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Master Thesis

Modelling and Validation of Evaporation Systems; Mass & Energy Balances

by

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Front page picture: 1-effect evaporation system

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Acknowledgement

For this master thesis the aim was to develop a model for acquiring performance parameters from measured data from evaporation plants. It was done at the Department of Chemical Engineering at Lund University in collaboration with the Evaporation Systems department at Alfa Laval Technologies AB. I have during this master thesis project learnt a lot about evaporation systems, working with measured data and most importantly to plan, carry out and complete a large project on my own. I am thankful to have been able to get the opportunity to do my master thesis at Alfa Laval. It has been a very educational experience and I now feel ready to graduate and take on the new challenges that it brings. I could however not have done this alone. I would first like to thank my supervisors Gert Ternström and Niklas Andersson for their assistance and guidance during the project. Thank you for always having time to help me even with the smallest things. I would also like to thank the rest of the Evaporation Systems team, Guilherme Tambascia and Anders Gidner as well as rest of the staff at Alfa Laval for all their help and warm welcome. Thanks also to Henrik Kockum for his help with the model. Lastly, I would like to thank my family and friends for always being there during these past 5 years at LTH. Without you this would not have been possible.

Abstract

To evaluate the performance of evaporation systems, performance parameters such as overall heat transfer coefficient and evaporation rate need to be evaluated. These parameters are difficult measure and therefore need to be calculated using other measured data. Alfa Laval Technologies AB have evaporation systems connected to the cloud that record measured data for evaluation. In this degree project 3 models for 3 different evaporation systems, a 1- effect system, a 2-effect system, and a 3-effect system, were developed in python. These models should be able to process the measured data and with it calculate and deliver information about system performance. The models were based on simple dynamic mass & energy balances for an evaporation system that were solved using the python function "scipy.ompimize.minimize" in the python package "scipy". In the end the models all models fulfil the requirements however, the 1-effect system cannot collect data from the cloud and can only be run with a specific set of measured data points. All systems were validated by comparing model results to validated results, the 1-effect system using measured data and the 2- and 3-effect systems using an existing program for determining system performance. The validation showed that the 2-effect models results were very accurate. The model results for the 1- and 3-effect systems were less accurate but still okay.

Popular Science Summary

Creating a model that continuously gives insight to evaporator performance.

Evaporation is method used in the industry to concentrate liquids. It is a energy intensive process and it is therefore important that it is run efficiently. Looking at performance parameters gives a good insight to evaporator efficiency. These parameters are not always easily measured and need to be calculated using other measured data. It is therefore useful to have a model that does this continuously and can handle a lot of data at once.

Evaporator systems can have very different designs. Generally, an evaporator consists of a heat exchanger where a liquid stream is evaporated by heat transfer from condensing steam, and a separation chamber where the evaporated vapour is separated from the concentrated liquid. This is called a single-effect evaporator. If the evaporated vapour is used to heat another single-effect evaporator it is called a multi-effect evaporator. Multi-effect evaporators can consist of 2 or more effects in succession. In this degree project 3-models for 3 different evaporator systems were developed, tested, and validated. A model for a 1-effect system, one for a 2-effect system and one for a 3-effect system. The models were meant to calculate the performance parameters of overall heat transfer coefficient (OHTC), how well the heat in the heating media is transferred to the liquid feed stream, and evaporation rate, how much of the feed stream is turned into vapour. In the end two of the models could import over 48 hour's of measured data from a cloud network, pre-process it by removing "nan" values, filter that data and divide it into segments based on if the plant is in production or not. For the segments where production is happening the models could calculate the performance parameters and display them. The other model could import, pre-process and filter data from 3 different excel datasets and with these data calculate the performance parameters. When comparing the calculated data with validated data it was found that the model results for the 2-effect model were very accurate and the results for the 1- and 3-effect models were less accurate but still sufficient.

Table of Contents

1 Introduction

1.1 Overview

For over 20 years Alfa Laval have sold plate evaporators. To gain information about these plate evaporator systems, Alfa Laval have been collecting measured data from the systems, and today approximately 20 systems are connected to a portal which allows access to the data. However, to gain insight and give feedback on system performance, this data needs to be processed. Alfa Laval currently only have one model in place with this function, and the model is not validated and is only configured for one specific system. Further there is a need for clarity on which system metrics are directly related to the system performance. It is therefore valuable to Alfa Laval to develop models for more of its connected systems and in the future develop a general model that processes the data from the different types of evaporation configurations and gives information about the performance of the systems.

1.2 Aim

The main objectives for the master thesis work are the following: To develop and validate a model in python that processes the data from the evaporation systems and delivers information about system performance. Firstly, a model on a single evaporator system should be made and validated and after that models for multi-effect systems should be evaluated and developed. These models should be able to process the measured data and deliver information on the evaporation system performance.

1.3 Outline of thesis

In chapter 2 the background of evaporators and previous work on the subject is presented. Chapter 3 describes the background and creation of the model, chapter 4 presents the results and findings, chapter 5 discusses the future work of the project and chapter 6 summarizes the project with conclusions.

2 Background

Evaporation is a common unit operation used to separate a liquid from solids by means of heat transfer via vaporization or boiling. The purpose of evaporation is to concentrate a solution of a nonvolatile solute (i.e., solids) and a solvent (i.e., liquid), typically water. Evaporation has many applications for example concentrating a product or waste stream, volume reduction for easier packaging and transportation, removing impurities or contaminants, and recovering distilled water. The product of evaporation can be a solid or a more concentrated form of the feed, for example salts, sugars, proteins and fruit juice concentrates. [1]

2.1 Evaporation

An evaporator, where evaporation takes place, has three functional parts, a heat exchanger, an evaporation section and a separation section. These can be separate units or combined in one unit. In the heat exchanger section steam is condensed to heat the feed solution until it evaporates. In the evaporation section the feed boils and vapour is created and in the separation section the evaporated vapour is separated from the remaining concentrated liquid. [2]. Evaporation can be done either as a single effect evaporator system or a multi-effect evaporator system. A single effect evaporator is what is described above. A general layout of a single effect evaporator can be seen in figure 2.1.

A multi-effect evaporator consists of many single effect evaporators in succession. In a single-effect evaporator the vapour leaving the effect still contains a lot of energy. In a multi-effect evaporator this vapour is therefore used as a heating media in a second effect with a lower operating pressure, hence a lower boiling point. The vapour produced in that effect can be used to heat another one, and so on. The liquid will also flow between the effects. The feed can flow in different patterns, a few common ones are forward feed, backward feed, parallel feed, and mixed feed. They all have different advantages and disadvantages and the one chosen depends on the feed material and its properties. In forward feed the feed is fed co-currently with the steam/vapour flow, in backward feed it flows counter-currently, in parallel feed the feed is fed into all the effects simultaneously and in mixed feed the flow is neither counter- nor co-current. [3] [4] A general layout for a multi-effect system, a 3-effect system with forward feed can be seen in figure 2.2

2.2 Evaporators

There are a few different types of evaporators. Two common ones are shell & tube evaporators and plate evaporators. Shell & tube evaporators have vertical tubes encased in a shell. They have between 100-1600 tubes in one evaporator. The steam will condense on the outside of the tubes and the liquid evaporates inside the tubes. The evaporator have a separate part where the vapour and concentrated liquid are separated. Plate evaporators works similarly to plate heat exchangers. In between plates steam and the liquid are flowing alternately. The steam heats the liquid and evaporates it. This can be done as falling film or rising film. The created vapour and liquid stream are then led outside the plate evaporator and separated. [5]

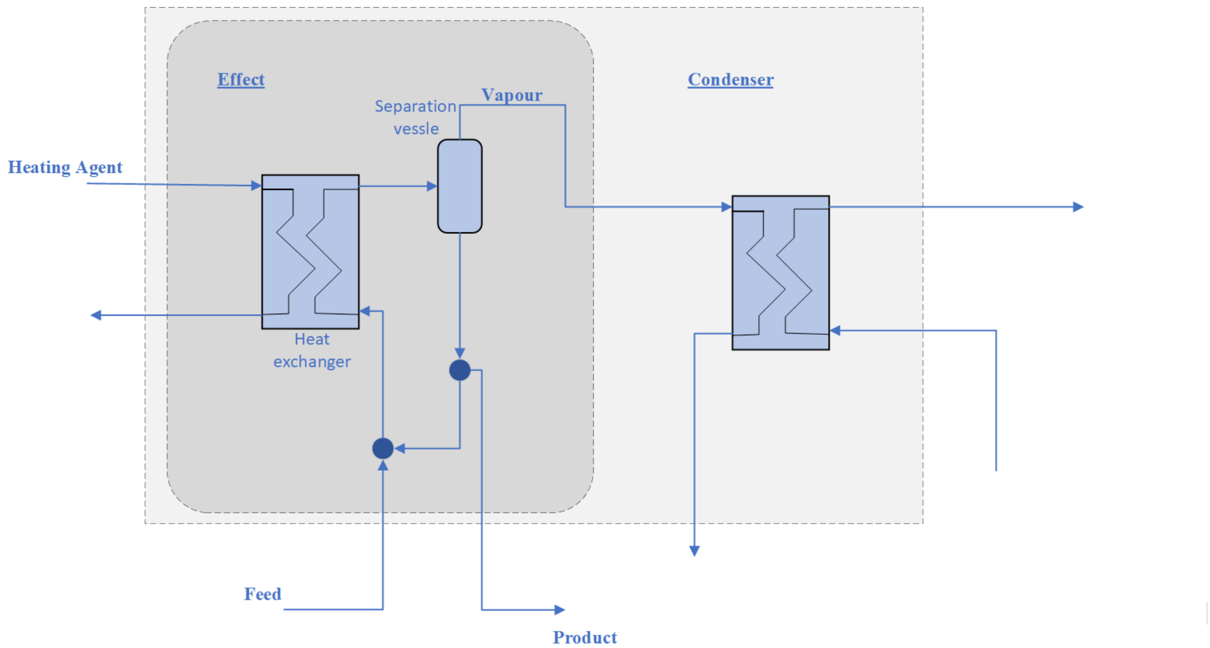

Figure 2.1 – General layout of a single effect system

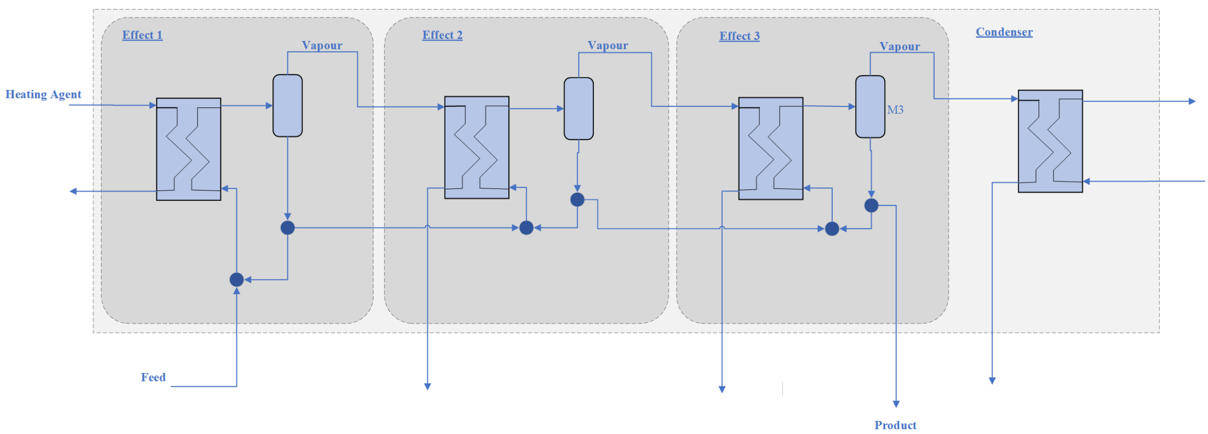

Figure 2.2 – General layout of a multi-effect system with three effects that is run as forward feed.

The evaporators can use different working principles. A few are described below:

Rising film evaporator

In a rising film evaporator, the feed is fed at the bottom of the evaporator into long vertical tubes. The liquid starts to boil inside the tubes and form a vapour. This vapour will drive liquid upward in a thin film. In order to create a well-developed film, there needs to be a temperature difference of at least 14 °C between the heating medium and product[6]. After the evaporator the vapour and liquid are led into a phase separator where they are separated. This type of evaporator is not well suited for highly viscous substances or evaporation that is operated near vacuum [7].

Falling film evaporator

In a falling film evaporator, the feed is fed at the top of the evaporator and falls down inside it forming a thin film. For this type of evaporator, a smaller temperature difference is needed between heating medium and feed compared to the rising film evaporator, therefore more effects can be used in succession. [6]

Forced circulation flash evaporators

Forced circulation flash evaporators works by heating the fluid in a heat exchanger under pressure, and then discharging it into a separation vessel with lower pressure making the liquid flash evaporate and separate into a vapour and a liquid. No boiling occurs in the heat exchanger. After the flashing the two phases are separated. [8]

2.3 Boiling Point Elevation (BPE)

Boiling point elevation (BPE) is a phenomenon that refers to the increase in boiling point of a solution compared to its pure solvent at identical pressures. The boiling point will be higher the higher the solid content of the solution is which means the BPE will be higher. In evaporation the BPE will increase as the mass fraction of solids in the solution increases. [3]

2.4 Previous work

Currently a model processing data and calculating performance parameters exists at Alfa Laval. It is designed for a specific 2 effect evaporation system, with no pre-heating and one condenser. The effects are both rising film plate evaporators with re-circulation and are run as forward feed. The system is operating with low particle concentrations and the feed concentration is unknown and varies between runs. The model used is specifically designed for this system and will need modification to be able to be used for other 2 effect evaporator systems. The design of the models in this master thesis are based on this model.

The existing model calculates the vapour flow rates from each evaporator as well as their individual overall heat transfer coefficients. The model also calculates the average liquid hold-up time in each evaporator as well as how much percent of the time that the plant is up and running.

3 Materials & Methods

In this work 3 models are created, tested, and validated. One model on a 1-effect system, one on a 2-effect system and one on a 3-effect system. They are described in detail below.

3.1 Data

For all models, logged data from real plants were used. This data consists of measured values such as process temperatures, flow rates, pressures, and densities, as well as information on when valves in the process are open or closed. This data is logged, uploaded, and saved in real time on a cloud solution and can then be collected and processed. Right now, the data from the different evaporation systems are collected every 5 seconds and displayed with graphs. The purpose of the models created in this project is to take this data and calculate performance parameters and display them in a similar fashion. To use the measured data, it needs to be retrieved from the cloud. For the 2-effect system and the 3-effect system successful data retrieval was made. However, for the 1-effect system; the evaporation plant was not connected to the cloud while test was running. This led to no data being logged on the cloud and the data used in this model were instead saved on excel-files and directly imported into python. Because of this the spacing between measurements is larger, around 60 seconds. An attempt to collect old data for the 1-effect system from the cloud was made and was successful but not used in the model. This is because there is no way of differentiating when the plant is in production or not.

3.2 Data processing

Before using the logged data in the model to calculate the performance parameters it needs to be processed in a few ways. The raw measured data from the evaporation facilities are scattered and contain "not a number" (nan) values. Therefore data processing is needed before it can be used in the model. Firstly, nan values due to for example data loss need to be dealt with. This is done by replacing the nan values with the value before or after it. After filling the data, it needs to be filtered. This will make the data less scattered and minimize the effects of time delays in the system. For the filtration 3 types of filters were tested: a moving average filter, a Savitzky-Golay filter and a finite impulse response (FIR) filter using the Parks-McClellan algorithm.

A moving average filter calculates an average value for each data point using a set size of data points around it. It therefore can reduce the noise while keeping the overall shape of the dataset. [9] A Savitzky-Golay filter uses the method of least squares with a predetermined polynomial to filter the data.[10] and FIR is a digital filter with no feedback implemented in its algorithm. The Parks-McClellan algorithm determines the filter coefficients for the filter, it does this by over a specified frequency evenly spread out the error of the data, and in turn minimizing the error. [11]. Ultimately it was decided to use the moving average filter to render the results in this report since it was the easiest and it gave sufficient results. However, all filters are implemented and can be used in the models.

The model gathers data from when the evaporation facilities both when they are in production and not. Therefore, there needs to be a way for the model to differentiate between "running" and "not running". This is done by dividing the data into segments based on certain parameters. For the 2-effect model these are the vapor pressure of the last effect and if a valve is open or not and for the 3-effect system it has the same vapour condition and also if a parameter called "step number" is of a certain value.

3.3 Variable list

In the model descriptions below, specific variable names are used. These are explained in detail in table 3.1.

