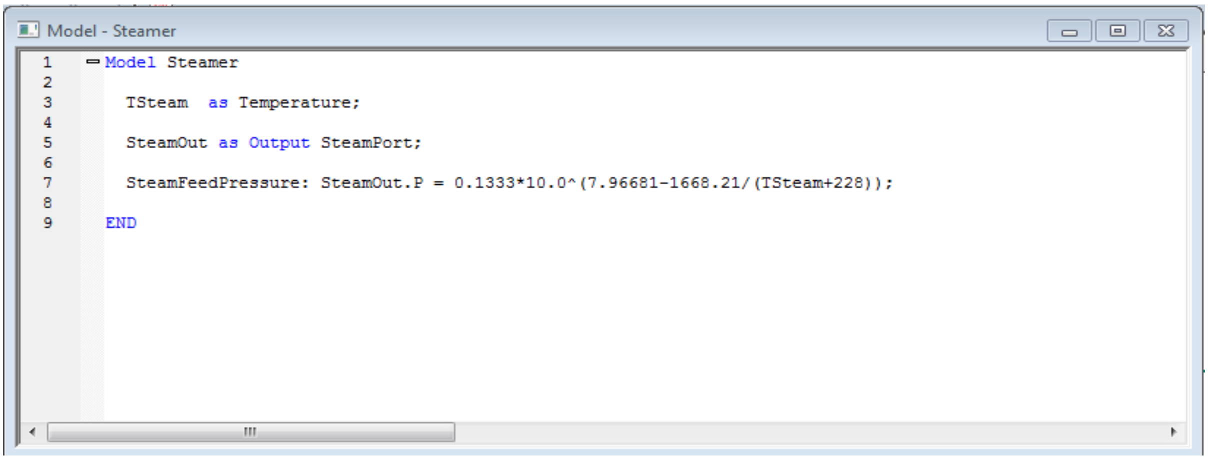
Model Liquid Pump



```
Model Pump

  TotFlow as FlowRate;
  DelP    as Pressure;

  Input1  as Input  MainStreamPort;
  Output1 as Output MainStreamPort;

  MassBalance:     Output1.MassFlow = Input1.MassFlow;
  HeatBalance:     Input1.h         = Output1.h;
  PressureBalance: DelP             = Output1.P-Input1.P;
  TotalFlowCalc:   TotFlow          = Sigma(Input1.MassFlow);

END
```

Figure 23: Model of Liquid Pump

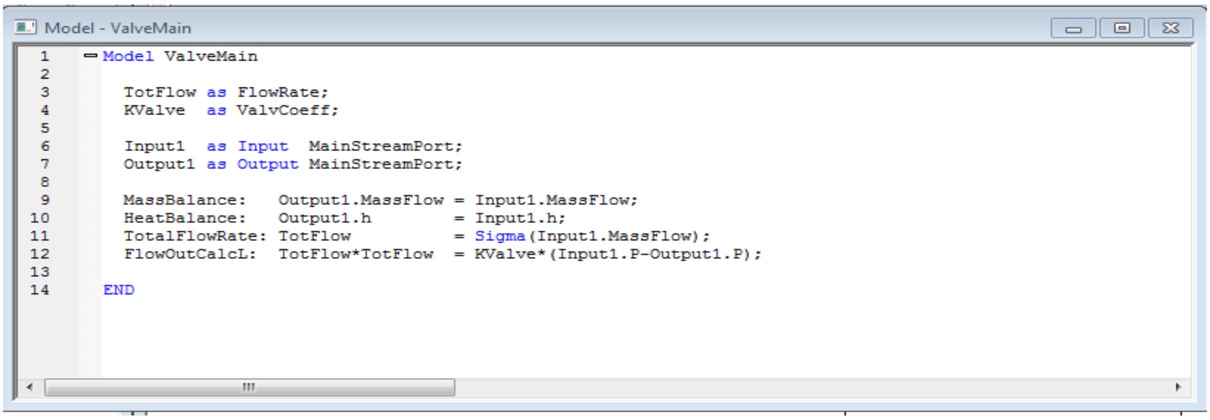
Model Steamer



```
Model Steamer

  TSteam  as Temperature;

  SteamOut as Output SteamPort;

  SteamFeedPressure: SteamOut.P = 0.1333*10.0^(7.96681-1668.21/(TSteam+228));

END
```

Figure 24: Model of Steamer

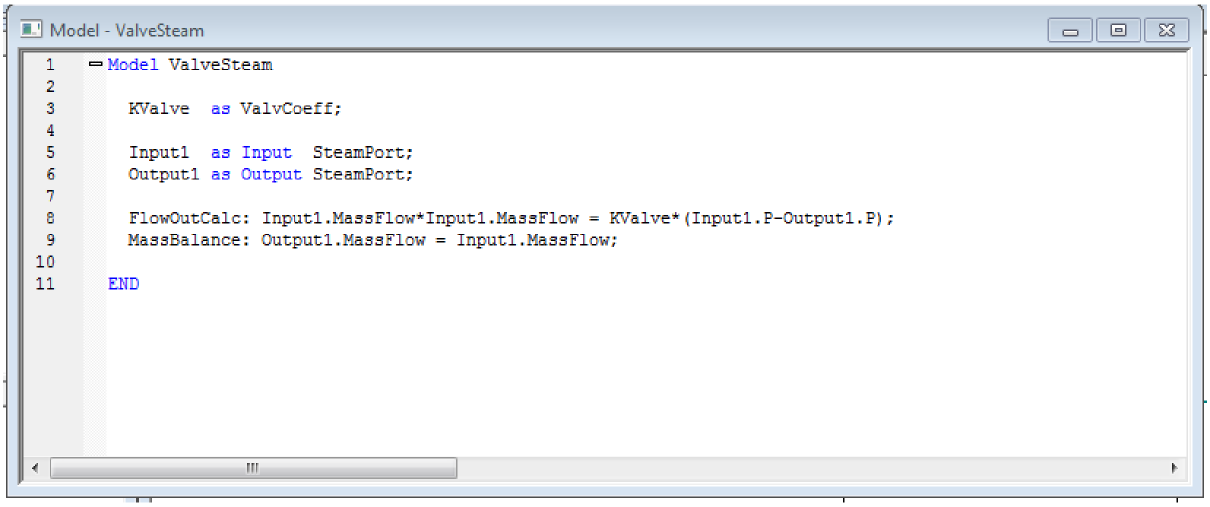
Model Liquid Valve



```
Model ValveMain

  TotFlow as FlowRate;
  KValve  as ValvCoeff;

  Input1  as Input  MainStreamPort;
  Output1 as Output MainStreamPort;

  MassBalance:   Output1.MassFlow = Input1.MassFlow;
  HeatBalance:   Output1.h        = Input1.h;
  TotalFlowRate: TotFlow          = Sigma(Input1.MassFlow);
  FlowOutCalcL:  TotFlow*TotFlow  = KValve*(Input1.P-Output1.P);

END
```

Figure 25: Model of Liquid Valve

Model Steam Valve



```
Model ValveSteam

  KValve  as ValvCoeff;

  Input1  as Input  SteamPort;
  Output1 as Output SteamPort;

  FlowOutCalc: Input1.MassFlow*Input1.MassFlow = KValve*(Input1.P-Output1.P);
  MassBalance: Output1.MassFlow = Input1.MassFlow;

END
```

Figure 26: Model of Steam Valve

Appendix C (Checking Process Model)

Single effect evaporator

🟨 Free
🟥 Fixed

Steamer		Calculation
Msteam =	42.6525	
Psteam =	120.782	120.7815253
Tsteam =	105	
hsteam=	2269.035	

	code	Matlab	
assume given	ST_Flow	42.6525	How they calculate
calculate	Pst_stm	120.7815	Calculate from formula
	Tst_stm	105	

Steam Supply			
Mst	42.6525		Same as steamer
Pst	120.782		Same as steamer

Steam Valve		Calculation
Min	42.6525	
Pin	120.782	
Kvalve	46.361	
Mout	42.6525	
Pout	81.5408	81.5413504
Tout	94.0318	
Ho_vst	2223.155	

	code	matlab	
assume given	ST_Flow	42.6525	Same as steamer
as steamer value	Pst_in	120.7815	Same as steamer
given	Kvst	46.361	
in=out	ST_Flow	42.6525	input = output
calculate	Pst_out	81.5409	Calculate from formula pressure drop (120.782-81.5408)
calculate	temp_chest	94.0318	

Feeder		Calculation
h^out	115.377	115.3767
mg	4.09476	4.094755
mw	112.898	112.8982
Pout	100	32.46873
Tout	88	88.00008
Mtotal	116.993	116.9928
X	0.035	

	code	matlab	
calculate	h_out	115.3767	Calculate from formula (different temp*((1-x)*Cpw)+Cpg*x)
calculate	Mg	4.0948	Calculate from formula
calculate	Mw	112.8982	Calculate from formula
given	Plf	100	
given	Tlf	88	correlation t and enthalpy
assume given	Feed	116.993	Calculate from formula (total=mg+mw)
given	Xf	0.035	Concentration require

Liquor in		Calculation
h^	115.377	
Mg	4.09476	
Mw	112.898	
P	100	

Same as feeder
Same as feeder
Same as feeder

Pump		Calculation
Del P =	44.27	
h^in	115.377	
mgin =	4.09476	
mwin =	112.898	
Pin =	100	
h^out	115.377	
mgout =	4.09476	
mwout =	112.898	
Po =	144.27	144.27
Mtotal	116.993	116.9928

	code	matlab	
given	dP	44.27	
			Same as feeder
			Same as feeder
			Same as feeder
			Same as feeder
			input=output
			input=output
			input=output
calculate	Plpo	144.27	Calculate from formula pressure increase(100-144.27) del=Pin-Pout
			Mtotal=mgo+mwo

ValveMain		Calculation
h^in	115.377	
mgin =	4.09476	
mwin =	112.898	
Pin =	144.27	
Kvalve	185	184.9999
h^out	115.377	
mgout =	4.09476	
mwout =	112.898	
Po =	70.2842	70.28426
Mtotal	116.993	116.9928

	code	matlab	
			Same as Pump out
			Same as Pump out
			Same as Pump out
			Same as Pump out
given	Kv1	185	
			input=output
			input=output
			input=output
calculate	Plvo	70.2843	Calculate from formula pressure drop
			Mtotal=mgo+mwo

Evaporator1		Calculation	
Hold	3300		
HTArea	168		
HTCoeff	150		
KVapLine	521.33		
Lambda	2080.8		
X =	0.054654	0.0546536	
Xin =	0.035	0.035000115	
X out =	0.054654	0.054653669	
h^	124.65		
Mtotal	74.922	74.92196	
h^liq in	115.377	=	
mgi =	4.09476	=	
mwi =	112.898	=	
Pli	70.2842	=	
h^liq out	124.65	124.6497985	
mgo =	4.09476		
mwo	70.8272	70.82724	
Plo =	70.2842		
h^steamout	2208.42	2208.422912	
msti =	42.6525	=	
Psti =	81.5408	81.54087045	
msto	42.071	42.07098148	1046.903154
Psto	66.8891	66.88909701	
TChest	94.0318	-94.03177786	
Temp	90.5099	90.50992214	

