Detection and Remediation of Fouling Problems within a Heat Exchanger Network at an Oil Refinery

Master's Thesis in Master Program Innovative and Sustainable Chemical Engineering

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Abstract

The industrial sector is one of the main contributing factors to Sweden's total territorial emissions of greenhouse gases. Emissions linked to refining and distributing oil and gas constitute 18 % of the total emissions from the Swedish industrial sector. Therefore, it is important to improve the energy efficiency of oil refineries to be able to reduce the total emissions of greenhouse gases and contribute to reaching the Swedish national target of zero net emissions in 2045. A common issue for decreased energy efficiency within heat exchanger networks at oil refineries is fouling. Fouling is defined as the accumulation of dirt, scale, corrosion products and other contaminants on process equipment surfaces over time. The lost heat recovery due to fouling must be compensated for by increasing the fuel consumption in furnaces, resulting in higher emissions of greenhouse gases. In this project, a large system of shell-and-tube heat exchangers was evaluated by first collecting data for mass flows, temperatures, physical and chemical properties for the different fluids. With the data collected, trends of temperature gradients and heat transfer in the heat exchangers were analyzed. The heat exchangers that exhibited repeated descending trends during different time intervals were identified as likely locations of high rate of fouling.

To increase the heat recovery within the system, bypass solutions were proposed to enable cleaning of heat exchanger surfaces while maintaining operations within the process unit. The bypass designs were evaluated in terms of economic feasibility to determine if they are worth investing in. The financial assessment also included a sensitivity analysis to examine how the investment payback period changes when different economic parameters vary. Two of the bypass solutions were identified as being potentially economically feasible with a payback period of only 1.52 year or 2.06 years depending on which type of fuel is used to fire the furnace. The economical feasibility remained relatively stable for scenarios in which different economic data varied. It was concluded that a large amount of energy could be recovered every year by installing two bypass configurations.

Keywords: emissions, greenhouse gases, fouling, shell-and-tube heat exchangers, heat recovery, bypass

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Charlotta Andersson, Gothenburg, January 2025

List of Acronyms

Below is a list of acronyms that have been used throughout this thesis listed in alphabetical order:

CDU	Crude Distillation Unit
IBP	Initial Boiling Point
FBP	Final Boiling Point
HEN	Heat Exchanger Network
LPG	Liquefied Petroleum Gas
PBP	Payback Period
SDS	Safety Data Sheet
TCU	Thermal Cracker Unit

Nomenclature

Below is the nomenclature of variables that have been used in equations throughout this thesis.

Variables

Q_c	Transferred heat on the cold side of a heat exchanger [kW]
Q_h	Transferred heat on the hot side of a heat exchanger [kW]
$\dot{m}_c$	Mass flow of cold fluid [kg/s]
$\dot{m}_h$	Mass flow of hot fluid [kg/s]
$C_{p,c}$	Specific heat capacity for cold fluid [kJ/kgK]
$C_{p,h}$	Specific heat capacity for hot fluid [kJ/kgK]
$T_{c,1}$	Temperature for cold fluid entering a heat exchanger [^{o}C]
$T_{c,2}$	Temperature for cold fluid leaving a heat exchanger [^{o}C]
$T_{h,1}$	Temperature for hot fluid entering a heat exchanger [^{o}C]
$T_{h,2}$	Temperature for hot fluid leaving a heat exchanger [^{o}C]
A_s	Cross-flow area for row of tubes at shell equator in shell-and-tube heat exchangers [m^2]
p_t	Tube pitch [m]
d_o	Tube outside diameter [m]
D_s	Shell inside diameter [m]
l_B	Baffle spacing [m]
G_s	Shell-side mass velocity [kg/m^{2}s]
$\dot{m}_s$	Fluid flow rate on the shell-side [kg/s]
u_s	Linear velocity shell-side [m/s]
ρ	Density [kg/m^3]
d_e	Hydraulic diameter [m]
R_e	Reynolds number