Table 3.1 – List of equation variable names, units and descriptions

Variable	Unit	Description
m_i	$\frac{kg}{s}$	Mass flow rate of, i=0 feed, i=1,2,3: liquid stream out of effect i
F_i	$\frac{m^3}{s}$	Volumetric flow rate of, i=0 feed, i=1,2,3: liquid stream out of effect i
m_{iv}	$\frac{kg}{s}$	Vapour mass flow rate in vapour stream out of effect i
x_i	$\frac{kg}{kg}$	Mass fraction of, i=0 feed, i=1,2,3: liquid stream out of effect i
h_i	$\frac{J}{kgK}$	Liquid enthalpy of, i=0 feed, i=1,2,3: liquid stream out of effect i
H_{iv}	$\frac{J}{kgK}$	Vapour enthalpy of vapour stream out of effect i
M_i	kg	Mass inventory in effect i
$\frac{dM_i}{dt}$	$\frac{kg}{s}$	Temporary change of mass inventory in effect i
$\frac{d(xM_i)}{dt}$	$\frac{kg}{s}$	Temporary change of component mass inventory in effect i
$\frac{d(hM_i)}{dt}$	$\frac{J}{s}$	Temporary change of energy inventory in effect i
Q_i	$\frac{J}{s}$	Transferred heat from heating agent in effect i
$OHTC_i$	$\frac{W}{m^2}$	Overall heat transfer coefficient in effect i
A_i	m^2	Heat transfer area in effect i
T_s	$^\circ C$	Steam temperature
T_i	$^\circ C$	Temperature of, i=0 feed, i=1,2,3: liquid and vapour stream out of effect i
p_s	$^\circ C$	Steam pressure
p_i	$^\circ C$	pressure of, i=0 feed, i=1,2,3: liquid and vapour stream out of effect i
ΔT_{L2}	$^\circ C$	The logarithmic middle temperature for effect 2

BPE_i	$°C$	Boiling point elevation of vapour in m_{iv}
D_i	m	Diameter of separation tank in effect i
Δp_{Li}	pa	Liquid level (pressure difference) in separation tank in effect i
g	$\frac{m}{s^2}$	Gravitational acceleration
m_s	$\frac{kg}{s}$	Steam mass flow rate
h_{sc}	$\frac{J}{kgK}$	Enthalpy of steam condensate
H_s	$\frac{J}{kgK}$	Steam enthalpy
m_{cond}	$\frac{kg}{s}$	Condensate mass flow rate

3.4 Result variables

The purpose of the models is to gain insight to the performance of the systems and to be able to evaluate this over time. Hence the chosen result variables for the systems are the Evaporation rate, both overall and for each effect (if more than one effect is used) and Overall Heat Transfer Coefficients (OHTC) for each effect.

For the evaporation systems the evaporation rate for each effect is designed to be of a certain value, for the 2-effect system this value is around 2.6 $\frac{ton}{h}$ and for the 3-effect system it is around 2 $\frac{ton}{h}$. For the 1-effect system no such value exists since it is a pilot plant that is run differently every time.

When it comes to the OHTC values, they can vary depending on evaporator type, viscosity of fluid etc. Some recorded values lie between 1800-5000 $\frac{W}{m^2K}$. [2]

3.5 1-effect system

As a base for the 1-effect model a single evaporator pilot plant is used. The model should take data from this existing plant and process it to give information about its performance. This plant collects more data than the average one effect pilot plant which makes it ideal to use for validation. The plant consists of a single-effect plate evaporator with re-circulation. The effect is a plate evaporator followed by a separation tank and can be operated as a rising film plate evaporator or a flash evaporator. It has one total condenser and no pre-heating. To keep a constant liquid volume in the separation tank, the feed flow rate is varied. When the product concentration reaches its target, it is withdrawn from the system, otherwise it is recycled back into the evaporator in an outer re-circulation loop that is separate from the other re-circulation loop. In other words, both the feed flow rate and product flow rate are non-constant. The condenser used in this system is oversized for the system which leads to very efficient cooling of the condensate. The level regulator on the separator tank that regulates the feed flow rate is not very good and the system measuring the feed flow is not always that accurate, so these values are rather inconsistent. For this system the product is taken out manually. An overview of the plant and its variables can be seen in figure 3.1

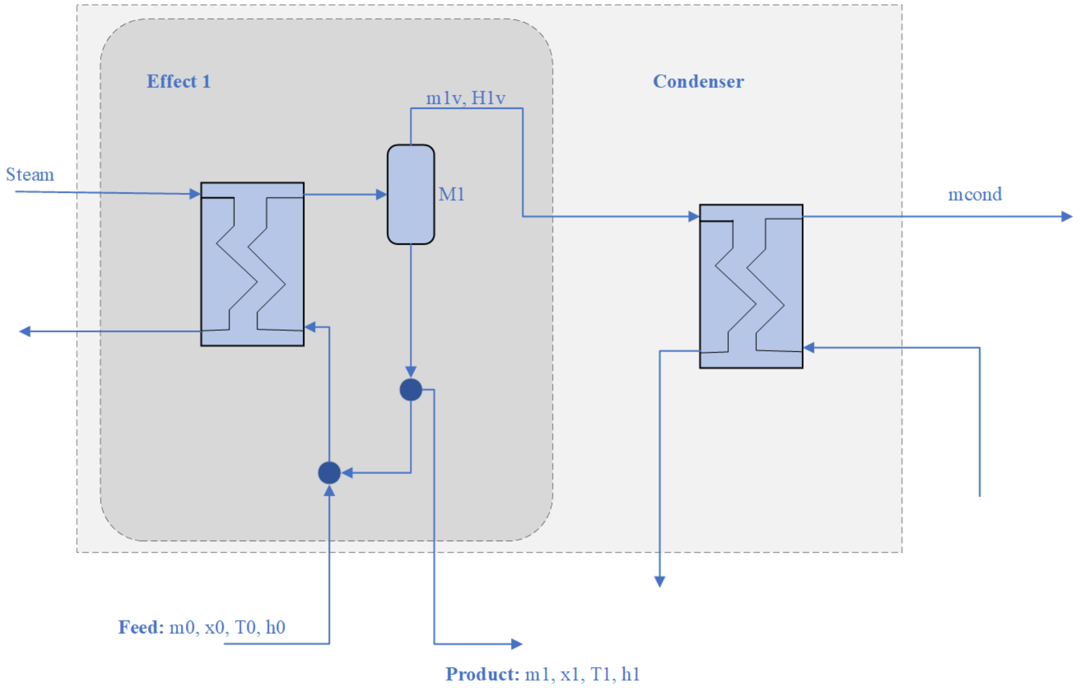

Figure 3.1 – An overview of the 1-effect system and its streams and variables.

3.5.1 Equations

To calculate the performance parameters a mix of mass & energy balances and other equations are used. They are explained below. For all equations, the variables are explained in table 3.1 in section 3.3.

Mass & Energy Balances

The main part of the model is based on mass and energy balances for a single evaporator, equations 3.1 to 3.3. Since the system is not in steady state, time derivatives are included in the balances. Equation 3.1 is the total mass balance, equation 3.2 is the component mass balance equation for the dissolved particles and equation 3.3 is the energy balance for the system.

$$\frac{dM}{dt} = m_0 - m_1 - m_{1v} \tag{3.1}$$

$$\frac{d(xM)}{dt} = m_0 x_0 - m_1 x_1 \tag{3.2}$$

$$\frac{d(hM)}{dt} = m_0 h_0 - m_1 h_1 - m_{1v} H_{1v} + Q \tag{3.3}$$

Other Equations

In order to calculate the overall heat transfer coefficient equation 3.4 is used.

$$OHTC = \frac{Q}{A(T_s - T_1)} \tag{3.4}$$

To be able to calculate the mass inventory and in turn changes in mass, component mass and heat inventory changes, $\frac{dM}{dt}$, $\frac{dxM}{dt}$ and $\frac{dhM}{dt}$, equation 3.5 is used.

$$M_1 = \frac{\Delta p_{L1}}{g} \frac{\pi D_1^2}{4} \tag{3.5}$$

3.5.2 Variables

To be able to solve the balance equations and calculate evaporation rate and OHTC using the equations in section 3.5.1 variables need to be measured, calculated and specified. Down below follows a rundown of each category as well as the unknown variables of the system.

- **Measured:** m_0, m_1, m_{cond}, ρ_1, T_0, T_1, p_1, p_s, Δp_{L1}, F_{1r} and p_{1r}.
- **Specified:** D, A, x_0 and m_1 .
- **Calculated:** x_1, h_0, h_1, H_{1v}, T_s, M_1, $\frac{dM}{dt}$, $\frac{dxM}{dt}$ and $\frac{dhM}{dt}$.
- **Unknown:** m_{1v} and Q

For this system the product is taken out before its measurements so the measurement of product flow rate m_1 cannot be used. Instead, a condition based on product mass fraction is used. That is why the variable is both present in the "measured" and "specified" category.

For the single-effect system only 2 unknowns exist, vapour flow rate m_{1v} and transferred heat Q. Therefore only 2 of the mass balances are needed. For this system only equation 3.1 and equation 3.3 are used.

3.5.3 Assumptions

For this model assumptions were made, these are stated below:

1. No solids in vapour streams.
2. The effect is a fully mixed tank.
3. The mixing between solvent and solute is small.
4. Significant effects due to accumulation is only because of the liquid hold-up in the separation tanks.

With assumption 1 the vapour part from the component mass balance can be left out. Assumption 2 makes sure that the temperature, mass fraction and enthalpy inside the evaporator is the same as in the outflow from the evaporator. Assumption 3 make sure that there are no partial enthalpies, such as mixing enthalpies. Assumption 4 makes that the inventory changes can be calculated using the hold-up volume in the separation tank.

3.6 2-effect system

The 2-effect system is based on a plant that consists of 2 effects and a condenser, and uses no pre-heating. The effects are both plate rising film evaporators with re-circulation and are run as forward feed. The first effect is heated with a mixture of steam and moist air that is a waste stream from another system. An overview of the system and its variables can be seen in figure 3.2. This plant is used to concentrate waste streams and therefore its inlet concentration varies and is unknown. An estimate value for the inlet concentration is used in the model.

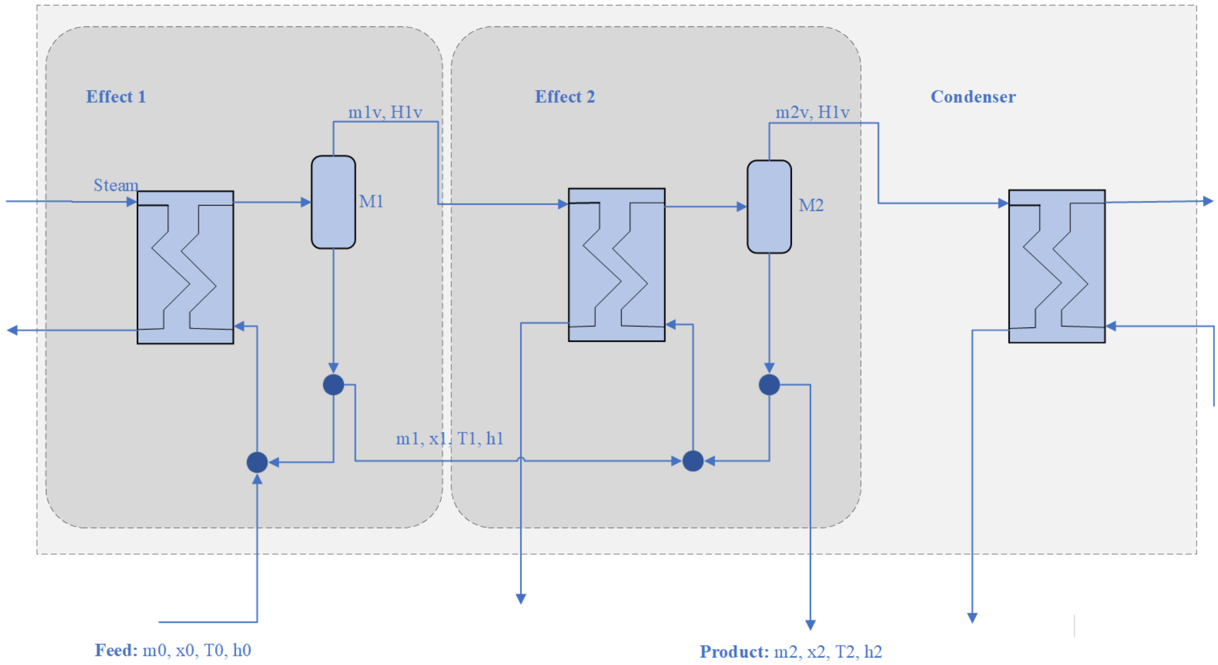

Figure 3.2 – An overview of the 2-effect system and its streams and variables.

3.6.1 Equations

To calculate the performance parameters a mix of mass & energy balances and other equations are used. They are explained below. For all equations, the variables are explained in table 3.1 in section 3.3.

Mass & Energy Balances

For this model, the main part of the model is based on mass and energy balances. This time for a two-effect system with forward feed. The balances are written the same way as the 1-effect model. However, since the system consists of 2 evaporators, there are 6 equations, see equations 3.6 to 3.11.

$$\frac{dM_1}{dt} = m_0 - m_1 - m_{1v} \tag{3.6}$$

$$\frac{d(xM_1)}{dt} = m_0 x_0 - m_1 x_1 \tag{3.7}$$

$$\frac{d(hM_1)}{dt} = m_0 h_0 - m_1 h_1 - m_{1v} H_{1v} + Q1 \tag{3.8}$$

$$\frac{dM_2}{dt} = m_1 - m_2 - m_{2v} \tag{3.9}$$

$$\frac{d(xM_2)}{dt} = m_1 x_1 - m_2 x_2 \tag{3.10}$$

$$\frac{d(hM_2)}{dt} = m_1 h_1 - m_2 h_2 - m_{2v} H_{2v} + Q2 \tag{3.11}$$

Other Equations

To calculate overall heat transfer coefficients for each effect equations 3.12 and 3.13 are used.

$$OHTC_1 = \frac{Q_1}{A_1(T_s - T_1)} \tag{3.12}$$

$$OHTC_2 = \frac{Q_2}{A_2(T_1 - T_2 - BPE_1)} \tag{3.13}$$

To calculate the mass inventories equation 3.14 is used. This is then used to calculate mass-, component mass- and heat inventory changes, $\frac{dM_1}{dt}$, $\frac{dM_2}{dt}$, $\frac{dxM_1}{dt}$, $\frac{dxM_2}{dt}$, $\frac{dhM_1}{dt}$ and $\frac{dhM_2}{dt}$.

$$M_i = \frac{\Delta p_{Li}}{g} \frac{\pi D_i^2}{4} \tag{3.14}$$

3.6.2 Variables

To be able to solve the balance equations and calculate evaporation rate and OHTC using the equations in section 3.6.1 variables need to be measured, calculated and specified. Down below follows a rundown of each category as well as the unknown variables of the system.

- **Measured:** F_0, F_2, ρ_0, ρ_2, T_0, T_1, T_2, p_1, p_2, p_{steam}, Δp_{L1}, Δp_{L2}, F_{1r} and F_{2r}.
- **Specified:** D_1, D_2, A_1, A_2 and x_0.
- **Calculated:** m_0, m_2, x_2, h_0, h_1, h_2, H_{1v}, H_{2v}, T_{steam}, M_1, M_2, $\frac{dM_1}{dt}$, $\frac{dM_2}{dt}$, $\frac{dxM_1}{dt}$, $\frac{dxM_2}{dt}$, $\frac{dhM_1}{dt}$ and $\frac{dhM_2}{dt}$
- **Unknown:** m_1, x_1, m_{1v}, m_{2v}, Q_1 and Q_2

For this system there are 6 unknowns and 6 balances which means there are enough balances to solve the system.

3.6.3 Assumptions

The assumptions for this model is similar to the 1 effect model. They are stated below:

1. No solids in vapour streams.
2. The effects are fully mixed tanks.
3. The mixing between solvent and solute is small.
4. Significant effects due to accumulation is only because of the liquid hold-up in the separation tanks.
5. The inlet concentration is known and constant.
6. Values for x_1 are assumed as a percentage of the product mass fraction for the calculations of $\frac{d(xM_1)}{dt}$ and h_1.

With assumption 1 the vapour part from the component mass balance can be left out. Assumption 2 makes sure that the temperature, mass fraction and enthalpy inside the evaporator is the same as in the outflow from the evaporator. Assumption 3 make sure that there are no partial enthalpies, such as mixing enthalpies. Assumption 4 makes that the inventory changes can be calculated using the hold-up volume in the separation tank. Assumption 5 and 6 is used to remove unknowns from the system so that there are enough equations to solve the system, the way the mass & energy balances are solved in the model these variables need to be known.