	Code	matlab	
given	Mhold	3300	Constant given for the whole process. Lambda is the latent heat of satuated steam at 160C or 6.2 bar. Liquid hold up is fixed at 3300 kg, to be used in dynamic run.
given	Atf	168	
given	Htf	150	
given	Kvapv	521.33	
given	Lambda	2080.8	
given	Xp	0.05465	X out= X
given	Xf	0.035	Xin=(mgi/(mgi+mwi))
			Xout=(mgi/(mgi+mwi))
			h^= h^liqo
calculate	Mp	74.9269	Mtotal=mgo+mwo
			Same as Valvemain out
			Same as Valvemain out
			Same as Valvemain out
			Same as Valvemain out
calculate	hv_out	124.65	enthalp liq increase 115.377-124.65 h^lo=difftemp*((1-xout)*4.183+Xout*2.4)
			input=output
calculate	Mv	70.8321	mw decrease 112.898-70.8272 mwo=mtotal-mgo
			Pli= Plo
			Latent heat of satuated steam at 150.5C or 4.8 bar.
			Same as steam valve output
			Same as steam valve output
			input=output
calculate	Psto	66.7947	Pressure steam decrease 81.5408 - 66.8891 pst=(msto*msto/Kval)- Pli
calculate	temp_chest	94.0318	Tchest=((Msti*lamda)/-(HTarea*Htcoef))-temp
Calculate	Temp	90.5099	Temp=((Msti*lamda)/-(HTarea*Htcoef))+Tchest

Steam out		Calculation	In Matlab	code	Matlab value	Comment
Msteam =	42.071		assume given	ST_Flow2		from evaporator1
Psteam =	66.8891	66.88909407	calculate	Pst_stm2		Calculate from formula
Tsteam =	88.7717		calculate	Tst_stm2		Calculate from first evaporator
hsteam	2201.152					

Liquid Out		Calculation		code	matlab	
h^out	124.65	124.65	calculate	h_out		Calculate from formula (different temp*((1-x)*Cpw)+Cpg*x)
mg	4.09476	4.094815	calculate	Mg		Calculate from formula
mw	70.8272	70.8272	calculate	Mw		Calculate from formula
Pout	70.2842		given	Plf		
Tout	90.50995	90.50996	given	Tlf		
Mtotal	74.92196	74.92196	assume given	Feed		Calculate from formula (total=mg+mw)
X	0.054654		given	Xf		Concentration require

Double effect evaporator

Continue from Single Effect Evaporator

Liquid In		Calculation
h^out	124.65	124.65
mg	4.09476	4.094784802
mw	70.8272	70.8272
Pout	70.2842	
Tout	90.50995	90.50995373
Mtotal	74.92196	74.92196
X	0.054654	

	code	matlab	
calculate	hl_out2	124.6504	Calculate from formula (different temp*((1-x)*Cpw)+Cpg*x)
calculate	Mg_2	4.0948	Calculate from formula mg=(X*Mtotal)
calculate	Mw_2	70.8275	Calculate from formula
given	Plf_2	100	
given	Tlf_2	90.51	
assume given	M_tol2	74.922	Calculate from formula (total=mg+mw)
calculate	Xf	0.035	calculate x=mg/mtotal

Pump2		Calculation
Del P =	10	
h^in	124.65	
mgin =	4.09476	
mwin =	70.8272	
Pin =	70.2842	
h^out	124.65	
mgout =	4.09476	
mwout =	70.8272	
Po =	80.2842	80.2842
Mtotal	74.922	74.92196
Tout		90.50995373

	code	matlab	
given	dP2	10	
			Same as evaporator1
			Same as evaporator1
			Same as evaporator1
			Same as evaporator1
			input=output
			input=output
			input=output
calculate	Plpo_2	80.284	Calculate from formula pressure increase(70.284-80.284) del=Pin-Pout
			Mtotal=mgo+mwo

Evaporator2		**Calculation**		**Code**	**matlab**	
Hold	2500		given	Mhold_2	2500	Constant given for the whole process. Lambda is the latent heat of satuated steam at 160C or 6.2 bar. Liquid hold up is fixed at 2500 kg, to be used in dynamic run.
HTArea	145		given	Atf_2	145	
HTCoeff	80		given	Htf_2	80	
KVapLine	703.35		given	Kvapv_2	703.35	
Lambda	2080.8		given	Lambda_2	2080.8	
X =	0.130054	0.130054	given	Xp2	0.1301	X out= X
Xin =	0.054654	0.054653669	given	Xf2	0.0547	Xin=(mgi/(mgi+mwi))
X out =	0.130054	0.130054064				Xout=(mgi/(mgi+mwi))
h^	83.8625					h^= h^liqo
Mtotal	31.4851	31.48506	calculate	Mp_2	31.4839	Mtotal=mgo+mwo
h^liq in	124.65	=				Same as Valvemain2 out
mgi =	4.09476	=				Same as Valvemain2 out
mwi =	70.8272	=				Same as Valvemain2 out
Pli	47.6825	=				Same as Valvemain2 out
h^liq out	83.8625	83.86238625	calculate	hv_out2	83.8627	enthalp liq increase 124.65-83.863 h^lo=difftemp*((1-xout)*4.183+Xout*2.4)
mgo =	4.09476					input=output
mwo	27.3903	27.39034	calculate	Mv_2	27.3895	mw decrease 70.827-27.39 mwo=mtotal-mgo
Plo =	47.6825					Pli= Plo
h^steamout	2169.58	2169.584175				Latent heat of satuated steam at 150.5C or 4.8 bar.
msti =	42.071	=		Mst_2	42.071	Same as steam valve output
Psti =	66.8891	66.88909407				Same as steam valve output
msto	43.4369	43.43657877				input=output
Psto	45	44.99996032	fixed	Psto_2	66.7947	Pressure steam decrease 66.889 - 45 pst=(msto*msto/Kval)-Pli
TChest	88.7717	-88.77166697	calculate	Tst_stm2	94.0318	Tchest=((Msti*lamda)/-(HTarea*Htcoef))-temp

ValveMain2		Calculation
h^in	124.65	
mgin =	4.09476	
mwin =	70.8272	
Pin =	80.2842	
Kvalve	172.178	172.1783246
h^out	124.65	
mgout =	4.09476	
mwout =	70.8272	
Po =	47.6825	47.68243854
Mtotal	74.922	74.92196

	code	Matlab	
			Same as Pump2 out
			Same as Pump2 out
			Same as Pump2 out
			Same as Pump2 out
given	Kv2	172.178	need to calculate kv=(Mtotal*Mtotal)/(Pin-pout)
			input=output
			input=output
			input=output
calculate	Plvo_2	47.6826	Calculate from formula pressure drop(80.284-47.683) pout=(mflow/Kval)- pin
			Mtotal=mgo+mwo

Steam out		Calculation	In Matlab	code	Matlab value	Comment
Msteam =	43.4369		assume given	ST_Flow3		from evaporator1
Psteam =	45	44.99998016		Pst_stm2	45	Pressure require
Tsteam =	78.7449		calculate	Tst_stm2	78.7449	Calculate from first evaporator
Hsteam=	2159.21					

Liquid out		Calculation
h^out	83.8625	83.863
mg	4.09476	4.094632053
mw	27.3903	27.3903
Pout	47.6825	
Tout	81.225	81.22498987
Mtotal	31.48506	31.48506
X	0.13005	

	code	matlab	
calculate	h_out		Calculate from formula (different temp*((1-x)*Cpw)+Cpg*x)
calculate	Mg		Calculate from formula
calculate	Mw		Calculate from formula
given	Plf		
given	Tlf		corelation t/p
assume given	Feed		Calculate from formula (total=mg+mw)
given	Xf		calculate x=mg/mtotal

Pump3		Calculation
Del P =	90.3	
h^in	83.8625	
mgin =	4.09476	
mwin =	27.3903	
Pin =	47.6825	
h^out	83.8625	
mgout =	4.09476	
mwout =	27.3903	
Po =	137.983	137.9825
Mtotal	31.4851	31.48506

	code	matlab	
given	dP		
			Same as feeder
			Same as feeder
			Same as feeder
			Same as feeder
			input=output
			input=output
			input=output
calculate	Plpo		Calculate from formula pressure increase(47.6825-137.983) del=Pin-Pout
			Mtotal=mgo+mwo

ValveMain3		Calculation
h^in	83.8625	
mgin =	4.09476	
mwin =	27.3903	
Pin =	137.983	
Kvalve	55.1262	55.1247847
h^out	83.8625	
mgout =	4.09476	
mwout =	27.3903	
Po =	120	120.0004617
Mtotal	31.48506	31.48506

	code	matlab	
			Same as Pump out
			Same as Pump out
			Same as Pump out
			Same as Pump out
	Kv1		need to calculate
			input=output
			input=output
			input=output
calculate	Plvo		Calculate from formula pressure drop(137.983-120) pout=(mflow/Kval)- pin
			Mtotal=mgo+mwo

Conentrate		Calculation
h^	83.8625	
mg =	4.09476	
mw =	27.3903	
P =	120	

	code	matlab	
			Same as Pump out
			Same as Pump out
			Same as Pump out
			Pressure require

Appendix D (Mathematical Model Description)

This section will explain the models equation according to the flow sheet in section 4.1. All equations are renamed and checked for easy understanding. These element models will be used to build the steady state, optimization, and dynamic models for the single effect or multiple effect evaporators, in ACM and MATLAB soon.

Model Steamer

The Steamer in the flow sheet is used to supply the steam to the process. The steamer is used once during starting of the process. The equation for the model steamer is explained below:

Steam temperature is given as 105°C. Pressure of steam is 120.78kPa obtain from:

$$P_{o\_SMst} = 0.1333 * 10^{\left(7.96681 - \frac{1668.21}{T_{o\_SMst} + 228}\right)} \tag{P1}$$

Steam Enthalpy is 2269.04; calculated from the equation below:

$$\hat{H}_{o\_SMst} = (T_{o\_SMst} - T_{ref}) * C_{pw} + \lambda \tag{H1}$$

Model Steam Valve

The green valve in the flow sheet indicates the steam valve. It is located before the evaporator. The equation for the model steam valve is explained below:

The Mass steam in is equal to mass steam out. KV_{st} given is 46.361. The equation below is used to calculate steam pressure of steam valve.

$$m_{i\_Vst} = m_{o\_Vst} = \sqrt{KV_{st} * (P_{i\_Vst} - P_{o\_Vst})} \tag{S1}$$

Steam pressure out of steam valve is 81.5408 kPa obtained after rearranging equation S1:

$$P_{o\_Vst} = P_{i\_Vst} - \frac{(M_{i\_Vst} * M_{i\_Vst})}{KV_{st}} \tag{P2}$$

To calculate steam temperature out of steam valve, the using pressure equation below is used:

$$P_{o\_Vst} = 0.1333 * 10^{\left(7.96681 - \frac{1668.21}{T_{o\_Vst} + 228}\right)} \tag{P3}$$

After rearranging equation P3, steam temperature out is 94.0318°C:

$$T_{o\_Vst} = \left(\frac{1668.21}{7.96681 - \log_{10}\left(\frac{P_{o\_Vst}}{0.1333}\right)} \right) - 228 \tag{T1}$$

Steam Enthalpy is 2223.16, calculated from equation below:

$$\hat{H}_{o\_Vst} = (T_{o\_Vst} - T_{ref})*C_{pw} + \lambda \tag{H2}$$

Model Feeder

The Feeder in the flow sheet is used to supply the glycol or water to the process. The Feeder is used once during the start of the process. The equation for the model feeder is explained below:

Liquid temperature and liquid pressure is given as 88°C and 100kPa. Feed flow rate x(1) is unknown. Specific enthalpy of liquid out in feeder is 115.377 obtained from the equation below:

$$\hat{H}_{o\_Fl} = (T_{o\_Fl} - T_{ref})*\{(1 - X_{Fo})C_{pw} + X_{Fo}C_{pg}\} \tag{H3}$$

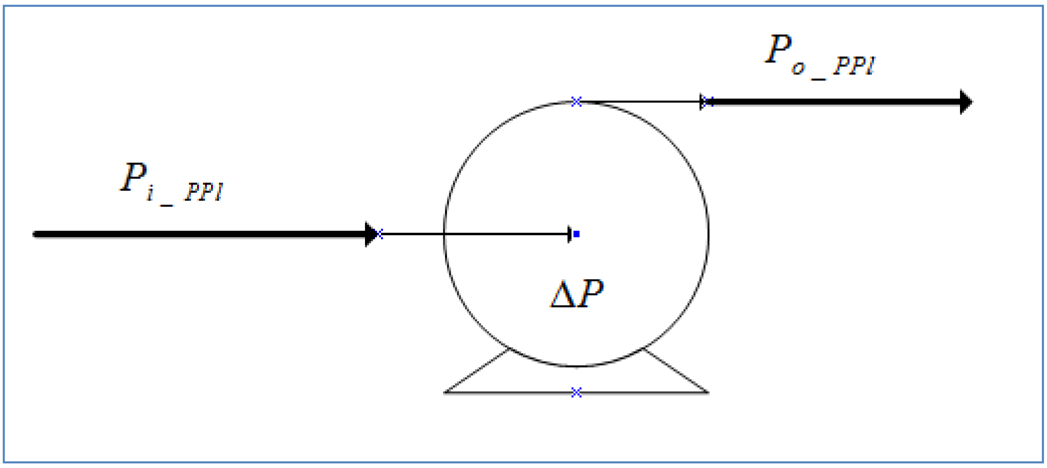
For total mass liquid in is equal to total mass liquid out. Mass flowrate out of liquid valve for glycol and water:

Glycol mass flowrate: $M_{o\_Fg} = M_{o\_Fl} * X_{Fo}$ (S2)

Water mass flowrate: $M_{o\_Fw} = (1 - X_{Fo}) * M_{o\_Fl}$ (S3)

Model Pump

The Pump in the flow sheet is located before the main valve. The same model equation is used for all pumps either in single effect or multiple effect evaporators. The equation for the model pump is explained below:



Pressure difference across the pump is 44.27 (fixed). To calculate liquid pressure out of main valve, pressure equation below is used:

$$\Delta P = P_{o\_PPl} - P_{i\_PPl} \qquad \text{(P4)}$$

After rearranging equation P4, liquid pressure out is 144.27kpa:

$$P_{o\_PPl} = \Delta P + P_{i\_PPl} \qquad \text{(P5)}$$

Specific enthalpy of liquid out in pump is 115.377 obtained from the equation below:

$$\hat{H}_{o\_PPl} = (T_{o\_PPl} - T_{ref}) * \{(1 - X_{Fo})C_{pw} + X_{Fo}C_{pg}\} \qquad \text{(H4)}$$

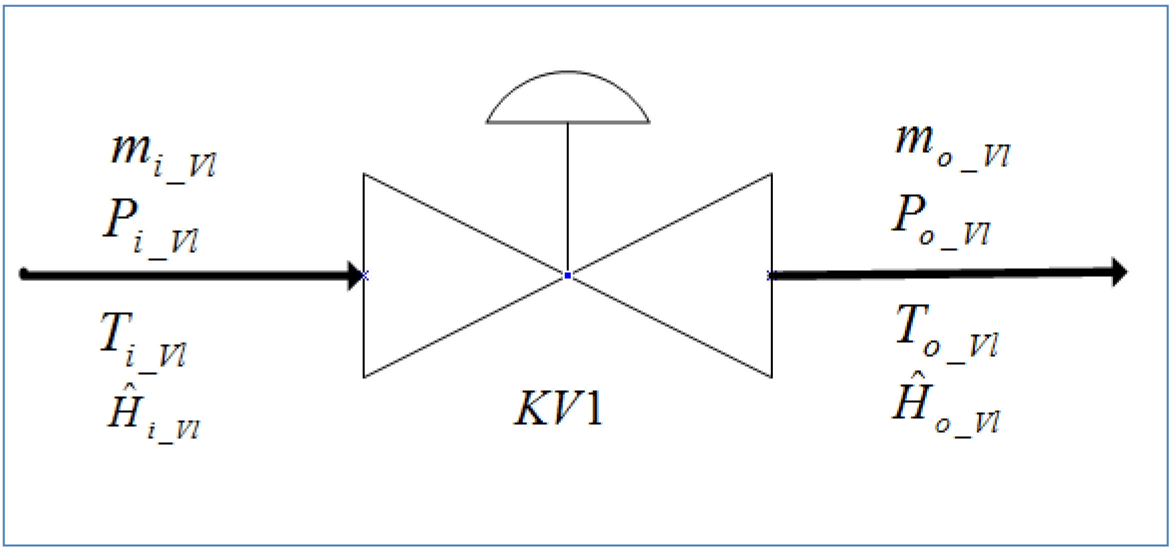
For total mass liquid in is equal to total mass liquid out. Mass flowrate out of liquid pump for glycol and water:

Glycol mass flowrate: $M_{o\_PPg} = M_{i\_PPl} * X_{Fo}$ (S4)

Water mass flowrate: $M_{o\_PPw} = (1 - X_{Fo}) * M_{i\_PPl}$ (S5)

Model Liquid Valve

The gray valve in the flow sheet is indicating the liquid valve. It is located after the pump and before the evaporator. The same model equation is used for all liquid valves either in single effect or multiple effect evaporators. The equation for the model liquid valve is explained below:



For Mass concentration in is equal to mass concentration out. $KV1$ given is 185. The equation below is used to calculate liquid pressure of liquid valve.

$$m_{i\_Vl} = m_{o\_Vl} = \sqrt{KV1 * (P_{i\_Vl} - P_{o\_Vl})} \qquad \text{(S6)}$$

Liquid pressure out of steam valve is 70.2842kpa obtained after rearranging equation S6:

$$P_{o\_Vl} = P_{i\_Vl} - \frac{(M_{i\_Vl} * M_{i\_Vl})}{KV1} \qquad \text{(P6)}$$

For total mass liquid in is equal to total mass liquid out. Mass flowrate out of liquid valve for glycol and water:

Glycol mass flowrate: $M_{o\_Vg} = M_{i\_Vl} * X_{Fo}$ (S7)

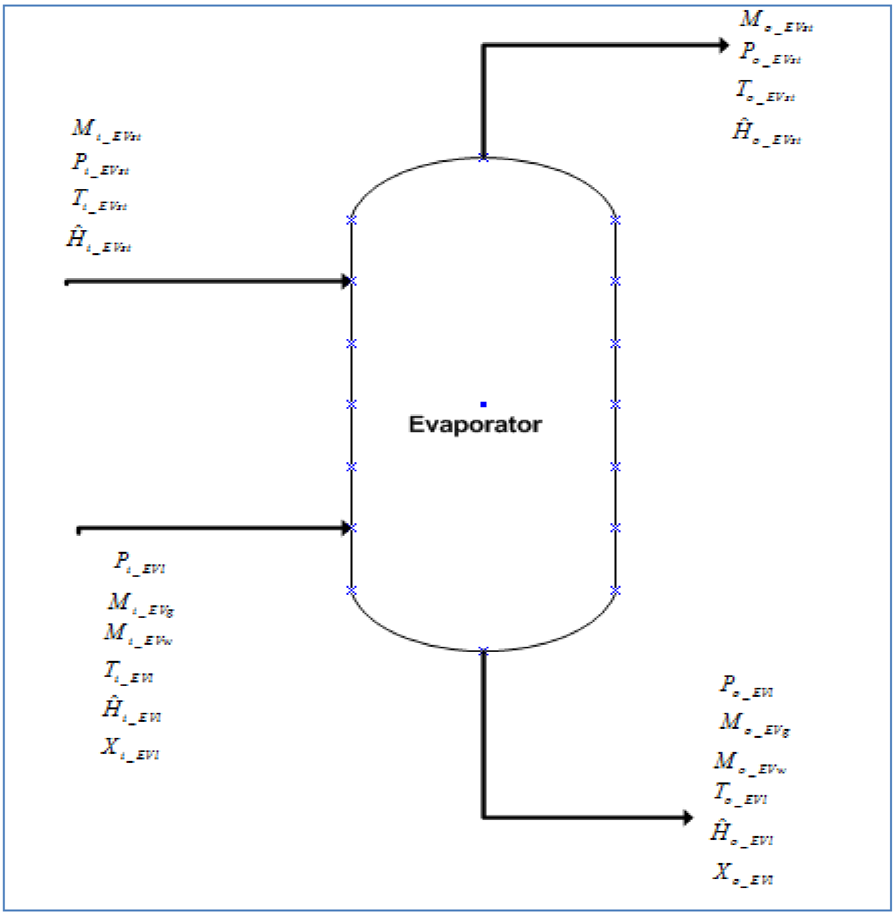
Water mass flowrate: $M_{o\_Vw} = (1 - X_{Fo}) * M_{i\_Vl}$ (S8)

Liquid Enthalpy is 2223.16, calculated from the equation below

$$\hat{H}_{o\_Vl} = (T_{o\_Vl} - T_{ref}) * \{(1 - X_{Fo})C_{pw} + X_{Fo}C_{pg}\} \qquad \text{(H5)}$$

Model Evaporator

The Evaporator tank in the flow sheet is located after steam and main valve. Inside this tank, water will evaporate and the remaining liquid in the tank will become more concentrated. The same model equation is used for all evaporator effect either in single effect or multiple effect evaporators. The equation for the model evaporator is explained below:



Steam

Vapour pressure out of the evaporator is 66.8891kpa obtain after rearranging steam flow equation below:

$$M_{o\_EVst} = \sqrt{KV_{apv} * (P_{i\_EVl} - P_{o\_EVst})} \tag{S9}$$

Rearranged equation S9 becomes:

$$P_{o\_EVst} = P_{i\_EVl} - \left(\frac{M_{o\_EVst} * M_{o\_EVst}}{KV_{apv}} \right) \tag{P7}$$

To calculate steam temperature out of evaporator, steam pressure equation below is used.

$$P_{o\_EVst} = 0.1333 * 10^{\left(7.96681 - \frac{166821}{T_{o\_EVst} + 228}\right)} \tag{P8}$$

After rearranging equation P8, vapour temperature out is 88.7717°C:

$$T_{o\_EVst} = \left(\frac{1668.21}{7.96681 - \log_{10}\left(\frac{P_{o\_EVst}}{0.1333}\right)}\right) - 228 \tag{T2}$$

Steam Enthalpy is 2201.15, calculated from the equation below:

$$\hat{H}_{o\_EVst} = (T_{o\_EVst} - T_{ref}) * C_{pw} + \lambda \tag{H6}$$

Total mass steam feed in is able to be calculated using Energy balance equation below:

$$\frac{dH}{dt} = M_{i\_EVl}(\hat{H}_{i\_EVl} - \hat{H}_{o\_EVl}) - M_{o\_EVst}(\hat{H}_{o\_EVst} - \hat{H}_{o\_EVl}) + M_{st}\lambda \tag{E1}$$