μ	Viscosity [Pas]
A_t	Tube cross-sectional area [m^2]
d_i	Tube inside diameter [m]
A_f	Total flow area [m^2]
G_t	Tube-side mass velocity [kg/m^2s]
u_t	Linear velocity tube-side [m/s]
A_p	Pipe cross-sectional area [m^2]
d_p	Pipe diameter [m]
v	Velocity [m/s]
$\dot{m}$	Mass flow [kg/s]
ΔP	Pressure drop [Pa]
ΔP_{loss}	Pressure drop due to contraction [Pa]
K_c	Contraction loss coefficient
$\dot{q}$	Volumetric flow [m^3/s]
W	Pump work [W]
P_{min}	Minimum pressure [Pa]
P_{static}	Static pressure [Pa]
P_{vapor}	Vapor pressure [Pa]
$\dot{m}_{fuel}$	Mass flow of fuel [kg/s]
Q_{loss}	Heat loss [kW]
LHV_{fuel}	Lower heating value of fuel [kJ/kg]
η	Efficiency factor [%]
X_{carbon}	Carbon content [mass%]
Q	Transferred heat [kW]
F	Net annual cash flow [SEK]
I_0	Investment cost [SEK]
r	Annuity factor
i	Interest rate per year [%]
n	Economic lifetime of investment
L	Lang factor
C	Total capital cost [SEK]
$\sum C_e$	Total purchase cost [SEK]

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1

Introduction

1.1 Background

In Sweden, a significant fraction of the total territorial emissions of greenhouse gases originate from the industry sector. In 2023, the total emissions of CO_2 were 44.4 million tons of CO_2 equivalents, of which the industry sector contributed 14.8 million tons. During the last 30 years, total greenhouse gas emissions have been reduced by approximately 38 %, but there is still a long way to go to reach the national goal of zero net emissions in 2045. To achieve this goal, Sweden must reduce its total emissions by at least 50 % [1]. An important environmental challenge related to the reduction of greenhouse gas emissions is the ability to increase the energy efficiency of oil refineries, since such plants constitute a significant share of greenhouse gas emissions from the industrial sector in Sweden. The main contributors to CO_2 emissions from the industrial sector are the iron and steel industry (37 %), refining and distribution of oil and gas (18 %), and the mineral industry (17 %) [1]. In oil refineries, a large amount of energy is required to produce a variety of products, and this results in large emissions of CO_2. To produce the energy required, furnaces are used to burn fuel and generate heat. To decrease the amount of fuel required in furnaces, large heat exchanger systems are installed. The warm process flows downstream from the furnace can thereby be used to heat the cold flows before the furnace. This results in a lower total energy requirement and therefore lower greenhouse gas emissions [2].

St1 operates an oil refinery located in Gothenburg that produces a wide variety of products, such as LPG, aviation fuel, gasoline, diesel, ship fuel and bio-diesel [3]. The refinery processes approximately 4000 kilotons of crude oil per year and produces approximately one-fifth of Sweden's total need for petroleum products. Around 99 % of the total energy demand for the refining processes is satisfied by internally produced fuel gas, but it is also necessary to combust other types of fuel, typically natural gas or LPG [4]. The refinery has turn-around stops every 4 years for maintenance, inspection, cleaning and development of the plant, together with an interim stop every two years for smaller cleaning and maintenance operations, see figure 1.1 for a timeline.

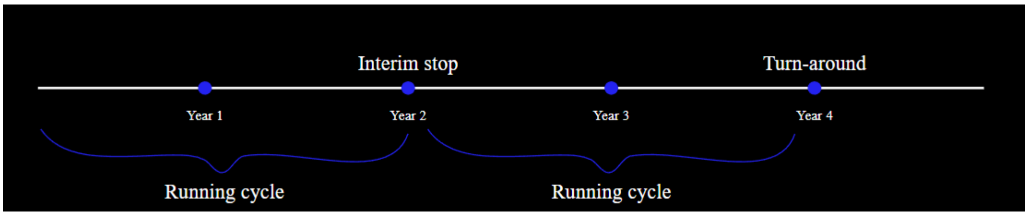


Figure 1.1: A timeline for different running cycles at the refinery

The total energy consumption was 2 332 GWh in 2023 and approximately a quarter of the total heat supplied within the refinery is recovered and delivered to the Gothenburg district heating network [4]. The refinery is one of the most energy efficient refineries in the world with its complex integrated heat exchanger systems [3]. The company strives to further increase its energy efficiency and therefore aims to evaluate their heat exchangers to examine if there are potential solutions for further reduction of carbon dioxide and other greenhouse gas emissions.