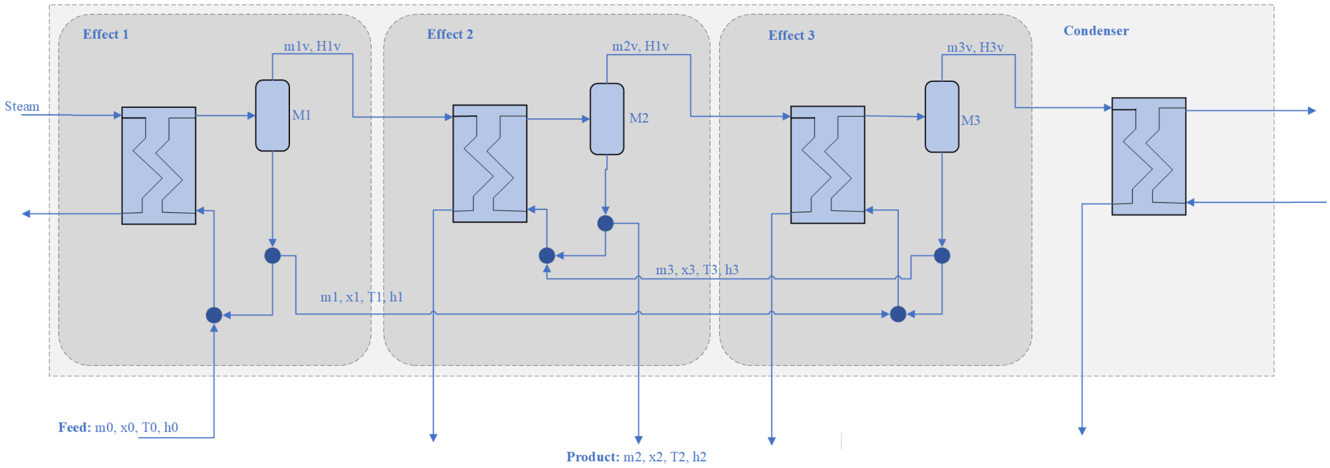

Figure 3.3 – An overview of the 3-effect system and its streams and variables.

3.7 3-effect system

The model for the 3-effect system is based on a plant with 3 effects, consisting of a plate heat exchanger and a separation tank, and one condenser. All effects are plate evaporators, two of them are rising film evaporators and one is a flash evaporator. The effects are operated with mixed flow and all of them have re-circulation. The feed is pre-heated with two pre-heaters. One using the steam condensate from effect 1 and one using the combined vapour condensate from effect 2 and 3. The first effect is heated by steam. The product is taken out from the second effect. An overview of the system can be seen in figure 3.3.

3.7.1 Equations

To calculate the performance parameters a mix of mass & energy balances and other equations are used. They are explained below. For all equations, the variables are explained in table 3.1 in section 3.3.

Mass & Energy Balances

For this model as well, the main part of the model is based on mass and energy balances. This time for a three effect system with mixed feed. The balances are written in similar fashion as the two other models. However, since the system consists of 3 evaporators, there are 9 equations, see equation 3.15 to 3.23. Since the plant is operated in mixed flow the balances look a bit different.

$$\frac{dM_1}{dt} = m_0 - m_1 - m_{1v} \tag{3.15}$$

$$\frac{d(xM_1)}{dt} = m_0 x_0 - m_1 x_1 \tag{3.16}$$

$$\frac{d(hM_1)}{dt} = m_0 h_0 - m_1 h_1 - m_{1v} H_{1v} + Q1 \tag{3.17}$$

$$\frac{dM_2}{dt} = m_3 - m_2 - m_{2v} \tag{3.18}$$

$$\frac{d(xM_2)}{dt} = m_3 x_3 - m_2 x_2 \tag{3.19}$$

$$\frac{d(hM_2)}{dt} = m_3h_3 - m_2h_2 - m_{2v}H_{2v} + Q2 \quad (3.20)$$

$$\frac{dM_3}{dt} = m_1 - m_3 - m_{3v} \quad (3.21)$$

$$\frac{d(xM_3)}{dt} = m_1x_1 - m_3x_3 \quad (3.22)$$

$$\frac{d(hM_3)}{dt} = m_1h_1 - m_3h_3 - m_{3v}H_{3v} + Q3 \quad (3.23)$$

Other Equations

To calculate overall heat transfer coefficients for each effect 3.24 to 3.26 is used. The second evaporator is a flash evaporator and therefore has another expression for the overall heat transfer coefficient.

$$OHTC_1 = \frac{Q_1}{A_1(T_s - T_1)} \quad (3.24)$$

$$OHTC_2 = \frac{Q_2}{A_2\Delta T_{L2}} \quad (3.25)$$

$$OHTC_3 = \frac{Q_3}{A_3(T_2 - T_3 - BPE_2)} \quad (3.26)$$

To calculate the mass inventories equation 3.27 is used. This is then used to calculate mass-, component mass- and heat inventory changes, $\frac{dM_1}{dt}$, $\frac{dM_2}{dt}$, $\frac{dM_3}{dt}$, $\frac{dxM_1}{dt}$, $\frac{dxM_2}{dt}$, $\frac{dxM_3}{dt}$, $\frac{dhM_1}{dt}$, $\frac{dhM_2}{dt}$ and $\frac{dhM_3}{dt}$.

$$M_i = \frac{\Delta p_{Li}}{g}\frac{\pi D_i^2}{4} \quad (3.27)$$

3.7.2 Variables

To be able to solve the balance equations and calculate evaporation rate and OHTC using the equations in section 3.7.1 variables need to be measured, calculated and specified. Down below follows a rundown of each category as well as the unknown variables of the system.

- **Measured:** F_0, m_2, ρ_2, T_0, T_1, T_2, T_3, p_1, p_2, p_3 p_{steam}, Δp_{L1}, Δp_{L2}, Δp_{L1}, F_{1r}, F_{3r}, p_{3r} and T_{3r}.
- **Specified:** D_1, D_2, D_3, A_1, A_2, A_3 and x_0.
- **Calculated:** m_0, x_2, h_0, h_1, h_2, h_3, H_{1v}, H_{2v}, H_{3v}, T_{steam}, M_1, M_2, M_3, $\frac{dM_1}{dt}$, $\frac{dM_2}{dt}$, $\frac{dM_3}{dt}$, $\frac{dxM_1}{dt}$, $\frac{dxM_2}{dt}$, $\frac{dxM_3}{dt}$, $\frac{dhM_1}{dt}$, $\frac{dhM_2}{dt}$, and $\frac{dhM_3}{dt}$
- **Unknown:** m_1, m_3, x_1, x_3, m_{1v}, m_{2v}, m_{3v}, Q_1, Q_2, Q_3

This system has 10 unknowns and 9 balance equation. Therefore an assumption is needed to reduce the amount of unknowns in the system, see assumption 7 below.

3.7.3 Assumptions

The assumptions for this model is similar to the 1-effect and 2-effect models. They are stated below:

1. No solids in vapour streams.
2. The effects are fully mixed tanks.
3. The mixing between solvent and solute is small.
4. Significant effects due to accumulation is only because of the liquid hold-up in the separation tanks.
5. The inlet concentration is known and constant.
6. Values for x_1 and x_3 are assumed as a percentage of the product mass fraction for the calculations of $\frac{d(xM_1)}{dt}$, $\frac{d(xM_3)}{dt}$, h_1 and h_3.
7. The energy transferred in effect 2 and 3 is the same, $Q_2 = Q_3$.

With assumption 1 the vapour part from the component mass balance can be left out. Assumption 2 makes sure that the temperature, mass fraction and enthalpy inside the evaporator is the same as in the outflow from the evaporator. Assumption 3 make sure that there are no partial enthalpies, such as mixing enthalpies. Assumption 4 makes that the inventory changes can be calculated using the hold-up volume in the separation tank. Assumption 5, 6 and 7 is used to remove unknowns from the system so that there are enough equations to solve the system, the way the mass & energy balances are solved in the model these variables need to be known.

3.8 Parameter calculation

In order to solve the mass and energy balance equations certain parameters need to be estimated such as enthalpies of fluids and vapour, mass fractions, density, boiling point elevation and saturation temperature. In the existing 2-effect model this is done using the python package "coolprop" [12] which gives data of water at different conditions. The calculated values are then combined with equations to account for the influence the solids have on the fluid streams. These equations are however not validated and are only adapted to this one system. When testing the equations on the 1-effect system it was found that it gave rather unreasonable values. Therefore, a new set of equations were needed.

To get more general equations and essentially moving away from the existing equations, relations was made for data from pure sucrose solution data found in "Sugar Technologists Manual" [13], these equations are used to calculate liquid enthalpy and boiling point elevation, and for the 2-effect system density and mass fractions as well. For the 1- and 3-effect models mass fractions and densities, are calculated using a relation based on measured values from the pilot plant tests of density and mass fraction. For parameters of pure water such as vapour enthalpy "coolprop" is continued to be used.

3.9 Model Validation

To determine how well the models work they were all validated on the two result parameters, evaporation rate and overall heat transfer coefficient. The 1-effect model was validated by comparing the results with measured data. For the 2-effect and 3-effect models validation was made using a Alfa Laval program for simulating evaporation systems. It works by building the evaporation process in a computer program with the different units, evaporators, condenser etc, and connecting them with streams. The initial running parameters are then specified such as feed flow rate, temperature and composition, heat exchanger areas and temperatures, steam temperature and outlet concentration from the last effect. The program then solves the steady state problem and the validated values are produced.When using this system the initial parameters are the median values of the measured data

The validation for the 1-effect system is described in more detail below.

3.9.1 Evaporation Rate

For the 1-effect pilot plant the volumetric flow rate of the condensed vapour is measured. By assuming its density as 1000 $\frac{kg}{m^3}$, a measured value for the evaporation rate is acquired. This value is then compared to the calculated evaporation rate. This assumes that the measurement value of the condensate flow rate is accurate and that all the vapour is condensed.

3.9.2 Overall Heat Transfer Coefficient

For this validation the heat transfer from the steam to the inlet flow is utilized, equation 3.28. This equation assumes that the steam flow is equal to the condensed steam flow, the steam is saturated and there is no sub-cooling of the condensate.

$$Q = m_s(H_s - h_{sc}) \tag{3.28}$$

To calculate H_s and h_{sc} it is assumed that the condensed steam has the same pressure and temperature as the steam. The steam flow is not measured so it's assumed that the steam flow is the same as the vapour condensate flow. To now calculate OHTC, the same formula as in the model is used, equation 3.4.

3.10 Model Calculations

The models were created using python 3.9. 3 models were created, one for each evaporation system. These models are operated separately. Each model consists of several python scripts that interact together. The model collect data over a certain time intervall. For each point in this dataset the performance parameters are calculated using the measured variables. The models work by rewriting the balance equations by moving the inventory part to the left side and adding a residual to the right side, see equation 3.29. All the residuals from all balance equations are then summed together and the sum is squared. To then solve the balance equation system and get values for the unknown variables this square sum is minimized using the python function "scipy.optimize.minimize" from the python package "scipy" [14]. For the 1- and 2-effect model the method used in this function is "SLSQP" and for the 3-effect model the method "Nelder-Mead" is used. The minimizing is done separately for each time point of the measured data using a for loop. From these calculations we get the specified unknown variables for each system, most importantly the evaporation rates. The OHTC values are then calculated using the results.

$$residual = m_0 - m_1 - m_{1v} - \frac{dM_1}{dt} \tag{3.29}$$

4 Results & Discussion

The purpose of the models is to process the collected data and delivers information on system performance. In the materials & methods section these parameters were established to be evaporation rate and overall heat transfer coefficient. Therefore, the results of these parameters from the three different models will be presented below. The aim was also to validate the models, so validation results on the performance parameters will also be presented.

4.1 1-effect model

An outline of the created model for the 1-effect system can be seen in figure 4.1. The model consists of 5 python files, "Run 1 effect.py", "Model 1 effect.py", "Importdata 1 effect.py", "Measurements 1 effect.py" and "Fluiddata 1 effect.py". The "Run 1 effect.py" file is where the equations are run. It calls on the "Model 1 effect.py" file which in turn calls on the other files. "Model 1 effect.py" calls on "Importdata 1 effect.py" to collect measured data from excel files, it calls on "Measurement 1 effect.py" to filter the data and on "Fluiddata 1 effect.py" to calculate equation parameters. When this is done the "Model 1 effect.py" file will then solve the balance equations of the evaporation system and plot the results. It will also validate the results against measured data. To be able to call on the equations in the "Model 1 effect.py" file a few things including excel file, data interval and filter preferences needs to be specified. This is done in the "Run 1 effect.py" file. Here results medians are also calculated.

Overall, the model does almost all it was intended to do. It can with given data solve the evaporation problem and produce information on the performance of the system. The model, however, cannot take data from the cloud and use them in the model. This is partly due to the plant not being connected to the cloud at the time when the model was created and also because the plant does not have a measured parameter that can be used to determine when the plant is in production or not. There is however a script created for retrieving data from the cloud. It is just not integrated with the model as it is written now. To further improve this model implementation of this needs to be researched and tested further. Another problem with the model is that to add sets of data that can be used in the model a lot of code needs to be added and changed. So, the model is unflexible.

4.1.1 Simulation results

In figures 4.2 to 4.4 the evaporation rate and overall heat transfer coefficient calculated with the 1-effect model can be seen. Each figures results are calculated with a different set of data taken from different tests called, "A", "B", and "C". The mean values of the results for dataset A-C is summarized in table 4.1.

The OHTC values look reasonable maybe a bit low compared to values mentioned in section 3.4. When it comes to the evaporation rates it is difficult to say if they are of reasonable value since there is no design value for the evaporation rate for this system. To know if those values are reasonable a look at the model validation is needed. The reason that the results are different between the different datasets are because they were

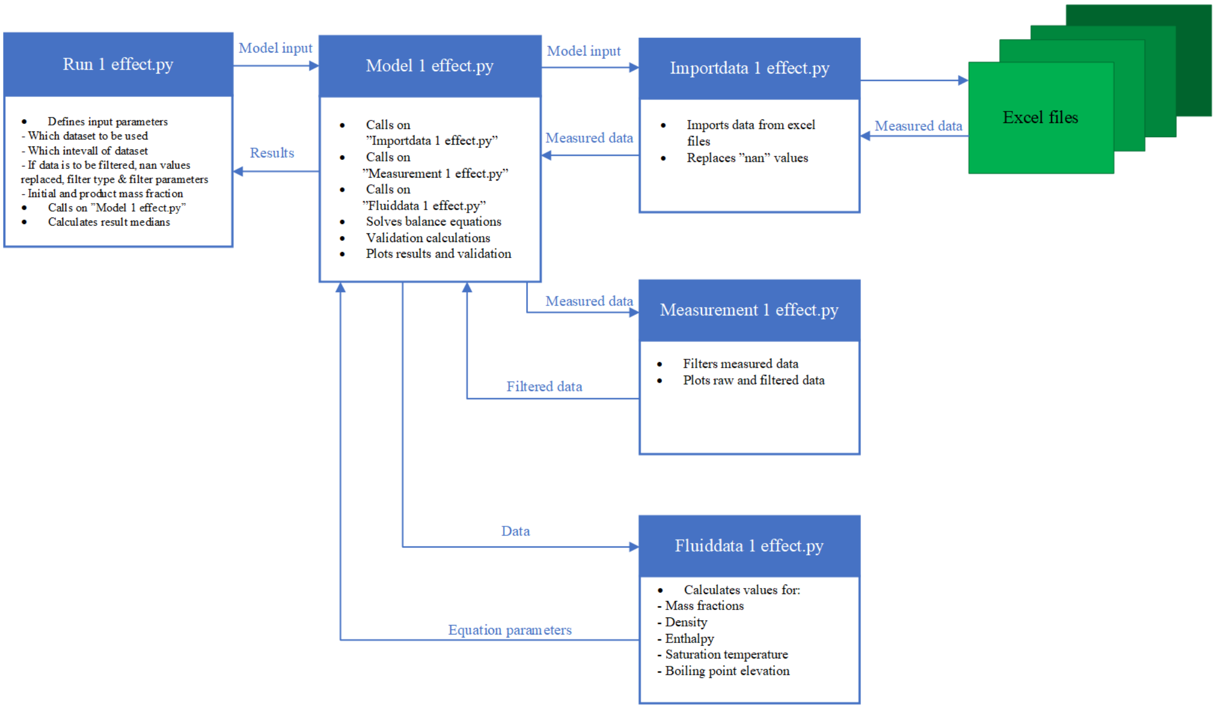

Figure 4.1 – Code structure of the 1-effect model

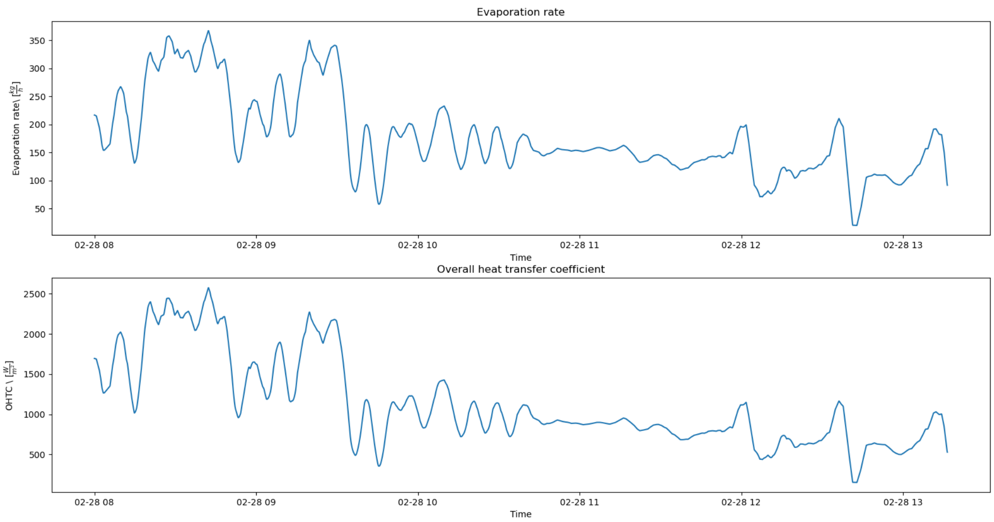

Figure 4.2 – 1-effect model results: Evaporation Rate and Overall Heat Transfer Coefficient for dataset "A"