After rearranging:

$$M_{st} = \frac{-M_{i\_EVl}(\hat{H}_{i\_EVl} - \hat{H}_{o\_EVl}) + M_{o\_EVst}(\hat{H}_{o\_EVst} - \hat{H}_{o\_EVl})}{\lambda} \tag{S10}$$

From Heat transfer equation below, steam temperature input of evaporator is calculated.

$$M_{st} = \frac{H_{tf} * A_{tf} * (T_{o\_EVl} - T_{i\_EVst})}{\lambda} \tag{S11}$$

After rearranging:

$$T_{i\_EVst} = \frac{(H_{tf} * A_{tf} * T_{o\_EVl}) + (M_{st} * \lambda)}{(H_{tf} * A_{tf})} \tag{T3}$$

Liquid

To calculate liquid temperature out of evaporator, liquid pressure equation below is used:

$$P_{li} = 0.1333 * \left\{ \frac{\dfrac{(1-X_{o\_EVl})}{MW_w}}{\dfrac{(1-X_{o\_EVl})}{MW_w} + \dfrac{X_{o\_EVl}}{MW_g}} \right\} 10^{\left(7.96681 - \frac{1668.21}{T_i + 228}\right)} \tag{P9}$$

Mass Fraction:

$MW_w = 18.02$, $\dfrac{(1-X_{o\_EVl})}{MW_w} = 0.052461$;

$MW_g = 62.0$, $\dfrac{X_{o\_EVl}}{MW_g} = 0.000882$;

Mole Fraction:

$Y_g = \dfrac{0.000882}{0.053342} = 0.016525$;

$Y_w = \dfrac{0.053342}{0.053342} = 0.983475$;

After rearranging equation P3, liquid temperature out is 90.51°C:

$$T_{o\_EVl} = \left(\frac{1668.21}{7.96681 - \log_{10}\left(\frac{P_{o\_EVst}}{0.1333 * 0.983475}\right)} \right) - 228 \tag{T4}$$

Liquid Enthalpy is 124.65 calculated from the equation below:

$$\hat{H}_{o\_EVl} = (T_{o\_EVl} - T_{ref}) * \{(1 - X_{o\_EVl}) C_{pw} + X_{o\_EVl} C_{pg}\} \tag{H7}$$

For total mass liquid in is equal to total mass liquid out. Mass Flowrate out of liquid valve for glycol and water:

Total liquid mass flowrate: $M_{o\_EVl} = \left(\frac{X_{Fo}}{X_{o\_EVl}} \right) * M_{i\_EVl}$ (S12)

Glycol mass flowrate: $M_{o\_EVg} = M_{o\_Fg}$ (S13)

Water mass flowrate: $M_{o\_EVw} = M_{o\_EVl} - M_{o\_EVg}$ (S14)

Appendix E (single effect Evaporator MATLAB code)

```
% Example of 1-effect evaporator
clear;
% Constants
XFo = 0.035; % given: Glycol mass fraction in feed
Xo_EV1 = 0.05465; % given: Glycol mass fraction in product
To_SMst = 105; % given: Steam Temperature from steamer
KVst = 46.361; % given: Steam Valve Coefficient
To_Fl = 88; % given: Temperature of liquid in feeder
Po_Fl = 100; % given: Pressure of liquid in feeder
dP = 44.27; % given: Pressure difference across the pump
KV1 = 185; % given: Liquid valve coefficient (in valve)
Mhold = 3300; % given: Liquid hold-up in evaporator 1
Htf = 150; % given:Heat transfer coefficient
Atf = 168; % given: Heat transfer area
Lambda = 2080.8; % given: Water laten heat of evaporation at 160C
KVapv = 521.33; % given: Steam valve coefficient
Cpg = 2.4; % given: Specific enthalpy of glycol
Cpw = 4.183; % given: Specific enthalpy of water
Tref = 60; % given: temperature referent
dP2 = 10; % %Pressure difference across the second pump (after 1st evap)

%------------Steamer--------------%
%x(1) = 42.6525; %Initial guess
%Mo_SMst = x(1); %assume mass flowrate for steam x1
%To_SMst= 105; %Steam temperature from steamer(given)
% Correlation to calculate P from T for gas
Po_SMst = 0.1333*10^(7.96681 - (1668.21/(To_SMst + 228))); %Pressure steam
in steamer
Ho_SMst = ((To_SMst-Tref)*Cpw) + Lambda; % Enthalpy value in the steamer
(calculate)



%-----Steam valve-------%
Pi_Vst = Po_SMst; %Pressure steam from steamer same as pressure steam input
for steam valve
%Mi_Vst = Mo_SMst;  %Mass steam from steamer same as mass steam input for
steam valve
%Po_Vst = Pi_Vst -((Mi_Vst*Mi_Vst)/KVst); %Steam pressure out of steam
valve
% Correlation to calculate T from P for gas
%beta=log10(Po_Vst/0.1333);
%To_Vst=(1668.21/(7.96681-beta))-228; % Temperature for steam valve
%Ho_Vst = ((To_Vst-Tref)*Cpw ) + Lambda; %Enthalpy for steam valve
%Mo_Vst= sqrt(KVst*(Pi_Vst-Po_Vst)); %Mass out from steam valve

%------------Feeder--------------%
%To_Fl = 88; %Temperature of liquid in feeder is given
%Po_Fl = 100; %Pressure of liquid in feeder is given
Ho_Fl = (To_Fl-Tref)*((1-XFo)*Cpw+(XFo*Cpg)); %enthalpy from feeder
x(2) = 116.993; % Initial guess
Mo_Fl =  x(2); % total Feed flowrate in feeder X(1) assume is given
Mo_Fg = Mo_Fl* XFo; % Glycol mass flowrate in feeder
Mo_Fw = (1-XFo)*Mo_Fl; %Water mass flowrate in feeder
```

```
%------------Liquid Pump--------------%
Xi_PPl = XFo;
Xo_PPl = Xi_PPl;
Ti_PPl = To_Fl;  %Temp out from the feeder as a input to the pump
Pi_PPl = Po_Fl;  %Pressure out from the feeder as a input to the pump

To_PPl = Ti_PPl; %temperature in equal with temp out
Po_PPl = dP+Pi_PPl; % Liquid outlet pressure from the pump
Ho_PPl =(To_PPl-Tref)*((1-Xo_PPl)*Cpw+(Xo_PPl*Cpg));  %enthalpy in the pump
Mo_PPl = Mo_Fl;  %total mass flowrate in equal to out
Mo_PPg = Mo_PPl* Xo_PPl;  %Glycol mass flowrate in pump
Mo_PPw = (1-Xo_PPl)*Mo_PPl;  %Water mass flowrate in pump


%------------Valve main--------------%
Xi_Vl = Xo_PPl;
Xo_Vl = Xi_Vl;  %concentration feed
Ti_Vl = To_PPl; %Temp out from the pump as a input to the valve
Pi_Vl = Po_PPl;  %Pressure out from the pump as a input to the valve
Mi_Vl = Mo_PPl;  %mass flowrate out from the pump as a input to the valve

To_Vl = Ti_Vl; %temperature in equal with temp out
Mo_Vl = Mi_Vl;
Po_Vl = Pi_Vl - ((Mi_Vl^2)/ KV1); %Liquid outlet pressure from the valve
Plvo
Mo_Vg = Mi_Vl* Xo_Vl;  %Glycol mass flowrate in valve
Mo_Vw = (1-Xo_Vl)*Mi_Vl;  %Water mass flowrate in valve
Ho_Vl= (To_Vl-Tref)*((1-Xo_Vl)*Cpw+(Xo_Vl*Cpg));  %enthalpy in the valve


%------------Evaporator one--------------%
Xi_EVl = Xi_Vl;   %concentration feed
%Pi_EVst = Po_Vst;    %Pressure out from the steam valve as a input to the
evaporator
%Ti_EVst = To_Vst;  %Temperature out from the steam valve as a input to the
evaporator
%Mi_EVst = Mo_Vst;   %Mass flowrate out from the steam valve as a input to
the evaporator
Pi_EVl = Po_Vl;%Pressure out from the  liquid valve as a input to the
evaporator
Mi_EVl = Mo_Vl;  %liquid mass out from the  valve as a input to the
evaporator
Mi_EVg = Mo_Vg ; %mass glycol out from the steam valve as a input to the
evaporator
Hi_EVl=Ho_Vl;  %Enthalpy liquid in

%liquid
Po_EVl = Pi_EVl;  %pressure liquid in equal to pressure out
% Correlation to calculate T from P for gas
b1 = log10(Po_EVl/(0.1333*(0.983475))); %equation E8 mass fraction water
To_EVl = (1668.21/(7.96681-b1))-228; % Temperature for steam
Ho_EVl = (To_EVl-Tref)*(((1-Xo_EVl)*Cpw)+(Xo_EVl*Cpg));  %enthalpy liquid
out
Mo_EVl = (Xi_EVl/Xo_EVl)*Mi_EVl; %total liquid Product flowrate out of the
evaporator Xf*X(1)=Xp*(mp)
Mo_EVg = Mi_EVg;  %inputs equal output for glycol
Mo_EVw = Mo_EVl-Mo_EVg; %mass fraction for water
```

```
%steam
Mo_EVst = Mi_EVl-Mo_EVl;  % mass steam from evaporator total mass balance
Po_EVst = Pi_EVl-((Mo_EVst*Mo_EVst)/(KVapv)); % Pressure for steam
% Correlation to calculate T from P for gas
beta1 = log10(Po_EVst/0.1333);
To_EVst = (1668.21/(7.96681-beta1))-228; % Temperature for steam
Ho_EVst = ((To_EVst-Tref)*Cpw)+Lambda;  % Enthalpy for steam

Mst=((-Mi_EVl*Hi_EVl)+(Mi_EVl*Ho_EVl)+(Mo_EVst*Ho_EVst)-
(Mo_EVst*Ho_EVl))/Lambda;

Ti_EVst=((Htf*Atf*To_EVl)+(Mst*Lambda))/(Htf*Atf);
To_EVl  = ((Htf*Atf*-Ti_EVst)+(Mst*Lambda))/-(Htf*Atf)   % temp
Mo_EVst= ((Mo_Fl*(Ho_Fl-Ho_EVl))+(Mst*Lambda))/ (Ho_EVst-Ho_EVl)

%------------Liquid Pump1( after 1st evapo)--------------%
Xi_PPl1 = Xo_EVl;
Xo_PPl1 = Xi_PPl1;%concentration in equal with temp out
Ti_PPl1 = To_EVl;  %Temp out from the evap1 as a input to the pump
Pi_PPl1 = Po_EVl;  %Pressure out from the evap1 as a input to the pump

To_PPl1 = Ti_PPl1; %temperature in equal with temp out
Po_PPl1 = dP2+Pi_PPl1; % Liquid outlet pressure from the pump
Ho_PPl1 = (To_PPl1-Tref)*((1-Xo_PPl1)*Cpw+(Xo_PPl1*Cpg));  %enthalpy in the
pump
Mo_PPl1 = Mo_EVl;  %total mass flowrate in equal to out
Mo_PPg1 = Mo_PPl1* Xo_PPl1;  %Glycol mass flowrate in pump
Mo_PPw1 =(1-Xo_PPl1)*Mo_PPl1;  %Water mass flowrate in pump



%------------Valve main1(after ist evap)--------------%
KV2=172.178;

Xi_Vl1 = Xo_PPl1;
Ti_Vl1 = To_PPl1; %Temp out from the pump as a input to the valve
Pi_Vl1 = Po_PPl1;  %Pressure out from the pump as a input to the valve
Mi_Vl1 = Mo_PPl1;  %mass flowrate out from the pump as a input to the valve

To_Vl1 = Ti_Vl1; %temperature in equal with temp out
Mo_Vl1 = Mi_Vl1;
Po_Vl1 = Pi_Vl1 - ((Mi_Vl1^2)/KV2) ; %Liquid outlet pressure from the valve
Plvo
Mo_Vg1 = Mi_Vl1* Xi_Vl1;  %Glycol mass flowrate in valve
Mo_Vw1 = (1-Xi_Vl1)*Mi_Vl1;  %Water mass flowrate in valve
Ho_Vl1 = (To_Vl1-Tref)*((1-Xi_Vl1)*Cpw+(Xi_Vl1*Cpg));%enthalpy in the valve
KV2 = (Mo_Vl1*Mo_Vl1)/(Pi_Vl1-Po_Vl1);
```