The main emissions released into the air from St1 refinery during the year 2023 are presented in table 1.1 [5]. The presented values are only the emissions generated at the refinery site and do not include emissions related to extraction of the crude oil, transport and use of the final products. If a life cycle analysis for the production of fuels at the refinery with a cradle-to-grave perspective were to be performed it would become clear that the total emissions from production is significantly larger than the values presented in table 1.1 [6].

Table 1.1: Emissions from St1 Refinery 2023

Substance	Emissions to air [kg]
CH_4	1 900
CO	59 000
CO_2	477 527 000
NH_3	380
NO_x	331 700
SO_2	74 150
Particles	16 500

With the increasing price of fuel gas and increasing costs for emitting CO_2, it has become a priority to evaluate the largest heat exchanger system at the refinery to see if energy efficiency improvements can be made. The refinery has historically had problems with fouling within crude feed pre-heater heat exchanger train. Fouling is a common problem for oil refineries and is often a result of the temperature change that the process flows undergoes through the preheating process [7]. At the moment, there is no possibility to clean the heat exchangers within the system without stopping operations for the whole unit since the heat exchangers used for preheating cannot be bypassed. Therefore, it is desirable to create a cleaning solution by implementing a bypass over the heat exchanger/heat exchangers that affects the heat transfer efficiency the most within the system, while still maintaining operations for the process unit. St1 shuts down the process unit every second year for maintenance and during this time, the majority of the heat exchangers are usually cleaned which is an expensive and time-consuming process. By installing bypass solutions within the network, cleaning could be performed without requiring a complete shut down of the process unit which would save both time and money. It would also result in a lower energy demand for the furnace and decreased emissions of greenhouse gases if the heat exchangers could be cleaned during operations. Figure 1.2 illustrates the equipment needed for bypass. The heat exchanger is bypassed by closing the valves for ingoing and outgoing flows and opening the adjacent valves leading the flows around the heat exchanger.