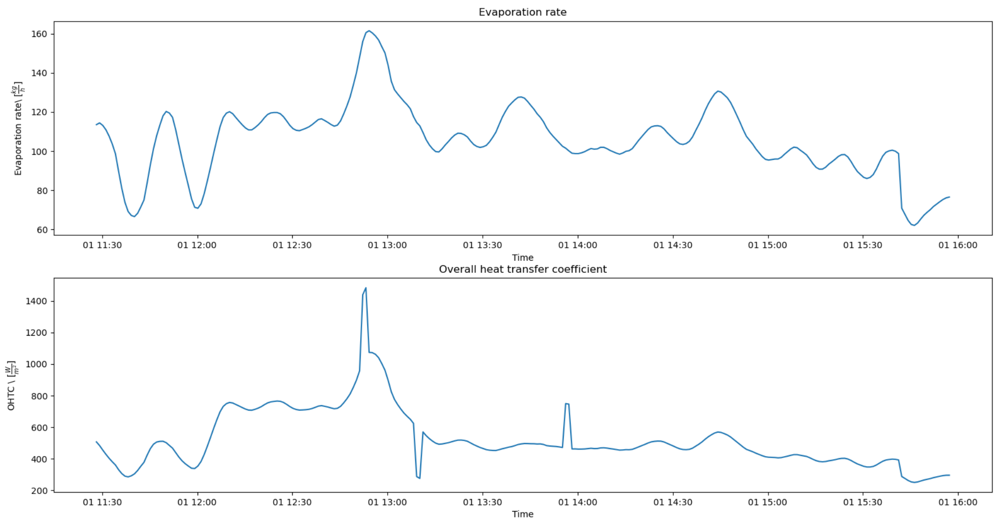

Figure 4.3 – 1-effect model results: Evaporation Rate and Overall Heat Transfer Coefficient for dataset "B"

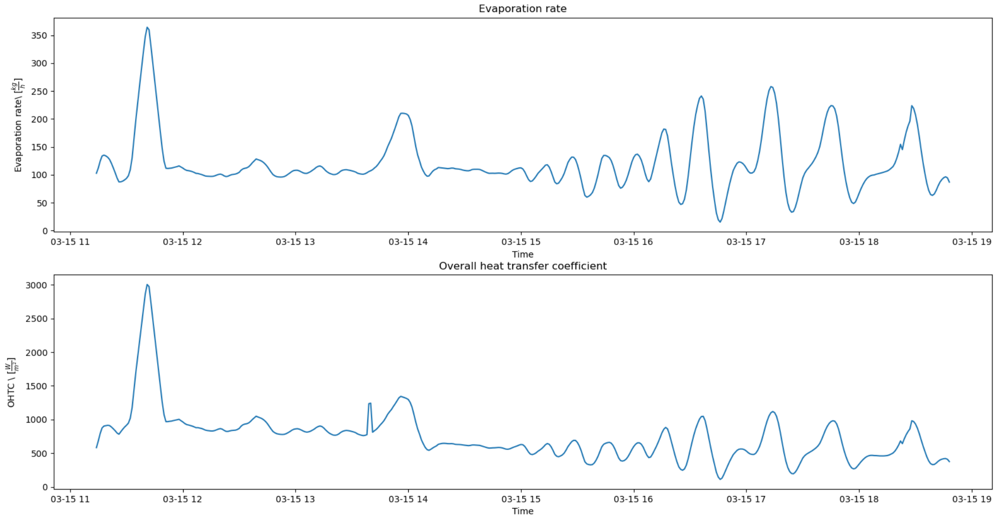

Figure 4.4 – 1-effect model results: Evaporation Rate and Overall Heat Transfer Coefficient for dataset "C"

run under different circumstances and with different products. Something less favourable about the results is that they oscillate and contain sharp peaks, for example in the OHTC for figure 4.3 at time "01 14:00". When looking at the input data it can be seen that they also oscillate, especially the feed flow rate and tank level, see appendix 1. This probably has an impact on the look of the results. It is possible that if the data was measured more frequently this would have less of an impact on the results. Another way to smooth out the results would be to filter the data more.

When it comes to the problem of sharp peaks in the OHTC data. By looking at the input data and calculated parameters, see appendix 1, the cause seems to stem from the $\frac{dhM}{dt}$ parameter. This because when calculating the enthalpy value used to calculate $\frac{dhM}{dt}$, functions based on values for sucrose solutions are used. These formulas are based on temperature ranges of 10 °C. One temperature range equals one equation. When the T surpasses the temperature range, another equation is used leading to a quick change in enthalpy value and in turn a large value for $\frac{dhM}{dt}$. To fix this another formula could be used to calculate the enthalpy.

Table 4.1 – Median results for Evaporation Rate and Overall Heat Transfer Coefficient from 1-effect model calculations

Dataset	**Evaporation rate** $[\frac{kg}{h}]$	**Overall heat transfer coefficient** $[\frac{W}{m^2K}]$
A	178	1123
B	106	521
C	121	743

4.1.2 Validation

In figure 4.5 to 4.7 a validation made by comparing measured results to results calculated by the model be seen. In general, for all data sets the results from the model and the measured results follow the same trajectory and values, this indicates that the calculated values are of reasonable size. However, the model results are more uneven with peaks and oscillations. As mentioned in section 4.1.1 the large variance and oscillations in the results are largely due to the unevenness and oscillatory nature of the input data and not because of the model. The graph for OHTC for the model results is also slightly higher that the validated graph. However the difference is not that large. In general, the validation result confirms that the model results seem reasonable and that the model works for calculating performance parameters for the 1-effect system. However, efforts can be made to make the results more even.

When it comes to the validation result themselves some assumptions were made. For the evaporation rate the density of the condensate were assumed to be 1000 $\frac{kg}{m^3}$. This assumption is reasonable because the temperature of the condensate is low, and will probably not affect the results that much leading to a good validation value.

For the OHTC calculations the steam flow rate was assumed to be the same as the measured condensate flow rate. This assumption is probably okay however it would have been better to use a measured steam flow value since this removes an assumption from the validation calculations and makes it more based on real measurements. In the calculations

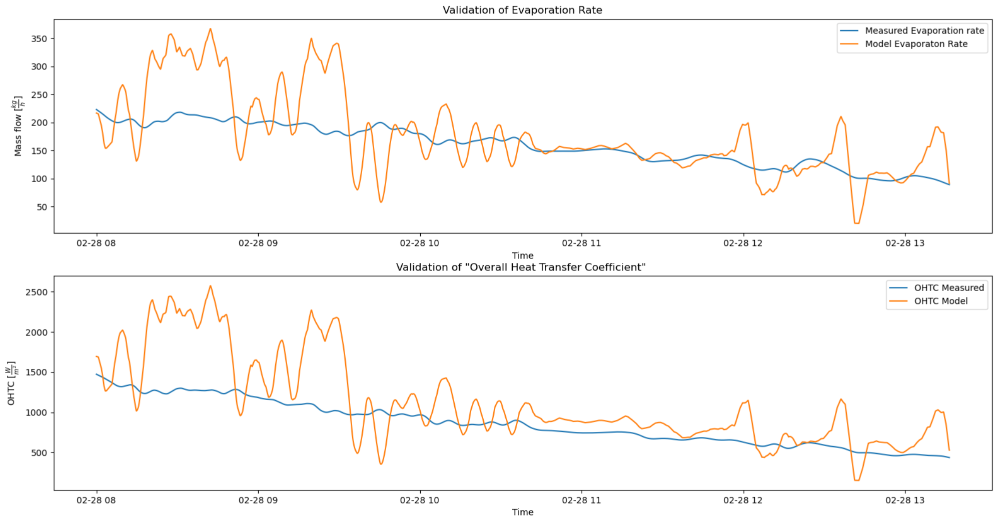

Figure 4.5 – 1-effect model: Validation of Evaporation Rate and Overall Heat Transfer Coefficient for dataset "A"

of the validated OHTC value the same equations for calculating the enthalpies in the model was used for calculating the enthalpy of the steam. This means that the value for OHTC is not only based on measured values. However, it is still a reasonable method to use for validation.

4.2 2-effect model

An outline of the created 2-effect model can be seen in figure 4.8. As can be seen in the figure the model consists of 4 python files, "Run effect.py", "Measurement effect.py", "Model effect.py" and "Fluiddata effect.py". The system is run with "Run effect.py". It first collects measured raw data for the database cloud by giving it the right access keys and specified time interval. It then sends this data to "Measurement effect.py" where "nan" values are replaced in the data, the data is then filtered and divided into segments based on if the plant is running or not. The filtered and segmented data is then sent into "Model effect.py" where they are converted to the correct units. The data together with specified parameters are then sent into "Fluiddata effect.py" to calculate equation parameters such as enthalpies and boiling point elevation. With the equation parameters and other parameters calculated within the model the model then solves the evaporation balance problem and packages the results into data frames to send back to "Run effect.py". Back in "Run effect.py" the results are unpacked. Result medians are calculated, and the results are plotted.

The created model fulfils the goals set for the model. It works with different sets of data and calculates and presents the desired performance parameters. The computation time is doable. Around 7 minutes for 48 hours of measured data.

4.2.1 Simulation results

Two simulations results are present, one for data taken in 2022 and one taken one year later in 2023. The results from the 2022 data can be seen in figure 4.9 and from

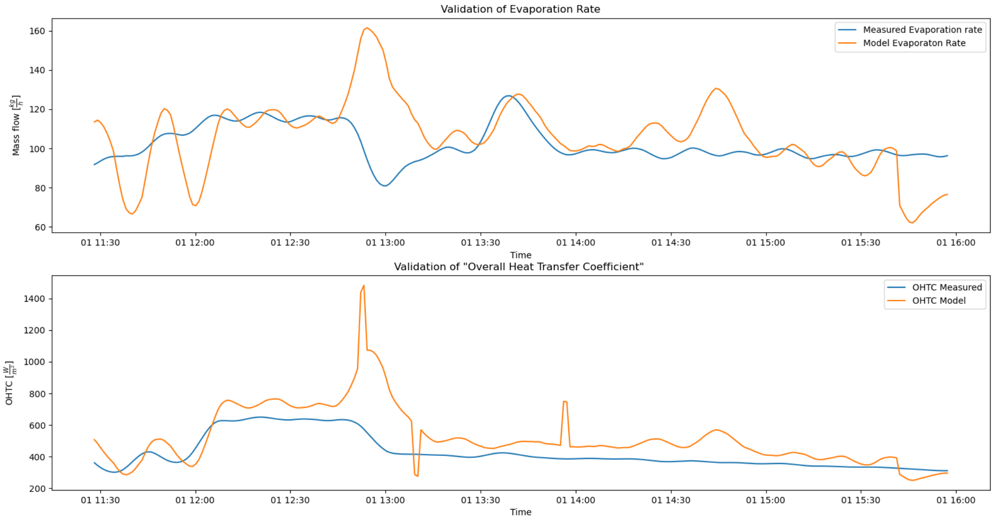

Figure 4.6 – 1-effect model: Validation of Evaporation Rate and Overall Heat Transfer Coefficient for dataset ”B”

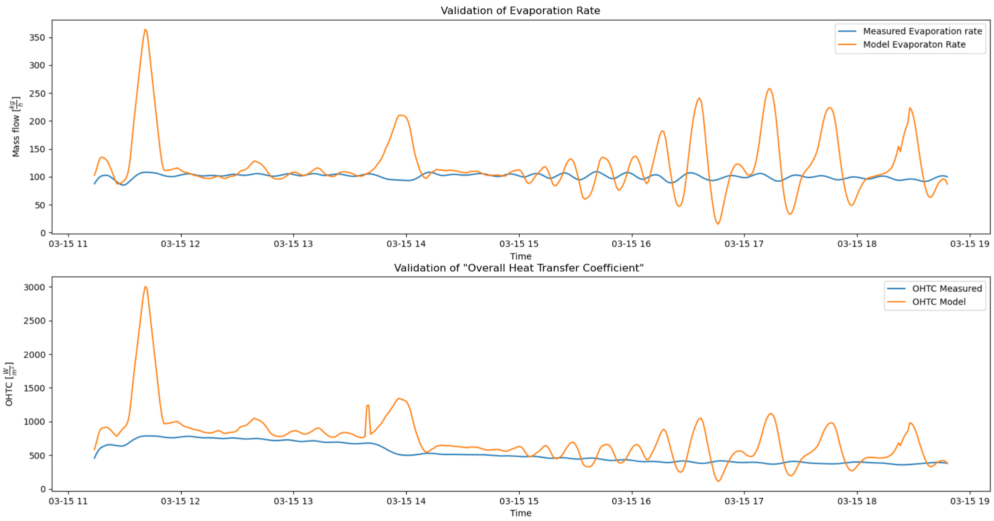

Figure 4.7 – 1-effect model: Validation of Evaporation Rate and Overall Heat Transfer Coefficient for dataset ”C”

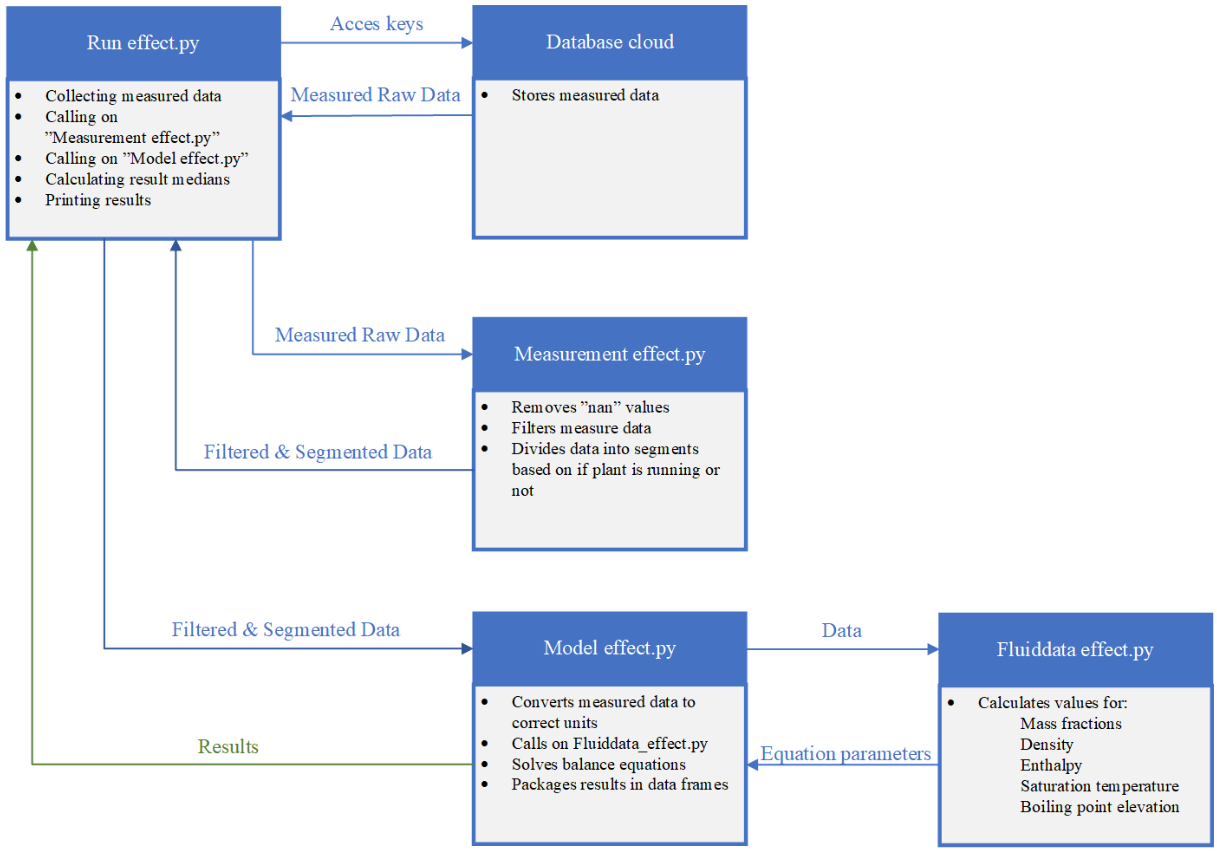

Figure 4.8 – Code structure of the 2-effect and 3-effect models

the 2023 data in figure 4.10. When comparing to the values in section 3.4 the values for evaporation rate are quite low. The OHTC values are also a bit low, especially $OHTC_2$. This however might not be because of the model, to know that we have to compare it to validated results. There is some difference between the results from 2022 and 2023. This is probably due to slightly different operation conditions. The results have some oscillation which is probably like with the 1-effect model due to non-constant measured data.