Appendix F (Double effect Evaporator MATLAB code)

```
% Example of 2-effect evaporator

clear;

% Constants for single evaporator
XFo = 0.035; %Glycol mass fraction in feed
%Xo_EVl = 0.05465; %Glycol mass fraction in product
To_SMst = 105; %Steam Temperature from steamer
KVst = 46.361; %Steam Valve Coefficient
To_Fl = 88; %Temperature of liquid in feeder
Po_Fl = 100; %Pressure of liquid in feeder
dP = 44.27; %Pressure difference across the pump
KV1 = 185; %Liquid valve coefficient (in valve)
Mhold = 3300; %Liquid hold-up in evaporator 1
Htf = 150; %Heat transfer coefficient
Atf = 168; %Heat transfer area
Lambda = 2080.8; %Water laten heat of evaporation at 160C
KVapv = 521.33; %Steam valve coefficient
%Cpg = 2.4; %Specific enthalpy of glycol
%Cpw = 4.183; %Specific enthalpy of water
%Tref = 60; % temperature referent
%dP2 = 10; % %Pressure difference across the second pump (after 1st evap)


% Constants for second evaporator
Xo_EVl = 0.05465; %Glycol mass fraction in feed after first evaporator
Xo_EVl1 = 0.13005; %Glycol mass fraction in product
dP2 = 10; %Pressure difference across the secondpump
Mhold2 = 2500; %Liquid hold-up in evaporator 1
Htf2 = 80; %Heat transfer coefficient
Atf2 = 145; %Heat transfer area
Lambda2 = 2080.8; %Water laten heat of evaporation at 160C
KVapv2 = 703.35; %Steam valve coefficient
Cpg = 2.4; %Specific enthalpy of glycol
Cpw = 4.183; %Specific enthalpy of water
Tref = 60; % temperature referance
Po_EVst1= 45; % Steam pressure require at the end of the process
Po_Vl2=120; % liquid pressure require at the end of the process
dP3=90.3;   %Pressure difference across the thirdpump

%------------Steamer--------------%
%x(1) = 42.6525; %Initial guess
%Mo_SMst = x(1); %assume mass flowrate for steam x1
%To_SMst= 105; %Steam temperature from steamer(given)
% Correlation to calculate P from T for gas
Po_SMst = 0.1333*10^(7.96681 - (1668.21/(To_SMst + 228))); %Pressure steam
in steamer
Ho_SMst = ((To_SMst-Tref)*Cpw) + Lambda; % Enthalpy value in the steamer
(calculate)
```

```
%-----Steam valve-------%
Pi_Vst = Po_SMst; %Pressure steam from steamer same as pressure steam input
for steam valve
%Mi_Vst = Mo_SMst;  %Mass steam from steamer same as mass steam input for
steam valve
%Po_Vst = Pi_Vst -((Mi_Vst*Mi_Vst)/KVst); %Steam pressure out of steam
valve
% Correlation to calculate T from P for gas
%beta=log10(Po_Vst/0.1333);
%To_Vst=(1668.21/(7.96681-beta))-228; % Temperature for steam valve
%Ho_Vst = ((To_Vst-Tref)*Cpw ) + Lambda; %Enthalpy for steam valve
%Mo_Vst= sqrt(KVst*(Pi_Vst-Po_Vst)); %Mass out from steam valve

%------------Feeder--------------%
%To_Fl = 88; %Temperature of liquid in feeder is given
%Po_Fl = 100; %Pressure of liquid in feeder is given
Ho_Fl = (To_Fl-Tref)*((1-XFo)*Cpw+(XFo*Cpg)); %enthalpy from feeder
x(2) = 116.993; % Initial guess
Mo_Fl =  x(2); % total Feed flowrate in feeder X(1) assume is given
Mo_Fg = Mo_Fl* XFo; % Glycol mass flowrate in feeder
Mo_Fw = (1-XFo)*Mo_Fl; %Water mass flowrate in feeder



%------------Liquid Pump--------------%
Xi_PPl = XFo;
Xo_PPl = Xi_PPl;
Ti_PPl = To_Fl;  %Temp out from the feeder as a input to the pump
Pi_PPl = Po_Fl;  %Pressure out from the feeder as a input to the pump

To_PPl = Ti_PPl; %temperature in equal with temp out
Po_PPl = dP+Pi_PPl; % Liquid outlet pressure from the pump
Ho_PPl = (To_PPl-Tref)*((1-Xo_PPl)*Cpw+(Xo_PPl*Cpg));  %enthalpy in the
pump
Mo_PPl = Mo_Fl;  %total mass flowrate in equal to out
Mo_PPg = Mo_PPl* Xo_PPl;  %Glycol mass flowrate in pump
Mo_PPw = (1-Xo_PPl)*Mo_PPl;  %Water mass flowrate in pump



%------------Valve main--------------%
Xi_Vl = Xo_PPl;
Xo_Vl = Xi_Vl;  %concentration feed
Ti_Vl = To_PPl; %Temp out from the pump as a input to the valve
Pi_Vl = Po_PPl;  %Pressure out from the pump as a input to the valve
Mi_Vl = Mo_PPl;  %mass flowrate out from the pump as a input to the valve

To_Vl = Ti_Vl; %temperature in equal with temp out
Mo_Vl = Mi_Vl;
Po_Vl = Pi_Vl - ((Mi_Vl^2)/ KV1); %Liquid outlet pressure from the valve
Plvo
Mo_Vg = Mi_Vl* Xo_Vl;  %Glycol mass flowrate in valve
Mo_Vw = (1-Xo_Vl)*Mi_Vl;  %Water mass flowrate in valve
Ho_Vl= (To_Vl-Tref)*((1-Xo_Vl)*Cpw+(Xo_Vl*Cpg));  %enthalpy in the valve
```

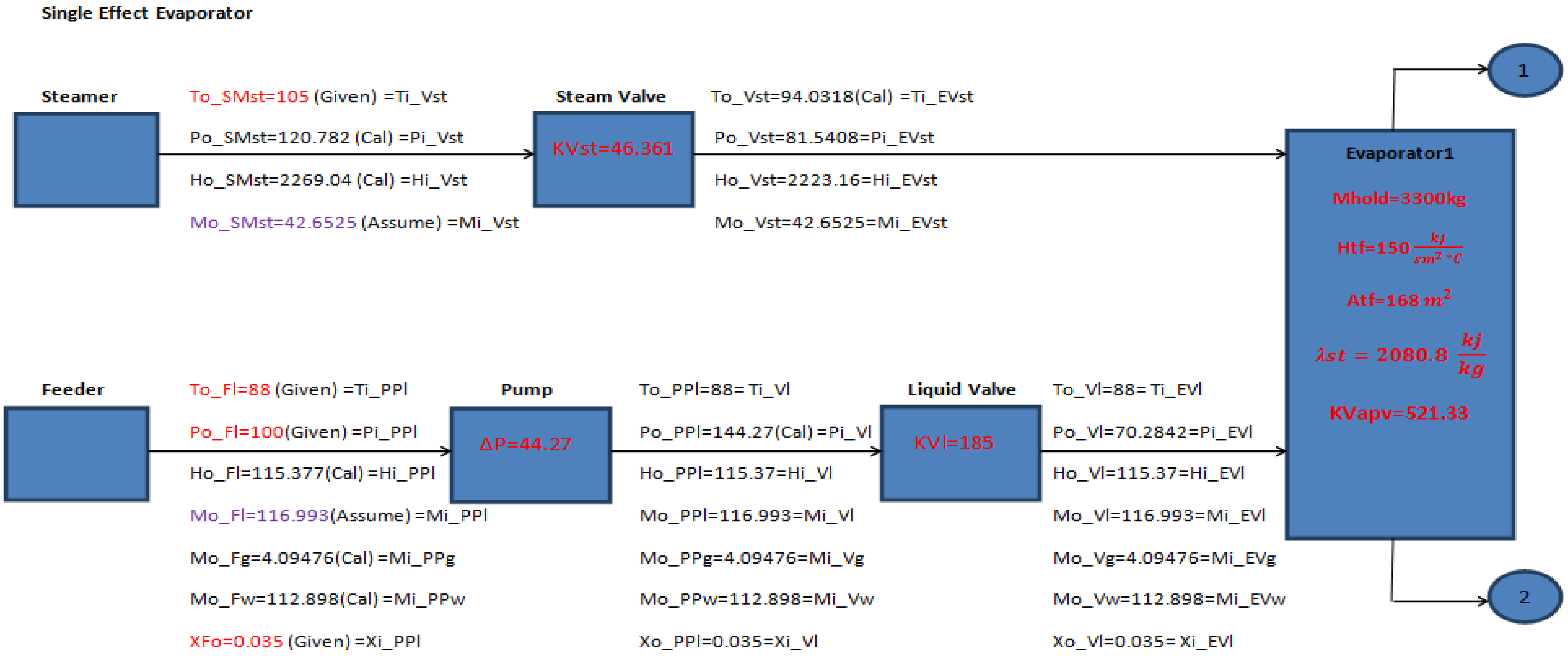
```
%------------Evaporator one--------------%
Xi_EVl = Xi_Vl;   %concentration feed
%Pi_EVst = Po_Vst;    %Pressure out from the steam valve as a input to the
evaporator
%Ti_EVst = To_Vst;  %Temperature out from the steam valve as a input to the
evaporator
%Mi_EVst = Mo_Vst;   %Mass flowrate out from the steam valve as a input to
the evaporator
Pi_EVl = Po_Vl;%Pressure out from the  liquid valve as a input to the
evaporator
Mi_EVl = Mo_Vl;  %liquid mass out from the  valve as a input to the
evaporator
Mi_EVg = Mo_Vg ; %mass glycol out from the steam valve as a input to the
evaporator
Hi_EVl=Ho_Vl;  %Enthalpy liquid in

%liquid
Po_EVl = Pi_EVl;  %pressure liquid in equal to pressure out
% Correlation to calculate T from P for gas
b1 = log10(Po_EVl/(0.1333*(0.983475))); %equation E8 mass fraction water
To_EVl = (1668.21/(7.96681-b1))-228; % Temperature for steam
Ho_EVl = (To_EVl-Tref)*(((1-Xo_EVl)*Cpw)+(Xo_EVl*Cpg));  %enthalpy liquid
out
Mo_EVl = (Xi_EVl/Xo_EVl)*Mi_EVl; %total liquid Product flowrate out of the
evaporator Xf*X(1)=Xp*(mp)
Mo_EVg = Mi_EVg;  %inputs equal output for glycol
Mo_EVw = Mo_EVl-Mo_EVg; %mass fraction for water



%steam
Mo_EVst = Mi_EVl-Mo_EVl;  % mass steam from evaporator total mass balance
Po_EVst = Pi_EVl-((Mo_EVst*Mo_EVst)/(KVapv)); % Pressure for steam
% Correlation to calculate T from P for gas
beta1 = log10(Po_EVst/0.1333);
To_EVst = (1668.21/(7.96681-beta1))-228; % Temperature for steam
Ho_EVst = ((To_EVst-Tref)*Cpw)+Lambda;  % Enthalpy for steam

Mst=((-Mi_EVl*Hi_EVl)+(Mi_EVl*Ho_EVl)+(Mo_EVst*Ho_EVst)-
(Mo_EVst*Ho_EVl))/Lambda;

Ti_EVst=((Htf*Atf*To_EVl)+(Mst*Lambda))/(Htf*Atf);



%------------Liquid Pump1( after 1st evapo)--------------%
Xi_PPl1 = Xo_EVl;
Xo_PPl1 = Xi_PPl1;%concentration in equal with temp out
Ti_PPl1 = To_EVl;  %Temp out from the evap1 as a input to the pump
Pi_PPl1 = Po_EVl;  %Pressure out from the evap1 as a input to the pump

To_PPl1 = Ti_PPl1; %temperature in equal with temp out
Po_PPl1 = dP2+Pi_PPl1; % Liquid outlet pressure from the pump
Ho_PPl1 = (To_PPl1-Tref)*((1-Xo_PPl1)*Cpw+(Xo_PPl1*Cpg));  %enthalpy in the
pump
Mo_PPl1 = Mo_EVl;  %total mass flowrate in equal to out
Mo_PPg1 = Mo_PPl1* Xo_PPl1;  %Glycol mass flowrate in pump
Mo_PPw1 =(1-Xo_PPl1)*Mo_PPl1;  %Water mass flowrate in pump
```