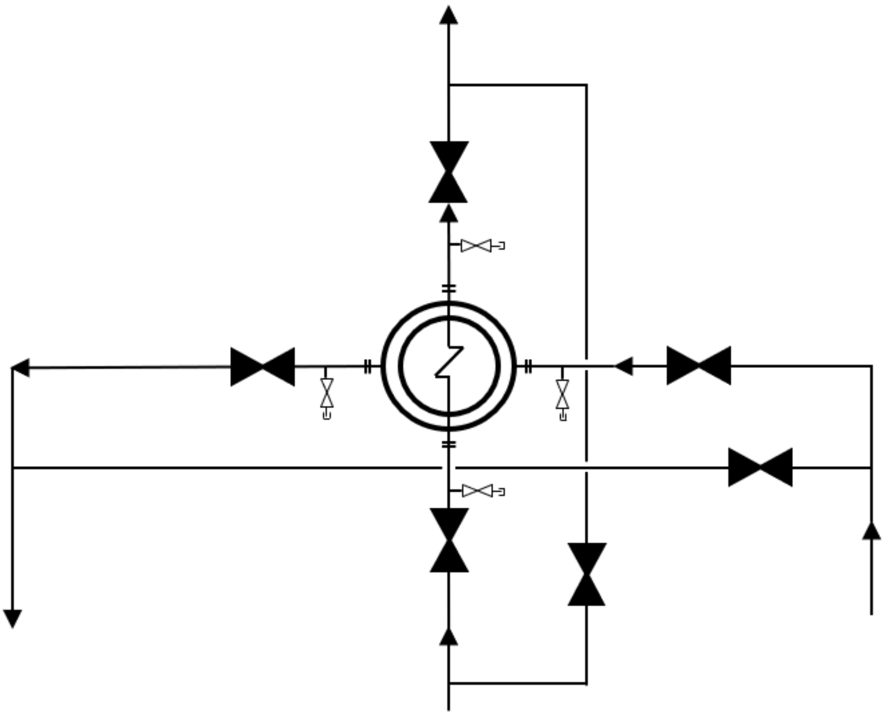


Figure 1.2: An example of bypass

1.2 Fouling

Fouling is defined as the accumulation of dirt, scale, corrosion products and other contaminants on process equipment surfaces over time. Fouling is a common problem within industrial processes and has been ever since the beginning of the industrial revolution. It is mainly a problem in heat transfer equipment since it is crucial to maximize the heat transfer efficiency of the installed surface area to enable the exchange of heat between a hot and cold fluid [8]. The formed layers of dirt will have two substantial effects on heat exchangers [8]:

1. Increased heat transfer resistance in addition to the resistance present due to

the inherent heat exchanger design. The dirt layer has a significantly lower thermal conductivity than the heat exchanger surface consisting of metal materials, leading to an increased heat transfer resistance.

2. Increased pressure drop over the heat exchanger due to reduced flow area. The accumulation of dirt will gradually obstruct the flow leading to a lower flow velocity and a higher pressure drop.

The listed consequences of fouling are the main reasons behind major loss of heat transfer efficiency in HEN:s [8]. The different fouling mechanisms that occur in crude oil refining processes are [7]:

1. Crystallization fouling: Precipitation of dissolved salts present in the fluid.
2. Particulate fouling: Deposition of suspended particles.
3. Chemical reaction fouling: Chemical reactions between different molecules in the fluid that accumulates on heat transfer surfaces over time.
4. Corrosion fouling: Chemical reaction between reactants in fluid and the metal surface.

The listed fouling phenomena all occur gradually over time and decrease the overall performance of the heat transfer surfaces in the preheating system [7]. The fouling rate increases with elevated temperatures, decreasing velocity and is further accentuated by laminar flow inside the heat exchanger. If the flow is turbulent, fouling will be minimized since the viscous shear stress in the fluid is higher near the surfaces in turbulent flows. If the flow is laminar, the wall friction will be lower and enables accumulation of dirt and scales to onto surfaces [7][9]. The process flows containing heavier hydrocarbons and paraffin molecules have tendencies for formation of coke and wax depositions on heat transfer surfaces when the fluid is being cooled, which could be a reason behind fouling in oil refineries [8].

1.3 Scope and Objectives

The main goal of this project is to identify the fouling issues within the system of heat exchangers and propose a solution for bypassing and cleaning while maintaining operations. To achieve this goal the system has to be evaluated by analyzing temperature data trends throughout running cycles of 2 years and pinpoint the heat exchangers that have the most severe fouling issues. The work includes a literature study of potential reasons why fouling occurs in the identified heat exchangers. Different bypass solutions for these heat exchangers are proposed and assessed with respect to energy efficiency gain and feasibility. A techno-economic assessment of selected bypass configurations is performed considering investment costs, potential cost savings and the PBP to determine whether it is worth the investment for St1 refinery.

The questions that are to be answered during this project are as follows:

- What is the total heating and cooling demand within the crude feed pre-heater HEN?
- Which heat exchangers have the most pronounced fouling issues?
- Why does extensive fouling occur in these heat exchangers?

- How can the heat exchangers be bypassed in order to enable cleaning during operations?
- How much net savings can be achieved by installing a bypass solution in terms of increasing the heat recovery and decreasing the fuel consumption in the furnace?
- What is the PBP for the proposed bypass solutions?

1.4 Delimitations

Since this project is time restricted, certain delimitations and assumptions must be made. The first delimitation is to not consider variations of composition of the crude oil. St1 imports different types of crude oils. The types of crude oils and the mixing ratios vary constantly over time which results in crude oil mixtures with different properties. St1 has experienced that the choice of crude oil mix highly affects the rate of fouling. It would be interesting to investigate how the crude oil composition affects the fouling rate, but this would be difficult to implement since the decision for which crude oils to import relies on different factors such as price and availability. During this project the crude oil mix and its physical data will be assumed to be constant and will be selected with expertise from process engineers at St1 refinery. An analysis of how the crude oil composition affects the rate of fouling is outside the scope of the study. The composition of the product flows also differs since the product specification varies over time, or due to process disturbances. The product specification depends on the market demand and potential profits. The product flow compositions will not be accounted for due to the time restriction and the physical properties will be assumed to be constant.