One peculiar thing about the results is that there are a few outliers for the OHTC results. Looking at calculated parameters, see appendix 2. it can be seen that this is most likely caused by the $\frac{dhM}{dt}$ parameter which is in turn caused by how the enthalpy is calculated, which was also observed for the 1-effect model. This seems to be a general problem for these models. To take away this issue the equations in "Fluiddata effect.py" need to be rewritten. However, in general this effects very few measured points and does not seem to impact the overall results and median results that much.

4.2.2 Validation

In table 4.2 a comparison between the median values from the model calculation and values from the Alfa Laval program (validated values) for the evaporation rate and overall heat transfer coefficients for each effect in the 2-effect system can be seen. The model results correspond well with the validated values according to the table, this indicates that the model results are reasonable even though they differ from the values stated in section 3.4. It can be seen that the low value of $OHTC_2$ that was discussed in section 4.2.1 seem to be correct.

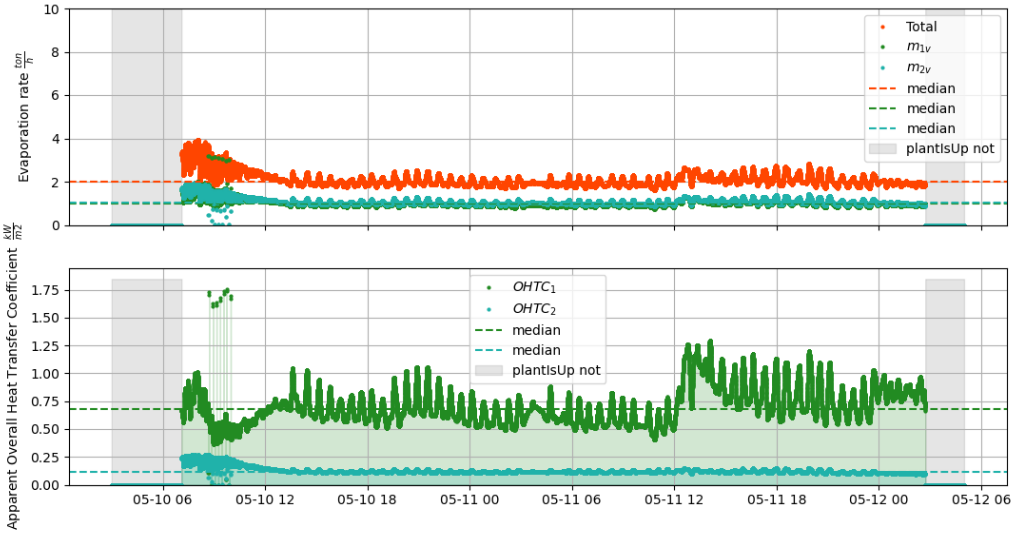

Figure 4.9 – 2-effect model results using data from 2022

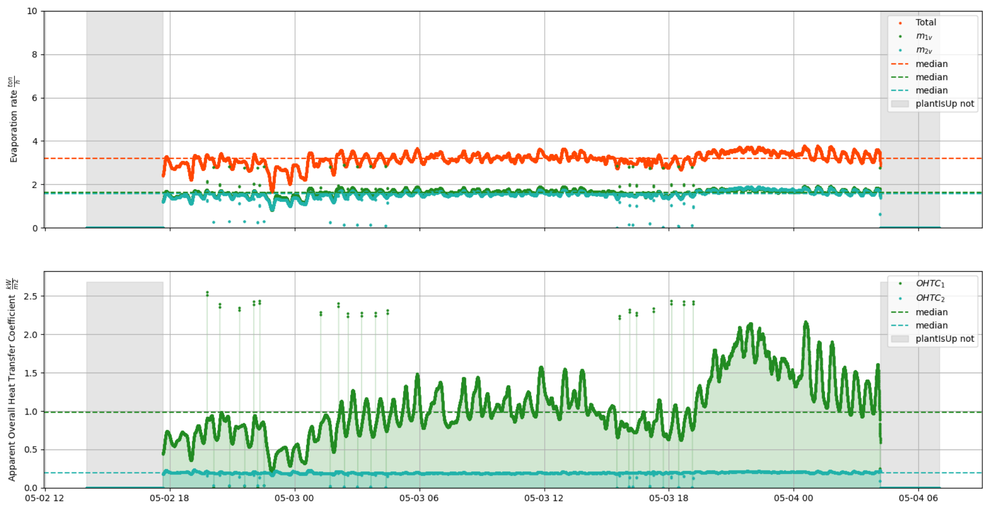

Figure 4.10 – 2-effect model results using data from 2023

The model used to acquire the validated results are rather sensitive to what input variables are used. For this case medians of the measured values were used as input variables. If these are not true to the calculated values as a whole it means that the validated results may not be fully accurate to compare to the calculated values. Since the inlet concentration, x_0, for this system is unknown and estimated it is important that this value is correct to get accurate validation values. To get the right inlet concentration, the inlet concentration of the program was varied so that the outlet flow rate, m_2 was the same as the model median value. The model was then re-run using this new value. The dependence on correct model medians might explain the slight difference between the validated and calculated values. In appendix 4 tables of all calculated data from the validation and from the model median and measured median values can be seen. These correspond very well which is probably another reason that the result variables correspond. It would be useful to run more sets of data to see if the values keep corresponding with each other or if it is only for these two runs.

Table 4.2 – Median results for Evaporation Rate and Overall Heat Transfer Coefficient from 2-effect model calculations on data from 2022 and 2023 compares to validated results using Alfa Laval program

Variable	Validated result [2022]	Model median result [2022]	Validated result [2023]	Model median result [2023]
m_{1v} $[\frac{ton}{h}]$	0.994	0.971	1.61	1.64
m_{2v} $[\frac{ton}{h}]$	1.05	1.04	1.67	1.56
$OHTC_1$ $[\frac{W}{m^2K}]$	680	667	956	984
$OHTC_2$ $[\frac{W}{m^2K}]$	119	117	212	196

4.3 3-effect model

The model structure for the 3-effect system is built the same way as the 2 effect model. For its description therefore see section 4.2. The difference is that the access keys for the database cloud are different, balance equations and other equations in the "Model effect.py" are different and the condition to decide if the plant is running or not is different. This model was built by expanding the 2-effect model. This was pretty easily done. The changes that were made was adding more equations to the model to accommodate for the extra effect as well as changing the equations a bit to make it fit with the new flow pattern. For the measured data the data keys, column names and unit conversion also needed changing. Lastly more result variables were added to accommodate the larger system. The most difficult part of the process was that the method for segmenting the data needed to be changed. For the 2-effect system this is done by looking if a valve is open or not. However for the 3-effect system this data did not accurately determine if the plant was running or not so another variable called step number had to be implemented.

Since the model structure is the same as for the 2-effect model it fulfils the same goals. The run-time of this model is however slower because of the increase in equations. For 48

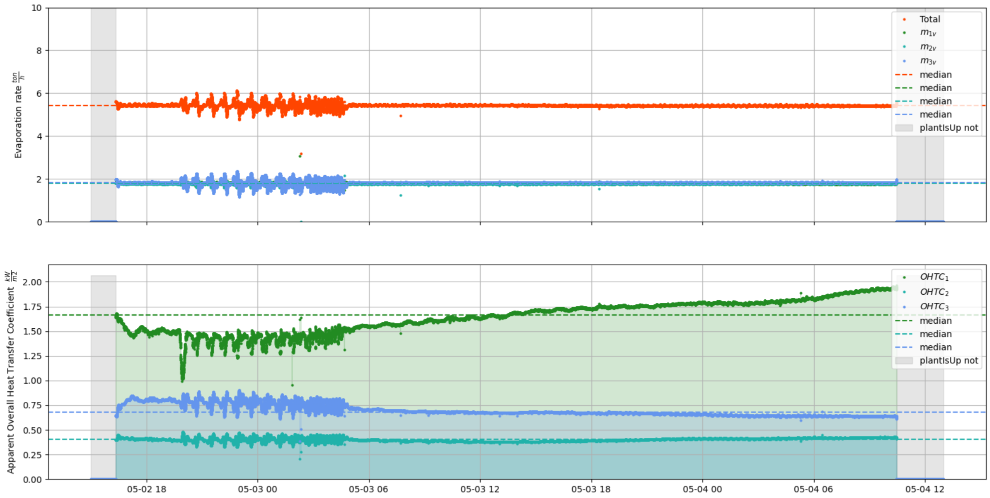

Figure 4.11 – 3-effect model results using data from 2022

hour's worth of data the computation time is around 15 minutes.

4.3.1 Simulation results

Two simulations were made for this model, one for data taken in 2022 and one around one year later in 2023. The results from the 2022 data can be seen in figure 4.11 and from the 2023 data in figure 4.12. Generally, the results look reasonable, maybe a bit low for the $OHTC_2$ and $OHTC_3$ results. The evaporation rates are of similar value for all effects which is reasonable and seem to be similar over the two different runs. For the OHTC values they are different between the different effects, however they are of similar values when comparing the two runs. To know if the difference in values is accurate a look at the validation results is needed. For the 2022 run there are some oscillations in the results. This is probably caused by the unevenness of the measured input data for the feed. See appendix 3. The results are however more stable when comparing it to the 2-effect model results.

4.3.2 Validation

In table 4.3 a comparison between the model calculated mean values and values from the Alfa Laval program (validated values) for the evaporation rate and overall heat transfer coefficients for each effect in the 3-effect system can be seen. In general the model values for the evaporation rate seems to correspond okay with the validated values, with m_{3v} for the data from 2022 having the largest difference. It can be seen that the values differ more than the 2-effect model results. For the OHTC values they correspond for $OHTC_2$ for both the 2023 and 2022 data and for $OHTC_3$ for the 2023 data. The values however differ quite a lot for $OHTC_1$ for both the 2023 and 2022 data and $OHTC_3$ for the 2022 data.

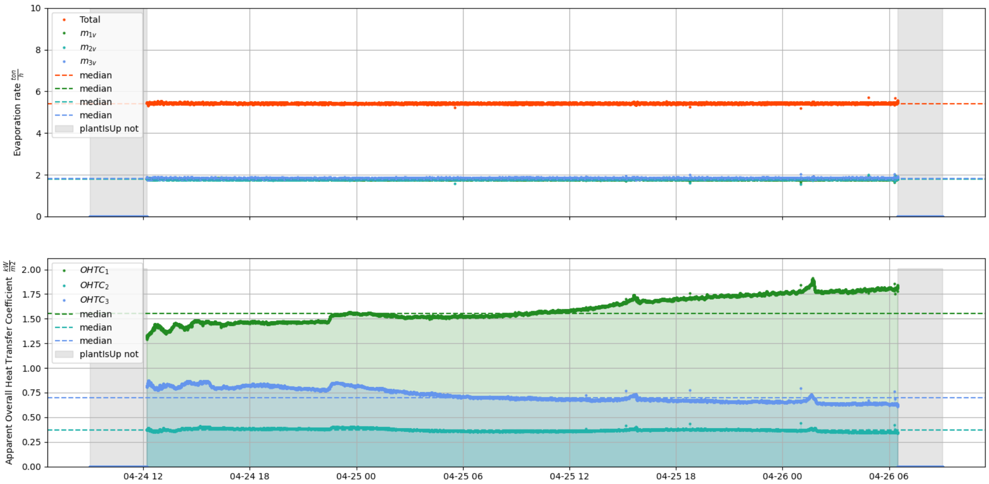

Figure 4.12 – 3-effect model results using data from 2023

Table 4.3 – Median results for Evaporation Rate and Overall Heat Transfer Coefficient from 3-effect model calculations on data from 2022 and 2023 compares to validated results using Alfa Laval program

Variable	Validated result [2022]	Model median result [2022]	Validated result [2023]	Model median result [2023]
m_{1v} $[\frac{ton}{h}]$	2.06	1.82	1.74	1.80
m_{2v} $[\frac{ton}{h}]$	1.91	1.79	1.61	1.80
m_{3v} $[\frac{ton}{h}]$	2.25	1.83	1.90	1.83
$OHTC_1$ $[\frac{W}{m^2K}]$	2290	1670	1800	1560
$OHTC_2$ $[\frac{W}{m^2K}]$	345	372	408	401
$OHTC_3$ $[\frac{W}{m^2K}]$	900	676	766	698

The model used to aqure the validation results works the same as the model described for the 2-effect validation. This time median values for the 3-effect system were used as input variables. In appendix 5 tables of all calculated data from the validation and from the model can be seen. In the table for the 2022 data it can be seen that the evaporation rate, liquid flow rates, and mass fractions are almost always higher for the validated values which seems unreasonable since they have the same inflow, m_0 and product flow rate, m_2. When looking closer at the model medians it can be seen that the total mass balance for the medians does not add up. In appendix 3 it can be seen that the feed flow rate for this dataset varies a lot, which might be why the medians don't add up. This can also be the reason why there is such a difference between some of the model result medians and validated values.

For the 2023 data, see appendix 5, the validated values and model medians correspond better overall which in turn is also reflected in table 4.3. There is however still a large difference in the $OHTC_1$ value. This could be an effect of the model medians but it might also be an inherent problem with how the model calculates this value. To know this more datasets need to be tested. It would also be useful to do the validation based on one data-point instead of a median from a dataset and see if the differences still occur. In the end the validated results show that the model produces results that are somewhat accurate, however it tends to underestimate the $OHTC_1$ values. To know for sure whether the model is accurate more tests need to be run.

5 Future Work

As the models are written right now, they are only able to run on one computer and the timestamp for data collection needs to be specified each time. To further develop the models, they need to connect to a system which can collect data, solve the balances and upload and display the results on its own, without needing someone to press "run" and specify the timestamps, creating a self-running system.

Another improvement to be made is that the models as they are written today only work for one specific system with a specific set of measured variables and a certain configuration. To expand the model, it would be useful to make it more general and easily applicable with all evaporation systems. One way of doing this is to make it into a structure of modules that can be combined together to create a new model for a new existing system. The different modules being for example different number of effects, flow patterns and evaporator types. Also, to be able to make it more general the same set of measured variables are needed for each set number of effects. Therefore, all systems with the same amount of effects need to measure these specified variables. As the code is written today a lot of the code can be reused to created the modules. For example the mass & energy balances and parameters calculations can be reused. If another flow pattern is used than the equations need to be changed a little as well as which variable that is considered as the product stream. What really needs changing to create a modular model is adding choices of number of effects, flow patterns and evaporator types etc and adding functions to accommodate to these choices. The data collection also need to be updated to be able to accommodate different systems as well as the naming of the columns for the measured data and for the result data.

One problem that exists for the created models is that the way the enthalpies are created sometimes causes outliers in the OHTC results. In the future it would be good to find a way to minimize or eliminate this problem by either adjusting the way the enthalpies or the energy inventories are calculated or by switching over to another calculation method all together.

6 Conclusions

Three different models for 3 different evaporation systems were created and validated. They can collect measured data, process it, and use it to calculate the specified performance parameters, OHTC and evaporation rate. The acquired results are reasonable for the most parts however oscillations and outliers occur. In general, the models work for estimating the performance parameters. Changes are needed to minimize the occurrence of oscillations and outliers, for example rewriting the equations for calculating the enthalpy.