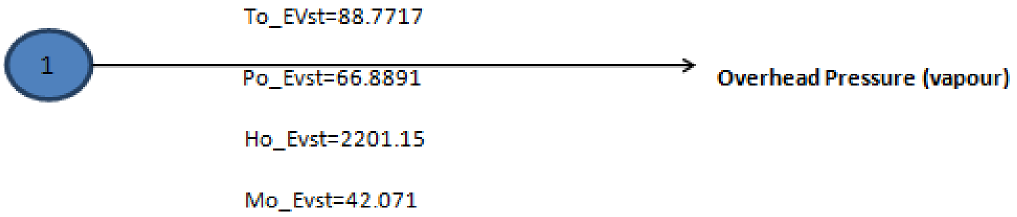
```
%------------Valve main1(after 1st evap)--------------%

Xo_PPl1=Xi_PPl1;%concentration in equal with concentration out
Xi_Vl1=Xo_PPl1;
Ti_Vl1=To_PPl1; %Temp out from the pump as a input to the valve
Pi_Vl1=Po_PPl1;  %Pressure out from the pump as a input to the valve
Mi_Vl1=Mo_PPl1;  %mass flowrate out from the pump as a input to the valve

Po_Vl1= 47.6825; %is calculate from second evaporator  which is Pi_EVl1
To_Vl1=Ti_Vl1; %temperature in equal with temp out
Mo_Vl1=Mi_Vl1;  %liquid concentration
Mo_Vg1 = Mi_Vl1* Xi_Vl1;  %Glycol mass flowrate in valve
Mo_Vw1 = (1-Xi_Vl1)*Mi_Vl1;  %Water mass flowrate in valve
Ho_Vl1= (To_Vl1-Tref)*((1-Xo_PPl1)*Cpw+(Xo_PPl1*Cpg));
KV2=(Mo_Vl1*Mo_Vl1)/(Pi_Vl1-Po_Vl1);  %valve coef (is not given)



%------------Steam In second evaporator(output first evaporator)-----------
--%
Ti_EVst1=To_EVst; %Temperature out from the steam valve as a input to the
evaporator
Pi_EVst1=Po_EVst; %Pressure out from the steam valve as a input to the
evaporator
Hi_EVst1=Ho_EVst; %Mass flowrate out from the steam valve as a input to the
evaporator
Mi_EVst1=Mo_EVst;  %value after first evaporator will used for second
evaporator


%------------second Evaporator --------------%

Xi_EVl1=Xi_Vl1;   %concentration feed
Mi_EVl1=Mo_Vl1;  %liquid mass out from the  valve as a input to the
evaporator
Mi_EVg1=Mo_Vg1 ; %mass glycol out from the steam valve as a input to the
evaporator

%liquid
To_EVl1 = ((Mi_EVst1*Lambda2)/-(Htf2*Atf2))+Ti_EVst1; %temp steam
Ho_EVl1 = (To_EVl1-Tref)*(((1-Xo_EVl1)*Cpw)+(Xo_EVl1*Cpg));  %enthalpy
liquid out
Mo_EVl1 = (Xo_EVl/Xo_EVl1)*Mi_EVl1; %total liquid Product flowrate out of
the evaporator Xf*X(1)=Xp*(mp)
Mo_EVg1 = Mi_EVg1;  %inputs equal output for glycol
Mo_EVw1 = Mo_EVl1-Mo_EVg1; %mass fraction for water

%steam
Mo_EVst1 = Mi_EVl1-Mo_EVl1;  % mass steam from evaporator
%Po_EVst1= 45; %is given
Pi_EVl1 = Po_EVst1+((Mo_EVst1*Mo_EVst1)/(KVapv2)); % Pressure for steam
% Correlation to calculate P from T for gas
a2 = log10(Po_EVst1/0.1333);
To_EVst1 = (1668.21/(7.96681-a2))-228; % Temperature for steam
Ho_EVst1 = ((To_EVst1-Tref)*Cpw)+Lambda2;  % Enthalpy for steam

Po_EVl1=Pi_EVl1;  %pressure liquid in equal to pressure out
```

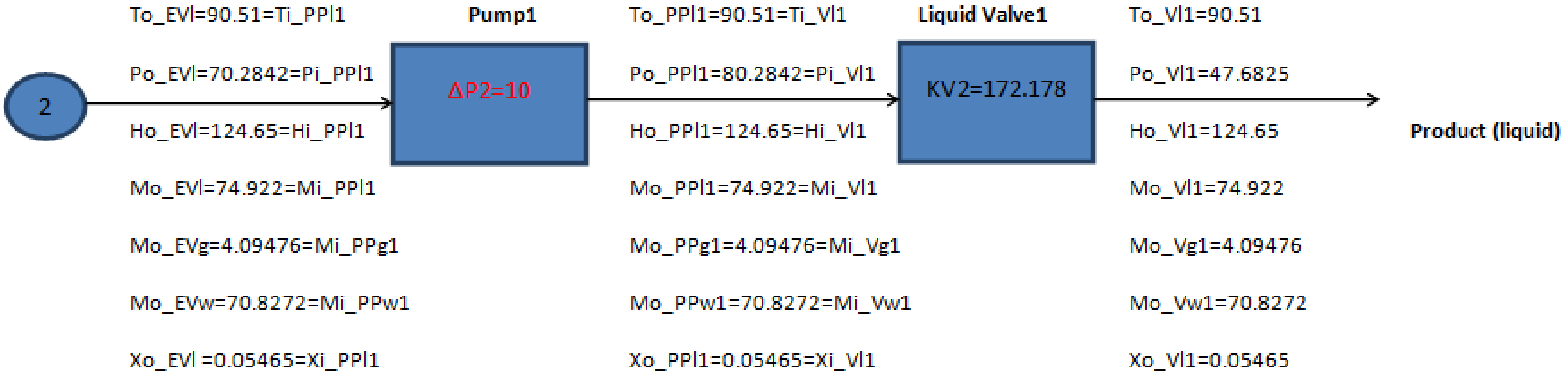
```
%------------Liquid Pump2( after 2st evapo)--------------%

Xi_PPl2=Xo_EVl1;
Ti_PPl2=To_EVl1;  %Temp out from the evap1 as a input to the pump
Pi_PPl2=Po_EVl1;  %Pressure out from the evap1 as a input to the pump
Mi_PPl2=Mo_EVl1;
Xo_PPl2= Xi_PPl2;

Po_PPl2 = dP3+Pi_PPl2; % Liquid outlet pressure from the pump
To_PPl2 = Ti_PPl2; %temperature in equal with temp out
Ho_PPl2 = (To_PPl2-Tref)*((1-Xi_PPl2)*Cpw+(Xi_PPl2*Cpg));  %enthalpy in the
pump
Mo_PPl2 = Mo_EVl1;  %total mass flowrate in equal to out
Mo_PPg2 = Mo_PPl2* Xi_PPl2;  %Glycol mass flowrate in pump
Mo_PPw2 = (1-Xi_PPl2)*Mo_PPl2;  %Water mass flowrate in pump

%------------Valve main2(after 2st evap)--------------%

Ti_Vl2 = To_PPl2;
Xi_Vl2 = Xo_PPl2;
Xo_Vl2 = Xi_Vl2;
Mi_Vl2 = Mo_PPl2;
Pi_Vl2 = Po_PPl2;

%Po_Vl2=120;  %pressure is given
To_Vl2 = Ti_Vl2;
Ho_Vl2 = (To_Vl2-Tref)*((1-Xi_Vl2)*Cpw+(Xi_Vl2*Cpg));
Mo_Vl2 = Mi_Vl2;
Mo_Vg2 = Mi_Vl2* Xi_Vl2; %Glycol mass flowrate in valve
Mo_Vw2 = (1-Xi_Vl2)*Mi_Vl2;  %Water mass flowrate in valve
KV3 = -(Mo_Vl2^2)/(Po_Vl2-Pi_Vl2); %need to calculate
```

Appendix G (Summarize of process checking)