The 2-effect model produced the best results when comparing it to the validated values. For the other models differences between the validation result and the model calculated values occur. For the 1-effect model the the OHTC values are generally slightly higher and the 3-effect model tend to overestimate the $OHTC_1$ value for both the 2023 and 2022 data, and it underestimates the values for $OHTC_3$ for the 2022 data. Generally the 3-effect model perform better for the 2023 dataset. To improve the models it would be good to look at more sets of data to see if these problems are still present and try to find ways to minimize the difference between validated and model results. It would also be useful for the 2- and 3- effect models to validate the data based on one data point instead of using median data to see if the influence of varying measured data affects the validation.

In general, the 2-effect model gived very accurate results for both tested dataset. The 1- and 3-effect models give less accurate results however they are still useful to use for estimating performance parameters.

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Appendix

Appendix 1: Imortant measured data & calculated pamameters from 1-effect model

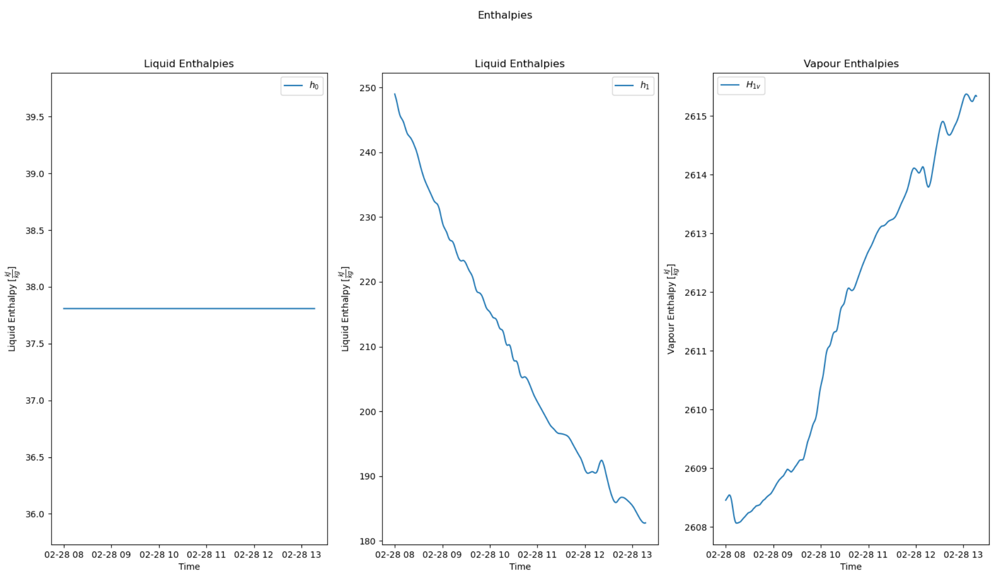

Figure 6.1 – Calculated enthalpy for dataset "A"

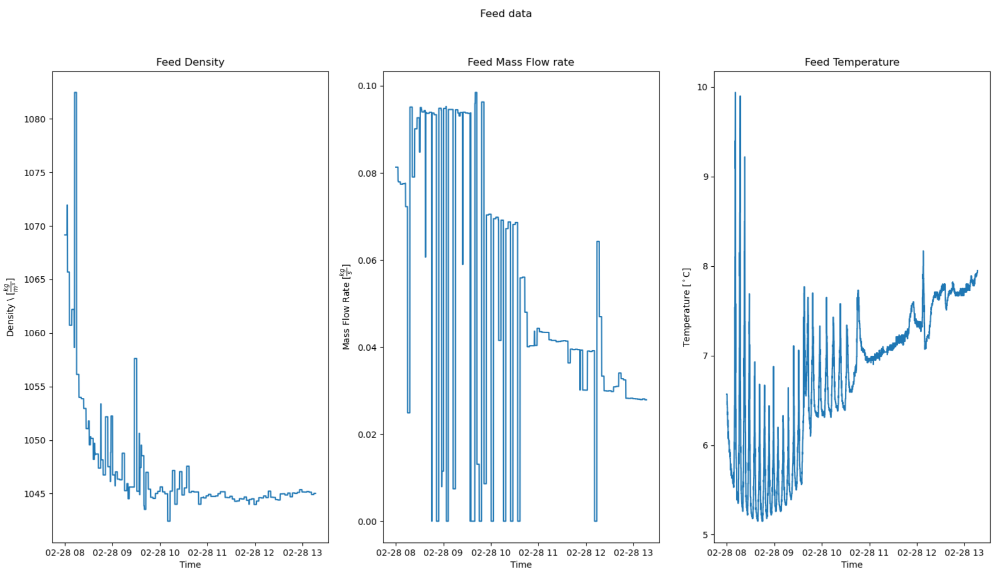

Figure 6.2 – Measured values of feed for dataset "A"

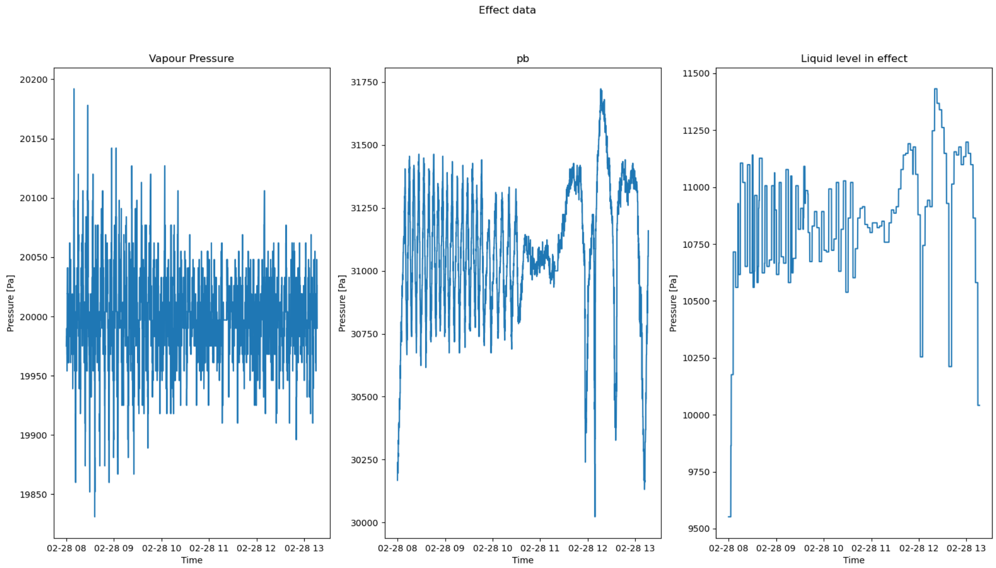

Figure 6.3 – Measured values for effect for dataset "A"

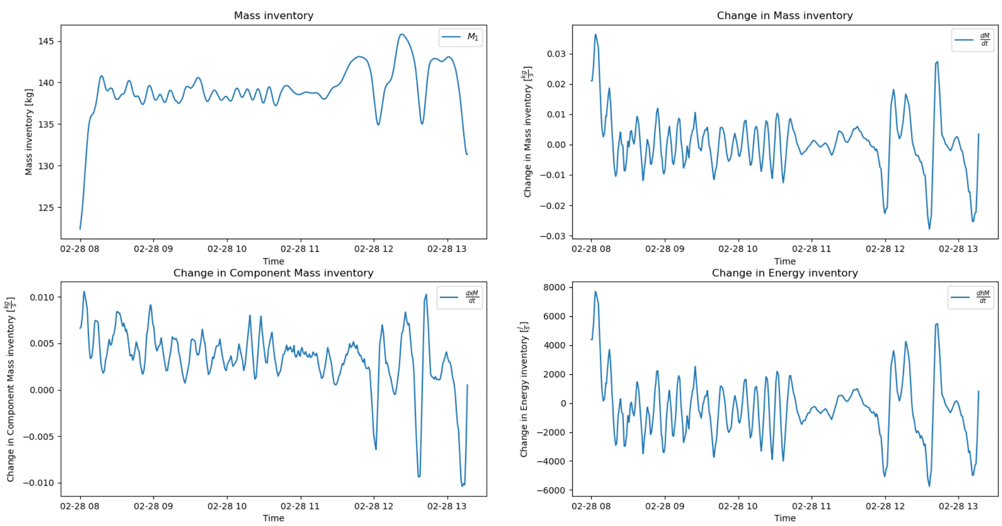

Figure 6.4 – Calculated values for mass inventory and inventory changes for dataset "A"

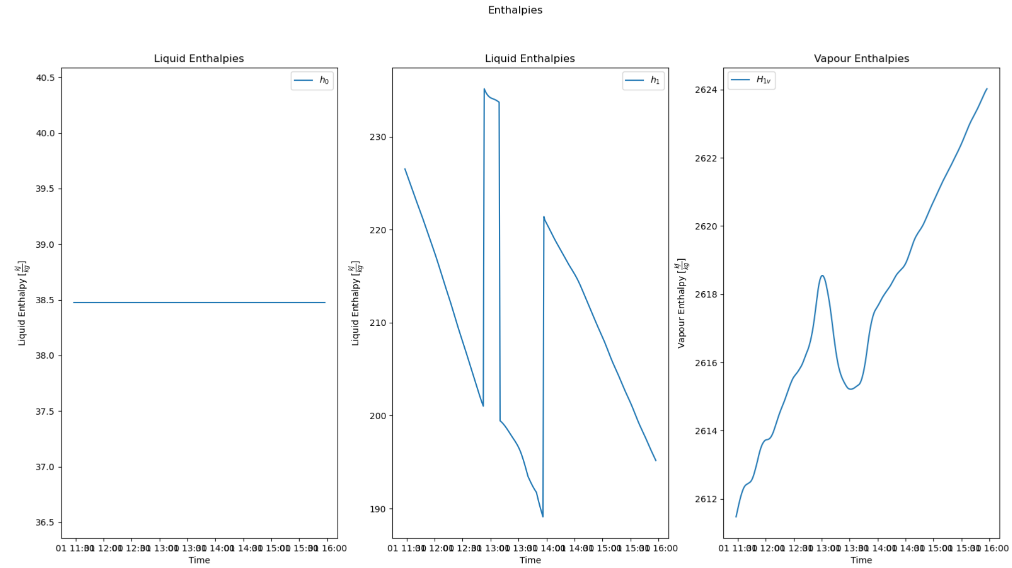

Figure 6.5 – Calculated enthalpy for dataset "B"

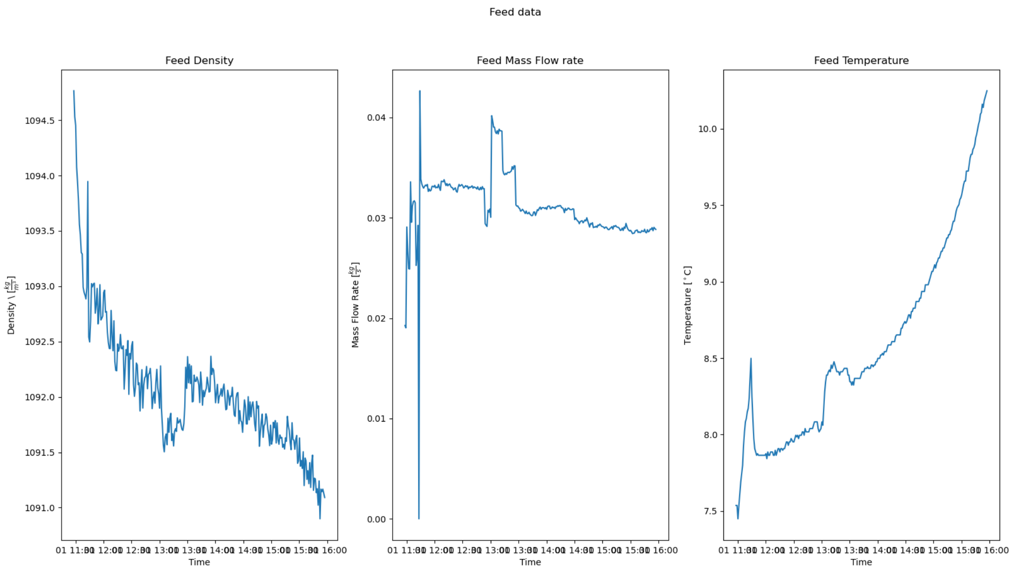

Figure 6.6 – Measured values of feed for dataset "B"

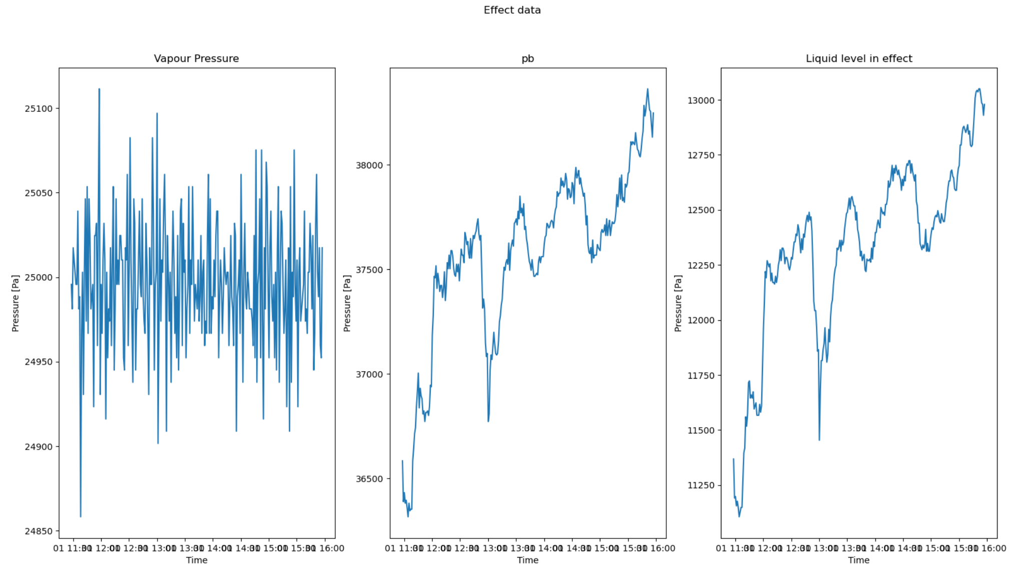

Figure 6.7 – Measured values for effect for dataset "B"

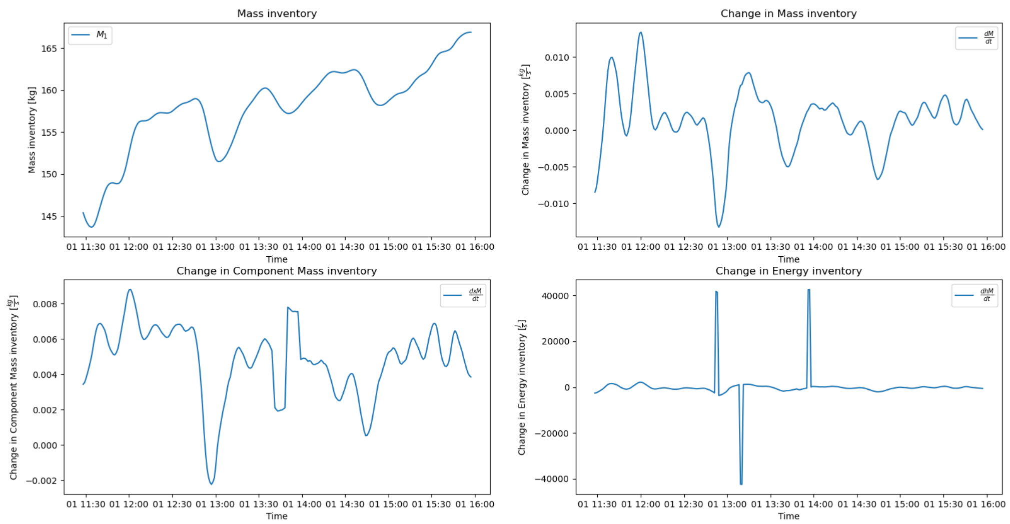

Figure 6.8 – Calculated values for mass inventory and inventory changes for dataset "B"