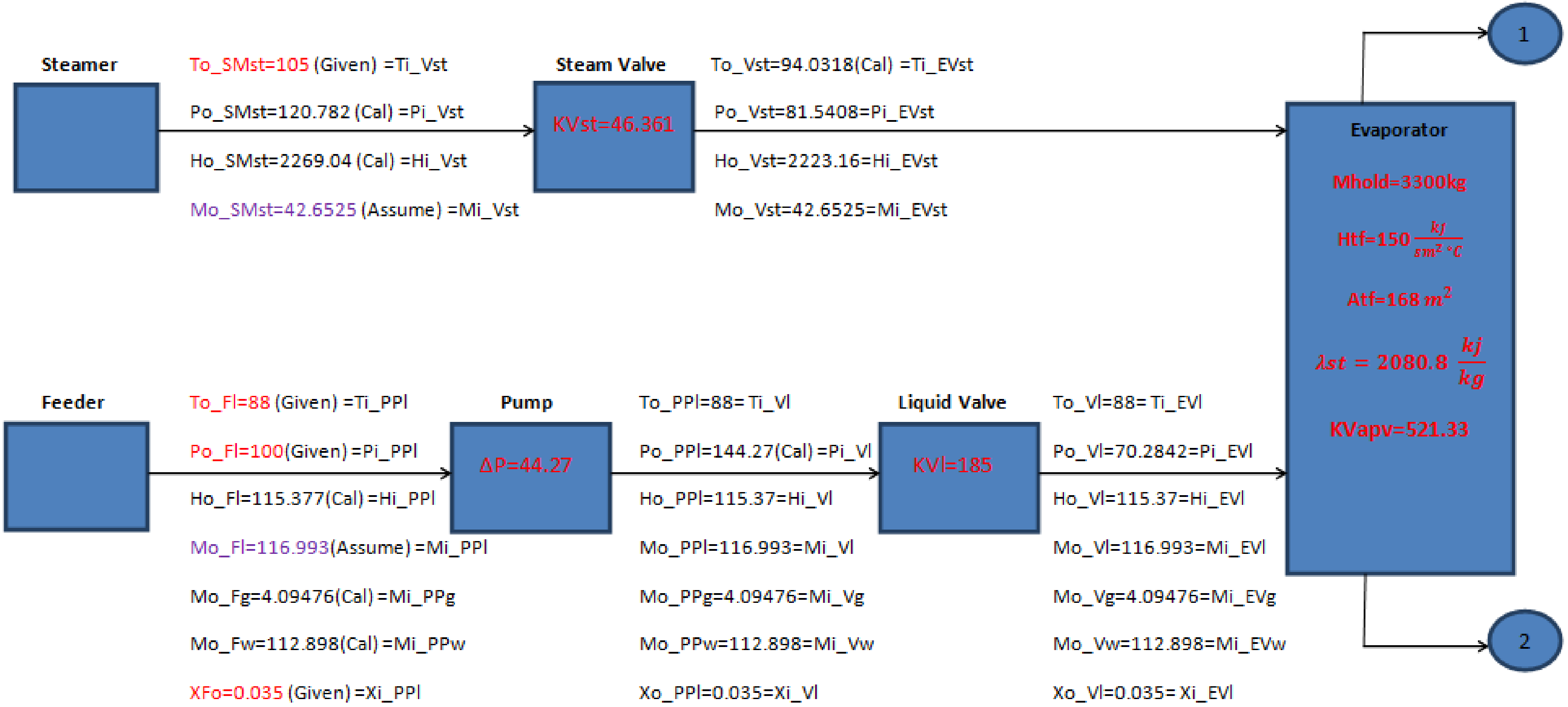
From process model equation all value is able to calculate and compare with reference steady state value from the example program. All calculation and checking value is shown in this section. All summarize value is shown in flow diagram for understand the steady state model. From block diagram, value in red colour is indicating given value and value in black colour is indicating calculation value.

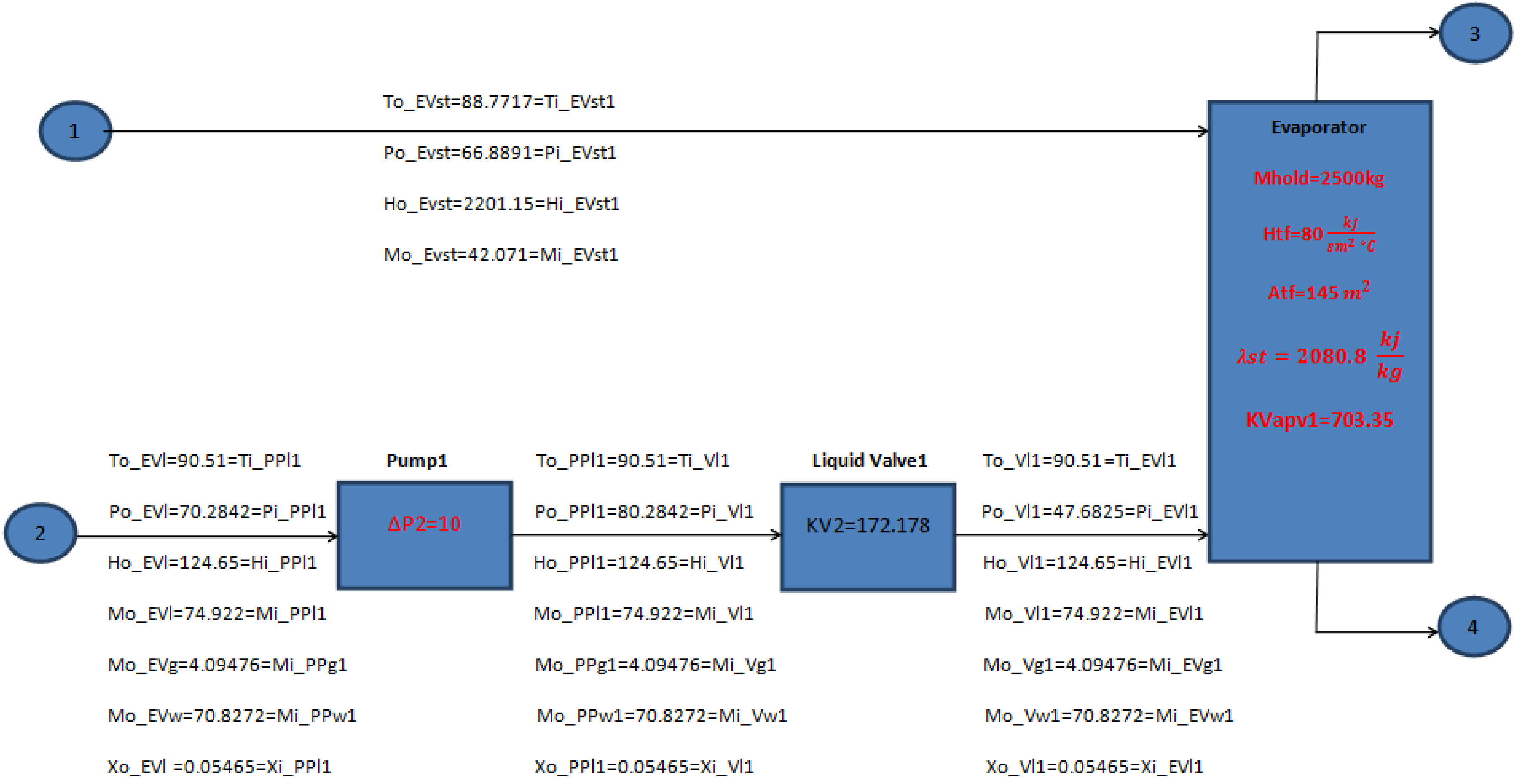


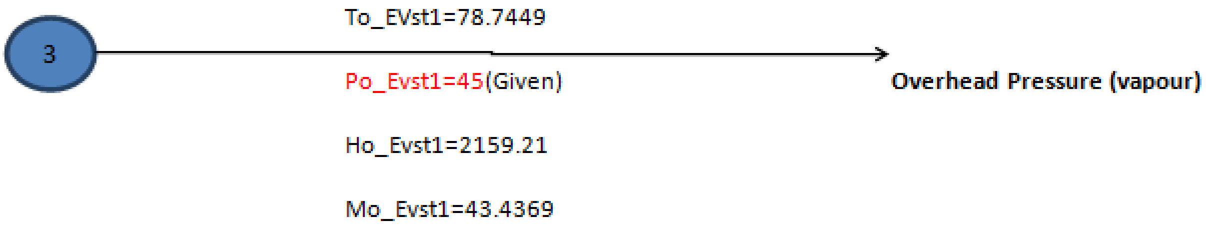

1
To_EVst=88.7717
Po_Evst=66.8891
Ho_Evst=2201.15
Mo_Evst=42.071
Overhead Pressure (vapour)

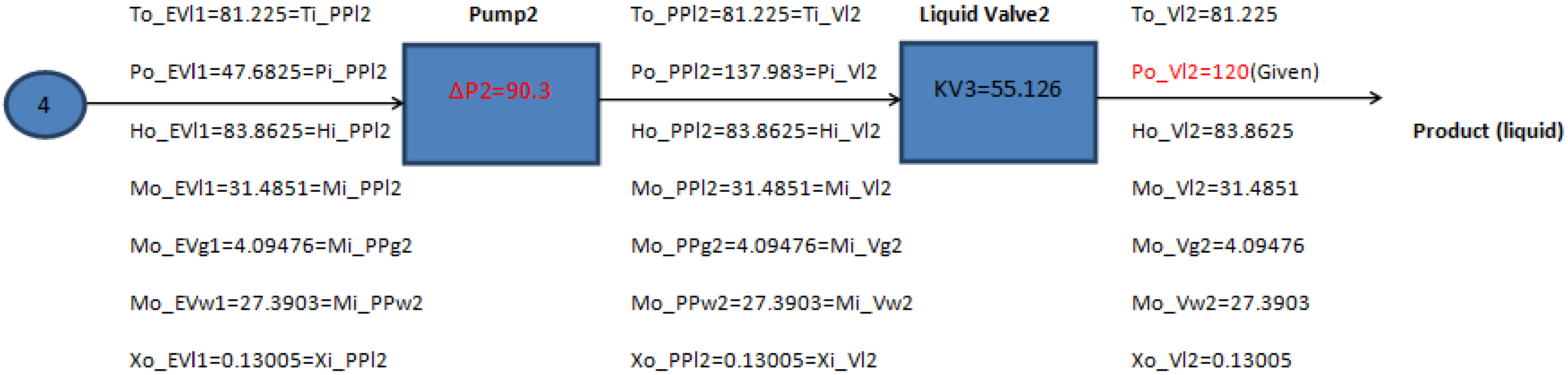

2
To_EVl=90.51=Ti_PPl1
Po_EVl=70.2842=Pi_PPl1
Ho_EVl=124.65=Hi_PPl1
Mo_EVl=74.922=Mi_PPl1
Mo_EVg=4.09476=Mi_PPg1
Mo_EVw=70.8272=Mi_PPw1
Xo_EVl =0.05465=Xi_PPl1
Pump1
ΔP2=10
To_PPl1=90.51=Ti_Vl1
Po_PPl1=80.2842=Pi_Vl1
Ho_PPl1=124.65=Hi_Vl1
Mo_PPl1=74.922=Mi_Vl1
Mo_PPg1=4.09476=Mi_Vg1
Mo_PPw1=70.8272=Mi_Vw1
Xo_PPl1=0.05465=Xi_Vl1
Liquid Valve1
KV2=172.178
To_Vl1=90.51
Po_Vl1=47.6825
Ho_Vl1=124.65
Mo_Vl1=74.922
Mo_Vg1=4.09476
Mo_Vw1=70.8272
Xo_Vl1=0.05465
Product (liquid)

Double Effect Evaporator




1
To_EVst=88.7717=Ti_EVst1
Po_Evst=66.8891=Pi_EVst1
Ho_Evst=2201.15=Hi_EVst1
Mo_Evst=42.071=Mi_EVst1
3
Evaporator
Mhold=2500kg
Htf=80 $\frac{kj}{sm^2 \,°C}$
Atf=145 m^2
$\lambda st = 2080.8 \frac{kj}{kg}$
KVapv1=703.35
4
2
To_EVl=90.51=Ti_PPl1
Po_EVl=70.2842=Pi_PPl1
Ho_EVl=124.65=Hi_PPl1
Mo_EVl=74.922=Mi_PPl1
Mo_EVg=4.09476=Mi_PPg1
Mo_EVw=70.8272=Mi_PPw1
Xo_EVl =0.05465=Xi_PPl1
Pump1
ΔP2=10
To_PPl1=90.51=Ti_Vl1
Po_PPl1=80.2842=Pi_Vl1
Ho_PPl1=124.65=Hi_Vl1
Mo_PPl1=74.922=Mi_Vl1
Mo_PPg1=4.09476=Mi_Vg1
Mo_PPw1=70.8272=Mi_Vw1
Xo_PPl1=0.05465=Xi_Vl1
Liquid Valve1
KV2=172.178
To_Vl1=90.51=Ti_EVl1
Po_Vl1=47.6825=Pi_EVl1
Ho_Vl1=124.65=Hi_EVl1
Mo_Vl1=74.922=Mi_EVl1
Mo_Vg1=4.09476=Mi_EVg1
Mo_Vw1=70.8272=Mi_EVw1
Xo_Vl1=0.05465=Xi_EVl1


3
To_EVst1=78.7449
Po_Evst1=45(Given)
Ho_Evst1=2159.21
Mo_Evst1=43.4369
Overhead Pressure (vapour)


4
To_EVl1=81.225=Ti_PPl2
Po_EVl1=47.6825=Pi_PPl2
Ho_EVl1=83.8625=Hi_PPl2
Mo_EVl1=31.4851=Mi_PPl2
Mo_EVg1=4.09476=Mi_PPg2
Mo_EVw1=27.3903=Mi_PPw2
Xo_EVl1=0.13005=Xi_PPl2
Pump2
ΔP2=90.3
To_PPl2=81.225=Ti_Vl2
Po_PPl2=137.983=Pi_Vl2
Ho_PPl2=83.8625=Hi_Vl2
Mo_PPl2=31.4851=Mi_Vl2
Mo_PPg2=4.09476=Mi_Vg2
Mo_PPw2=27.3903=Mi_Vw2
Xo_PPl2=0.13005=Xi_Vl2
Liquid Valve2
KV3=55.126
To_Vl2=81.225
Po_Vl2=120(Given)
Ho_Vl2=83.8625
Mo_Vl2=31.4851
Mo_Vg2=4.09476
Mo_Vw2=27.3903
Xo_Vl2=0.13005
Product (liquid)

Appendix H (Sensitivity Analysis Data -Single Effect Evaporator)

Vary Mass flowrate of Steam

Table 8: Single Effect Evaporator- Vary Mass Flowrate of Steam

liquid pressure in	Mass Steam in	Concentration out,X	Total Mass Product Out,Mliq	Mass Product Out,Mwater	Mass Vapour out,Mst_out	Kvalve Out Evaporator	Temp Out Evp	Tchest	kvsteam
146.6244	5.6526	0.035566	115.1326	111.0379	1.86042	0.069196	104.3681	104.8349	46.361
143.2007	10.6526	0.037246	109.9385	105.8438	7.054507	1.068038	103.5304	104.41	46.361
138.8071	15.6526	0.039116	104.6815	100.5867	12.31155	3.591614	102.421	103.7134	46.361
133.4821	20.6526	0.041212	99.35763	95.26287	17.63541	8.433599	101.0231	102.7284	46.361
127.2644	25.6526	0.043579	93.96108	89.86632	23.032	17.302	99.31145	101.4296	46.361
120.1938	30.6526	0.04628	88.48339	84.38839	28.50964	34.45682	97.24961	99.78064	46.361
112.3122	35.6526	0.049387	82.91249	78.8177	34.0805	73.94535	94.78543	97.72931	46.361
103.6636	40.6526	0.05302	77.23093	73.13618	39.7621	223.984	91.84364	95.20038	46.361
100	42.6526	0.054654	74.92197	70.82721	42.07112	521.33	90.50988	94.03177	46.361
98.12598	43.6256	0.055516	73.75861	69.66386	43.23442	1228.866	89.80497	93.40943	46.361

Vary Steam Valve Coefficient

Table 9: Single Effect Evaporator- Vary Steam Valve Coefficient

liquid pressure in	Kvalve Out Evaporator	Mass Steam in	Concentration out,X	Total Mass Product Out,Mliq	Mass Water Out,Mwater	Mass Vapour out,Mst_out	Temp Out Evp	Tchest	kvsteam
140.7307	2	13.59438	0.038321	106.8534	102.7586	10.1397	102.9115	104.034	46.361
136.618	5	17.81334	0.039992	102.3893	98.29452	14.60376	101.854	103.324	46.361
131.8839	10	22.00735	0.041825	97.9029	93.8082	19.0901	100.592	102.409	46.361
125.6779	20	26.82766	0.044181	92.68143	88.58667	24.31161	98.86	101.075	46.361
118.522	40	31.7564	0.046925	87.2621	83.1674	29.7309	96.7424	99.3646	46.361
116.19	50	33.2549	0.047838	85.5966	81.5018	31.3965	96.0214	98.7673	46.361
109.5	100	37.3264	0.050538	81.0239	76.9292	35.9691	93.8584	96.9405	46.361
106.2585	150	39.1966	0.051899	78.8981	74.8034	38.0949	92.75525	95.9918	46.361
104.329	200	40.2824	0.05273	77.6559	73.5612	39.3371	92.08	95.4062	46.361
103.046	250	40.9941	0.053291	76.8382	72.7435	40.1548	91.62275	95.0077	46.361
102.13	300	41.4974	0.053696	76.2584	72.1636	40.7347	91.2922	94.7187	46.361
101.4425	350	41.87242	0.054003	75.8254	71.7306	41.1677	91.0419	94.4993	46.361
100.908	400	42.1628	0.054243	75.4896	71.3948	41.5035	90.8457	94.3271	46.361
100.48	450	42.3943	0.054436	75.2215	71.1267	41.7716	90.6877	94.1883	46.361
100.129	500	42.5832	0.054595	75.0025	70.9077	41.9906	90.5578	94.074	46.361
100	521.33	42.6526	0.054654	74.92197	70.82721	42.07107	90.50988	94.03177	46.361
99.8367	550	42.7403	0.054728	74.8201	70.7254	42.1729	90.4491	93.9782	46.361
99.5892	600	42.873	0.054841	74.666	70.5712	42.327	90.3567	93.8968	46.361
99.377	650	42.9867	0.054938	74.534	70.4392	42.4591	90.2773	93.8268	46.361
98.8896	800	43.2469	0.055162	74.2313	70.1366	42.7617	90.0942	93.6651	46.361
98.4559	1000	43.4776	0.055363	73.9626	69.8679	43.0304	89.9302	93.5202	46.361

Appendix I (Sensitivity Analysis Data -Double Effect Evaporator)

Vary Mass flowrate of Steam

Table 10: Double Effect Evaporator- Vary Mass Flowrate of Steam

liquid pressure in	Mass Steam in	Concentration out,X	Total Mass Product Out,Mliq	Mass Product Out,Mwater	Mass Vapour out,Mst_out	Kvalve Out Evaporator	Temp Out Evp	Tchest	kvsteam
147.1895	4.6526	0.035535	115.2312	111.1365	0.932972	0.012324	104.0513	104.2	46.361
146.6245	5.6526	0.036196	113.1261	109.0314	2.006576	0.058099	103.7265	104.0602	46.361
143.2007	10.6526	0.039935	102.5342	98.43948	7.404377	0.88199	101.9213	103.1868	46.361
138.8072	15.6526	0.044591	91.82837	87.73362	12.8532	3.04533	99.8029	102.0113	46.361
133.4822	20.6526	0.050552	81.00127	76.90651	18.35645	7.376607	97.34808	100.5115	46.361
127.2645	25.6526	0.058462	70.04144	65.94668	23.91973	15.64941	94.52199	98.65343	46.361
120.1939	30.6526	0.069487	58.9319	54.8369	29.55158	32.3514	91.27353	96.3875	46.361
112.3124	35.6526	0.085938	47.64795	43.55316	35.26463	72.8478	87.52802	93.64135	46.361
103.6637	40.6526	0.113261	36.15336	32.05859	41.07767	246.1913	83.17352	90.306	46.361
100	42.6526	0.130054	31.48506	27.3903	43.4369	703.35	81.22504	88.77171	46.361
98.12614	43.6256	0.14055	29.13385	25.03909	44.62486	3470.444	80.19962	87.95496	46.361

Vary Steam Valve Coefficient

Table 11: Double Effect Evaporator- Vary Steam Valve Coefficient

liquid pressure in	Kvalve Out Evaporator	Mass Steam in	Concentration out,X-vary Kv	Total Mass Product Out,Mliq	Mass Water Out,Mwater	Mass Vapour out,Mst_out	Temp Out Evp	Tchest	kvsteam
139.9829	2	14.41487	0.043336	94.48929	90.39454	11.49958	100.3575	102.3314	46.361
135.665	5	18.70461	0.048041	85.2343	81.13955	16.20573	98.34634	101.1362	46.361
130.8655	10	22.84326	0.053725	76.21638	72.12163	20.78619	96.1581	99.74397	46.361
124.7858	20	27.47366	0.062029	66.01342	61.91867	25.96253	93.39102	97.87857	46.361
117.9793	40	32.10942	0.073563	55.6633	51.56854	31.20719	90.23759	95.64095	46.361
115.792	50	33.50633	0.077973	52.51476	48.42	32.80142	89.20272	94.88489	46.361
109.5632	100	37.2894	0.093253	43.91024	39.81548	37.15554	86.17639	92.62099	46.361
106.5573	150	39.02663	0.102582	39.91708	35.82232	39.17495	84.66534	91.46399	46.361
104.7693	200	40.03635	0.108953	37.58284	33.48808	40.35508	83.74813	90.75381	46.361
103.5801	250	40.69882	0.113599	36.04574	31.95098	41.13207	83.12985	90.27188	46.361
102.7311	300	41.16757	0.117143	34.95533	30.86057	41.6832	82.68416	89.92292	46.361
102.0941	350	41.51698	0.119937	34.141	30.04624	42.09476	82.3474	89.6584	46.361
101.5984	400	41.78758	0.122197	33.50943	29.41467	42.41394	82.08386	89.45091	46.361
101.2016	450	42.00337	0.124064	33.00518	28.91043	42.66876	81.87197	89.28376	46.361
100.8768	500	42.1795	0.125632	32.59323	28.49847	42.87694	81.69787	89.14621	46.361
100.6059	550	42.32599	0.126968	32.25032	28.15557	43.05021	81.55226	89.03103	46.361
100.3766	600	42.44976	0.12812	31.96043	27.86567	43.1967	81.42867	88.93316	46.361
100.18	650	42.55571	0.129123	31.71212	27.61737	43.32217	81.32246	88.84898	46.361
100	703.35	42.65254	0.130054	31.48506	27.3903	43.4369	81.22504	88.77171	46.361
99.86028	750	42.72762	0.130785	31.30896	27.2142	43.52589	81.14929	88.71159	46.361
99.72857	800	42.79831	0.131482	31.14305	27.0483	43.60971	81.07778	88.6548	46.361
99.61145	850	42.86111	0.132107	30.99564	26.90088	43.6842	81.01411	88.60421	46.361
99.50663	900	42.91726	0.132672	30.86378	26.76902	43.75082	80.95705	88.55886	46.361
99.32687	1000	43.01346	0.13365	30.63782	26.54306	43.86499	80.85906	88.48093	46.361