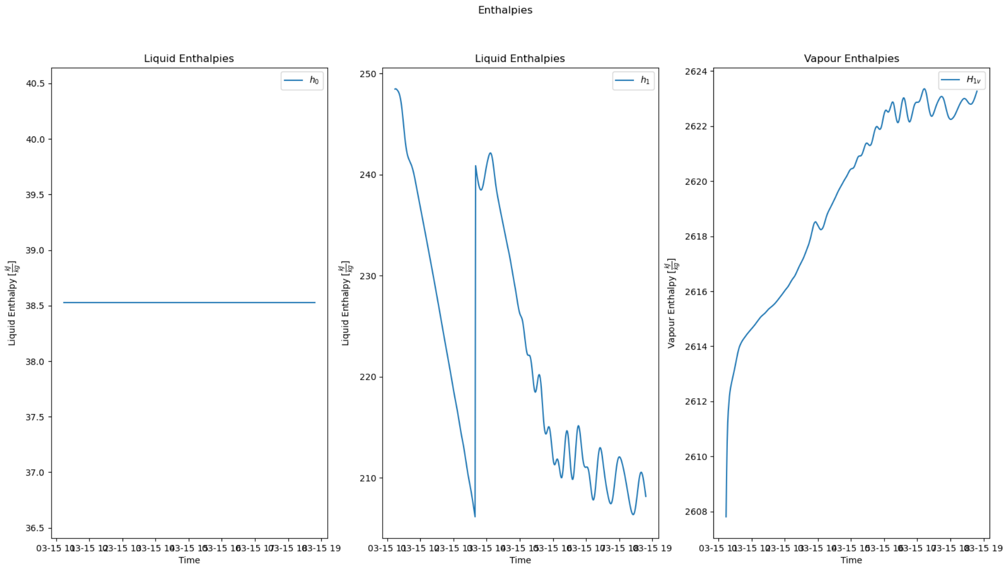

Figure 6.9 – Calculated enthalpy for dataset "C"

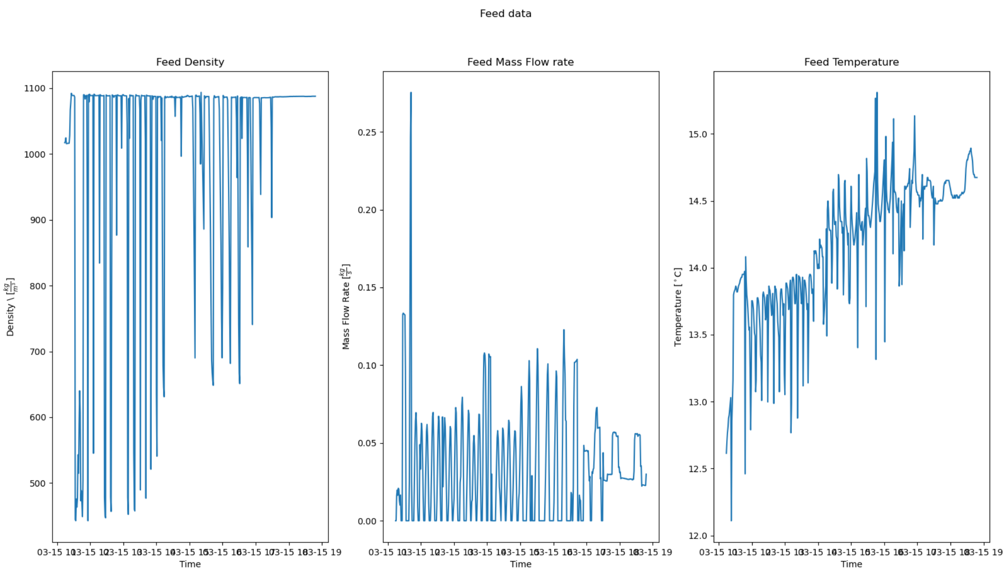

Figure 6.10 – Measured values of feed for dataset "C"

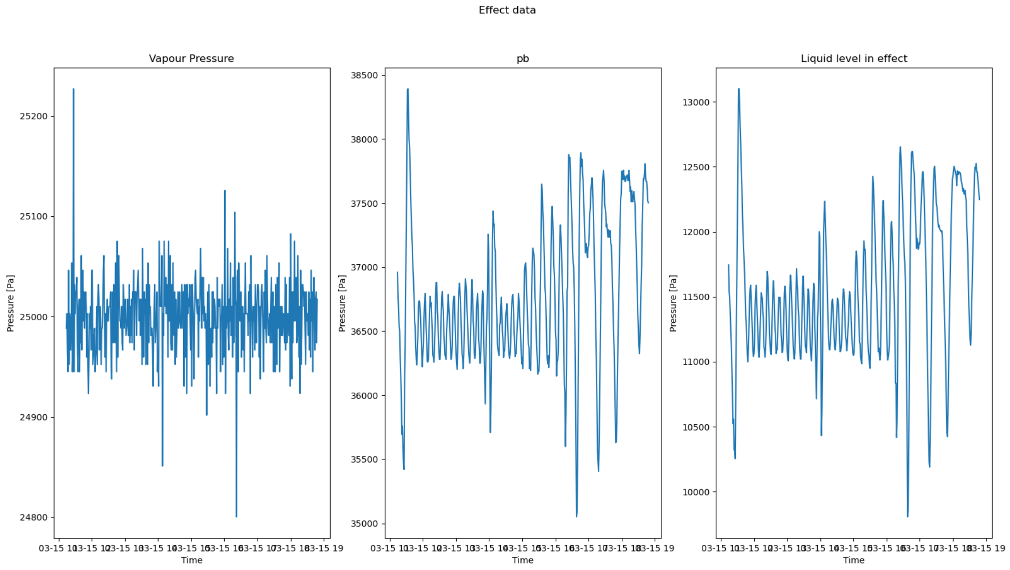

Figure 6.11 – Measured values for effect for dataset "C"

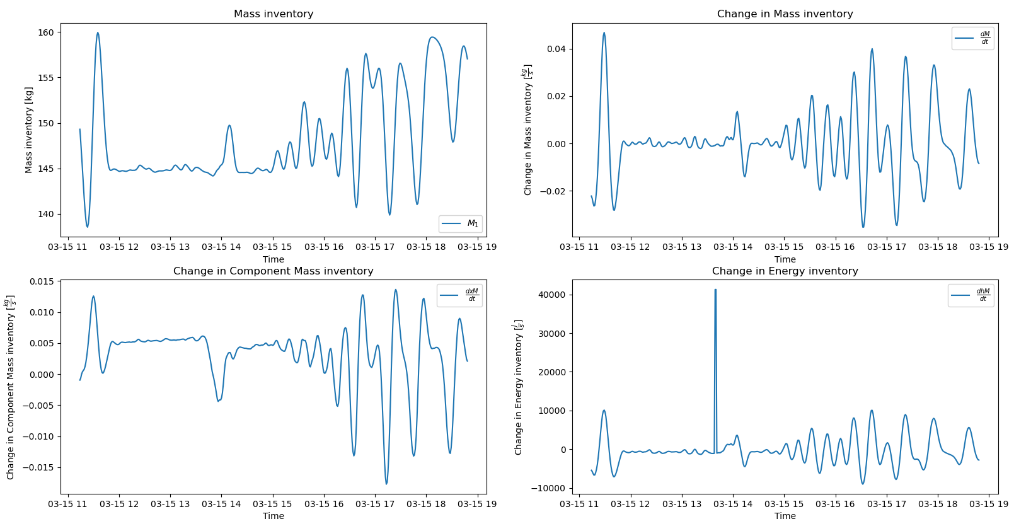

Figure 6.12 – Calculated values for mass inventory and inventory changes for dataset "C"

Appendix 2: Imortant measured data & calculated pamameters from 2-effect model

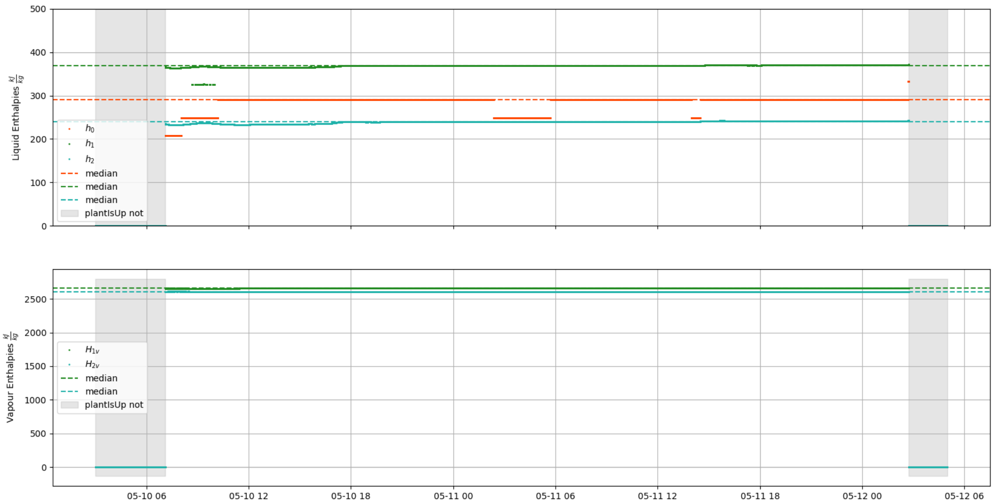

Figure 6.13 – Calculated values for enthalpies for data from 2022

Figure 6.14 – Calculated values for mass inventory and inventory changes for data from 2022

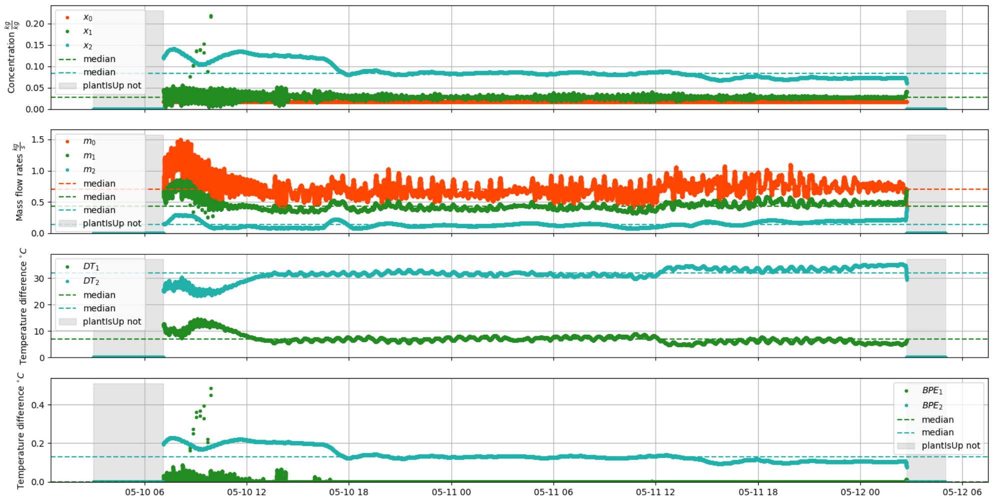

Figure 6.15 – Calculated mass flow, mass fraction, temperature differences and BPE for data from 2022

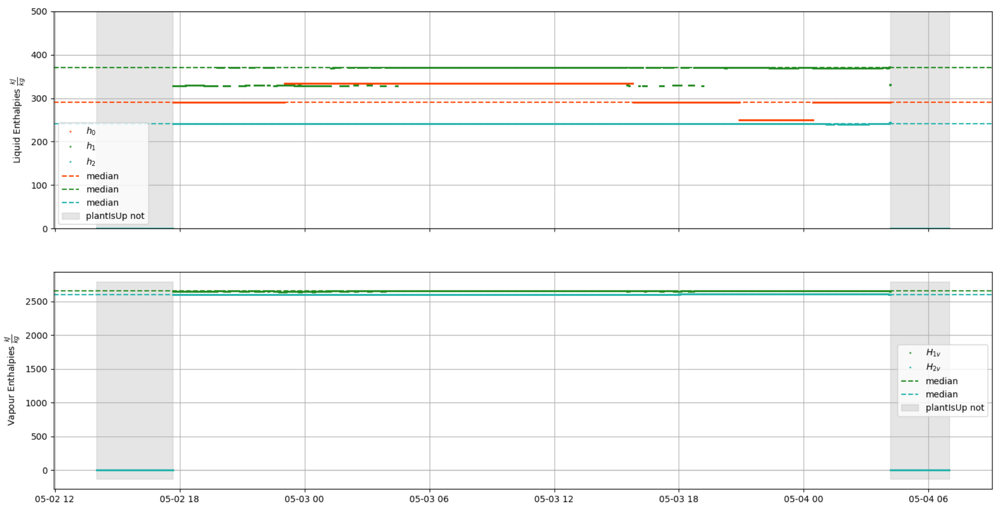

Figure 6.16 – Calculated values for enthalpies for data from 2023

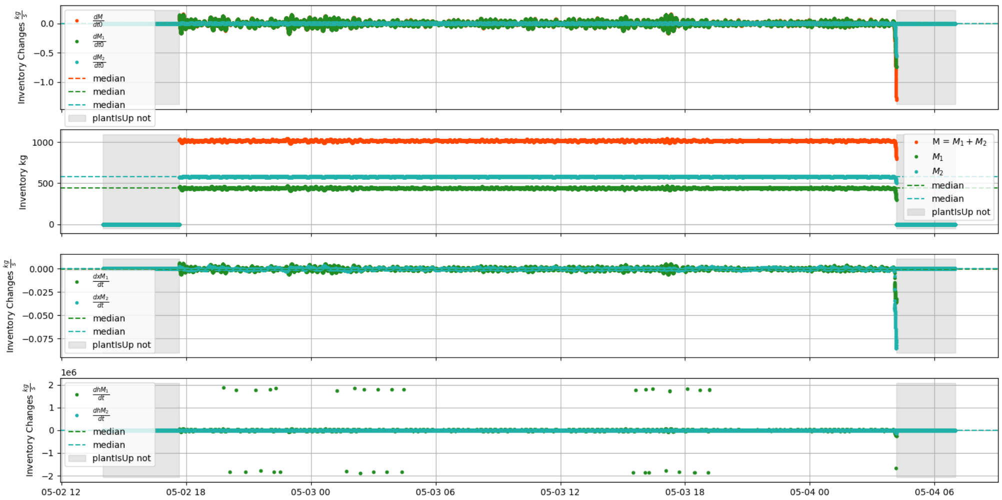

Figure 6.17 – Calculated values for mass inventory and inventory changes for data from 2023

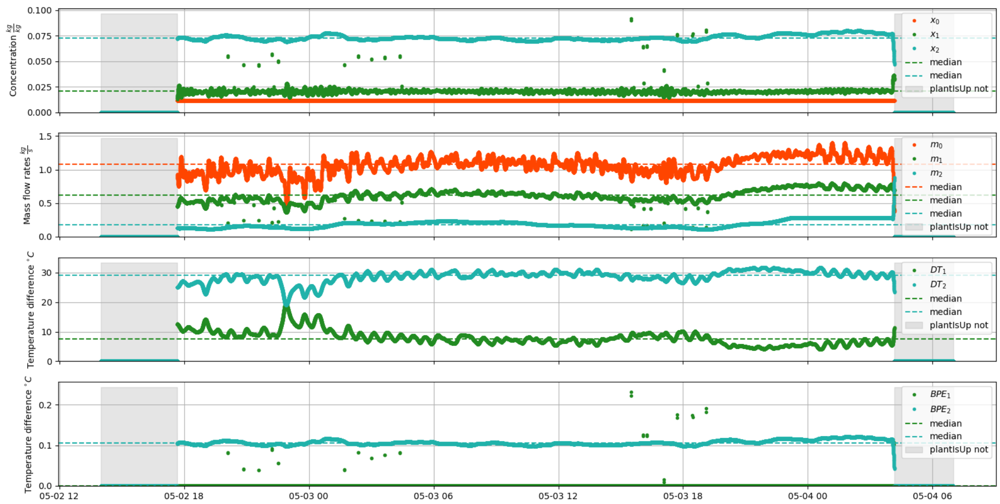

Figure 6.18 – Calculated mass flow, mass fraction, temperature differences and BPE for data from 2023

Appendix 3: Imortant measured data & calculated pamameters from 3-effect model

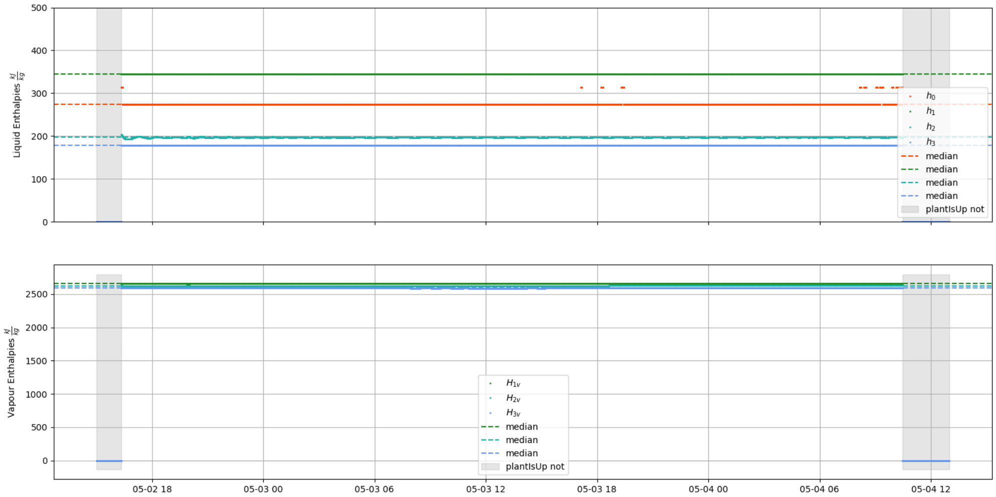

Figure 6.19 – Calculated values for enthalpies for data from 2022

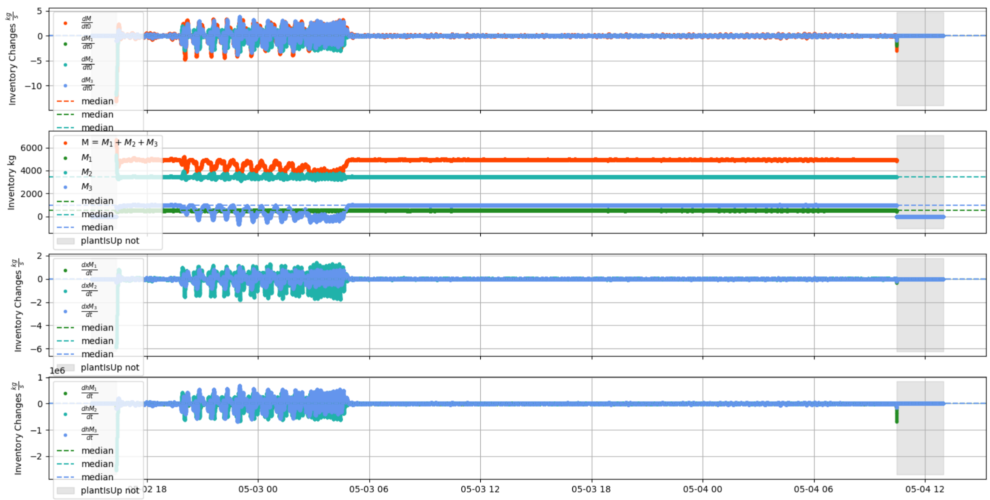

Figure 6.20 – Calculated values for mass inventory and inventory changes for data from 2022

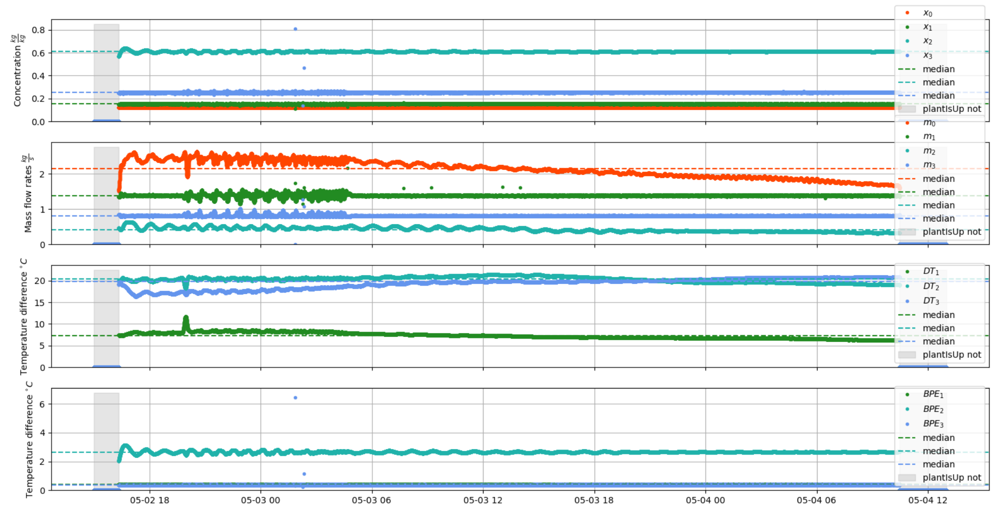

Figure 6.21 – Calculated mass flow, mass fraction, temperature differences and BPE for data from 2022

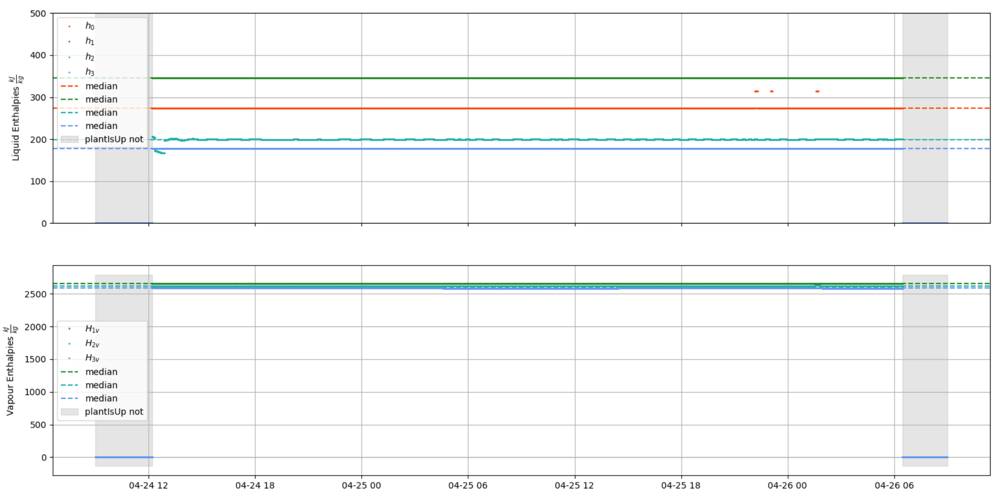

Figure 6.22 – Calculated values for enthalpies for data from 2023

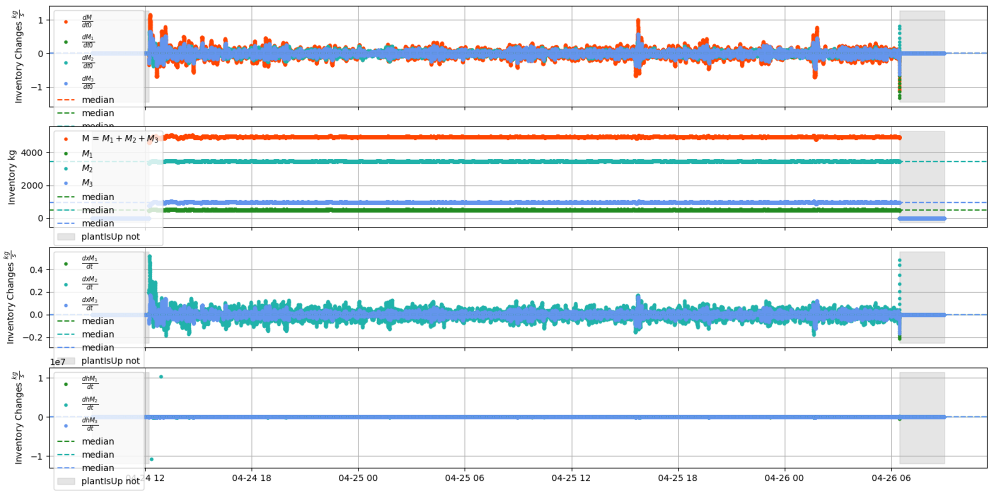

Figure 6.23 – Calculated values for mass inventory and inventory changes for data from 2023

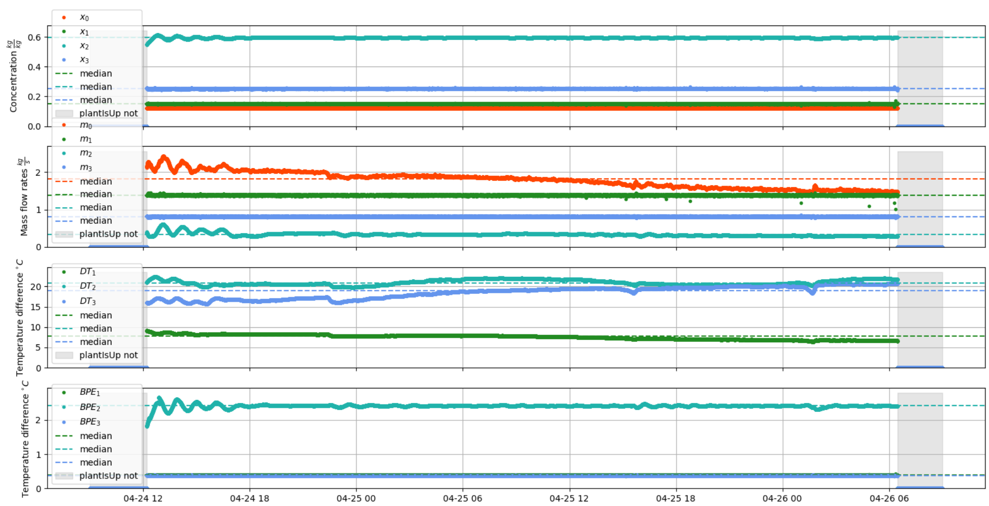

Figure 6.24 – Calculated mass flow, mass fraction, temperature differences and BPE for data from 2023

Appendix 4: Validation results 2-effect model

2022															
Effect 1				Effect 2				Feed				Steam			
		Model	Validation			Model	Validation			Model	Validation			Model	Validation
m_{1v}	$[\frac{ton}{h}]$	0.971	0.994	m_{2v}	$[\frac{ton}{h}]$	1.035	1.048								
$OHTC_1$	$[\frac{W}{K\,m^2}]$	677	682	$OHTC_2$	$[\frac{W}{K\,m^2}]$	117	119								
x_1		0.027	0.028	x_2		0.084	0.084	x_0		0.017	0.017				
m_1	$[\frac{kg}{h}]$	0.43	0.43	m_2	$[\frac{kg}{h}]$	0.137	0.143	m_0	$[\frac{kg}{h}]$	0.71	0.71				
BPE_1	[°C]	0	0	BPE_2	[°C]	0.13	0.1								
h_1	$[\frac{kJ}{kg\,K}]$	369	376	h_2	$[\frac{kJ}{kg\,K}]$	240	237	h_0	$[\frac{kJ}{kg\,K}]$	290	286				
H_{1v}	$[\frac{kJ}{kg\,K}]$	2662	2662	H_{2v}	$[\frac{kJ}{kg\,K}]$	2607	2608								
T_{1v}	[°C]	91.1	91.1	T_{2v}	[°C]	59.2	59.2								
T_1	[°C]	91.2	91.1	T_2	[°C]	59.3	59.3	T_0	[°C]	69	69	T_s	[°C]	98	98.1
p_1	[pa]	73002	73100	p_2	[pa]	200000	19200	p_0	[pa]		81300	P_{steam}	[pa]	94757.7	94757.7

Figure 6.25 – Validated values and model values for 2-effect result based on 2022 data

2023															
Effect 1				Effect 2				Feed				Steam			
		Model	Validation			Model	Validation			Model	Validation			Model	Validation
m_{1v}	$[\frac{ton}{h}]$	1.640	1.606	m_{2v}	$[\frac{ton}{h}]$	1.557	1.674								
$OHTC_1$	$[\frac{W}{K\,m^2}]$	984	956	$OHTC_2$	$[\frac{W}{K\,m^2}]$	196	212								
x_1		0.02	0.019	x_2		0.07	0.07	x_0		0.0115	0.0115				
m_1	$[\frac{kg}{h}]$	0.62	0.64	m_2	$[\frac{kg}{h}]$	0.18	0.18	m_0	$[\frac{kg}{h}]$	1.09	1.09				
BPE_1	[°C]	0	0	BPE_2	[°C]	0.11	0								
h_1	$[\frac{kJ}{kg\,K}]$	370	357	h_2	$[\frac{kJ}{kg\,K}]$	241	230	h_0	$[\frac{kJ}{kg\,K}]$	291	311				
H_{1v}	$[\frac{kJ}{kg\,K}]$	2654	2654	H_{2v}	$[\frac{kJ}{kg\,K}]$	2604	2605								
T_{1v}	[°C]	86.2	86.2	T_{2v}	[°C]	57.1	57.1								
T_1	[°C]	86.3	86.2	T_2	[°C]	57.2	57.1	T_0	[°C]	74.7	74.7	T_s	[°C]	93.9	94
p_1	[pa]	58224	60600	p_2	[pa]	15899	17400	p_0	[pa]	-	81300	P_{steam}	[pa]	81323	81323

Figure 6.26 – Validated values and model values for 2-effect result based on 2023 data

Appendix 4: Validation results 3-effect model

2022																			
Effect 1				Effect 2				Effect 3				Feed				Steam			
		Model	Validation			Model	Validation			Model	Validation			Model	Validation			Model	Validation
m_{1v}	$[\frac{ton}{h}]$	1.82	2.059	m_{2v}	$[\frac{ton}{h}]$	1.79	1.912	M_{3v}	$[\frac{ton}{h}]$	1.83	2.25								
$OHTC_1$	$[\frac{W}{K\,m^2}]$	1665	2286	$OHTC_2$	$[\frac{W}{K\,m^2}]$	401	408	$OHTC_3$	$[\frac{W}{K\,m^2}]$	676	900								
x_1		0.152	0.163	x_2		0.61	0.61	x_3		0.252	0.271	x_0		0.12	0.12				
m_1	$[\frac{kg}{h}]$	1.385	1.578	m_2	$[\frac{kg}{h}]$	0.421	0.423	m_3	$[\frac{kg}{h}]$	0.814	0.954	m_0	$[\frac{kg}{h}]$	2.15	2.15				
BPE_1	[°C]	0.39	0.2	BPE_2	[°C]	2.656	2.7	BPE_3	[°C]	0.379	0.4								
h_1	$[\frac{kJ}{kg\,K}]$	345	343	h_2	$[\frac{kJ}{kg\,K}]$	197	193	h_3	$[\frac{kJ}{kg\,K}]$	178	178	h_0	$[\frac{kJ}{kg\,K}]$	274	291				
H_{1v}	$[\frac{kJ}{kg\,K}]$	2659	2660	H_{2v}	$[\frac{kJ}{kg\,K}]$	2625	2626	H_{3v}	$[\frac{kJ}{kg\,K}]$	2590	2592								
T_{1v}	[°C]	89.5	89.5	T_{2v}	[°C]	66.3	66.3	T_{3v}	[°C]	49.6	49.6								
T_1	[°C]	89.9	89.7	T_2	[°C]	69	69	T_3	[°C]	50	50	T_0	[°C]	74.14	74.2	T_s	[°C]	97.1	97.1
p_1	[pa]	70863	68800	p_2	[pa]	27413	26500	p_3	[pa]	16764	12100	p_0	[pa]	356281	91300	P_{steam}	[pa]	91349	91349

Figure 6.27 – Validated values and model values for 3-effect result based on 2022 data

2023																			
Effect 1				Effect 2				Effect 3				Feed				Steam			
		Model	Validation			Model	Validation			Model	Validation			Model	Validation			Model	Validation
m_{1v}	$[\frac{ton}{h}]$	1.795	1.739	m_{2v}	$[\frac{ton}{h}]$	1.799	1.613	M_{3v}	$[\frac{ton}{h}]$	1.83	1.897								
$OHTC_1$	$[\frac{W}{K\,m^2}]$	1556	1800	$OHTC_2$	$[\frac{W}{K\,m^2}]$	372	345	$OHTC_3$	$[\frac{W}{K\,m^2}]$	698	766								
x_1		0.152	0.163	x_2		0.595	0.595	x_3		0.253	0.368	x_0		0.12	0.12				
m_1	$[\frac{kg}{h}]$	1.385	1.344	m_2	$[\frac{kg}{h}]$	0.329	0.368	m_3	$[\frac{kg}{h}]$	0.814	0.816	m_0	$[\frac{kg}{h}]$	1.827	1.827				
BPE_1	[°C]	0.39	0.2	BPE_2	[°C]	2.42	2.4	BPE_3	[°C]	0.38	0.4								
h_1	$[\frac{kJ}{kg\,K}]$	345	335	h_2	$[\frac{kJ}{kg\,K}]$	199	189	h_3	$[\frac{kJ}{kg\,K}]$	178	171	h_0	$[\frac{kJ}{kg\,K}]$	274	288				
H_{1v}	$[\frac{kJ}{kg\,K}]$	2656	2656	H_{2v}	$[\frac{kJ}{kg\,K}]$	2621	2622	H_{3v}	$[\frac{kJ}{kg\,K}]$	2587	2589								
T_{1v}	[°C]	87.4	87.4	T_{2v}	[°C]	64.2	64.2	T_{3v}	[°C]	47.8	47.8								
T_1	[°C]	87.8	87.6	T_2	[°C]	66.8	66.8	T_3	[°C]	48.2	48.2	T_0	[°C]	73.4	73.4	T_s	[°C]		
p_1	[pa]	66225	63500	p_2	[pa]	25558	24300	p_3	[pa]	15762	11100	p_0	[pa]	359697	86200	P_{steam}	[pa]	86162	86162

Figure 6.28 – Validated values and model values for 3-effect result based on 2023 data