Initially, it was planned to perform a pinch analysis of the HEN to evaluate the performance by visualizing the thermal profiles in balanced composite curves. It was later on realized that this did not yield reliable results due to a lack of dependable temperature data and that the focus of the project should be on fouling assessment instead. Fouling is a common issue at the refinery and there are several heat exchangers that lack bypass solutions for cleaning during operations. In this project it would not be possible to include all of the heat exchangers at the refinery, therefore a delimitation was made to only evaluate the heat exchangers that preheat the crude oil in one of the crude oil distillation units since this system of heat exchangers is the largest at the refinery with substantial process flows.

It is likely that multiple heat exchangers within the system have fouling issues. As a result there are numerous possible bypass solutions and therefore delimitations must be made for this. It was therefore decided to restrict the study to the three of heat exchangers that have the highest fouling rate during a running cycle and propose bypass solutions for these. After the bypass configurations have been evaluated, the most feasible option will be proposed.

2

Process Description

In this chapter the process units involved in the HEN will be described more in detail.

2.1 Crude Distillation Unit

The largest HEN at St1 refinery is located in the beginning of the refining process where the crude oil is preheated using warm process flows from a crude distillation tower along with flows from a thermal cracker process unit before entering a furnace. The crude distillation process unit that will be in focus during this project is shown in in figure 2.1. The figure shows an overview of the main equipment and the different operating stages happening in the process unit, including the system boundary where the HEN is located.

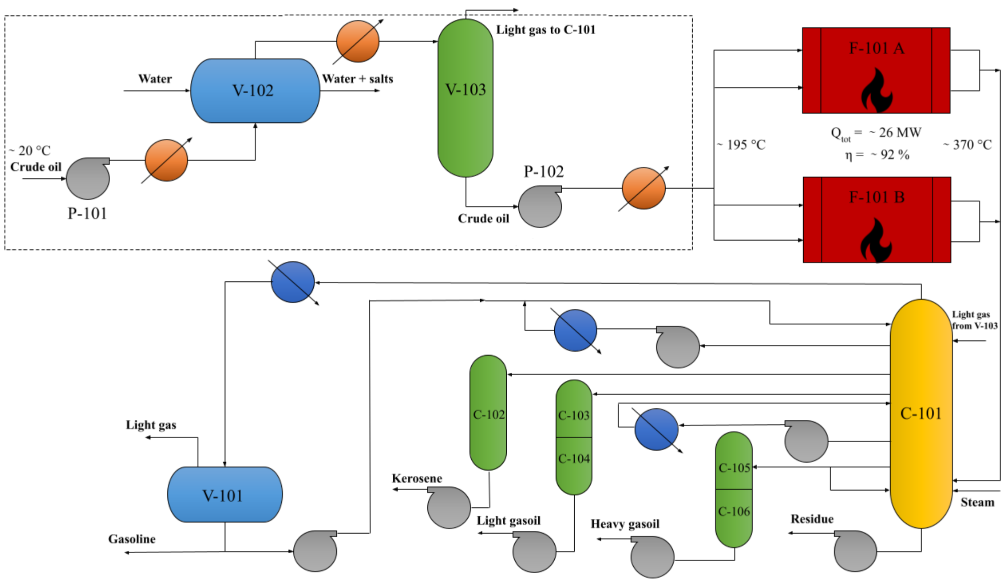


Figure 2.1: A schematic picture of the CDU

First the crude oil is pumped from a storage tank with pump P-101 and preheated in a series of shell-and-tube heat exchangers. Note that only one heat exchanger symbol is used to represent multiple heat exchangers in the figure. When the crude oil has been heated to around 120°C it is mixed with process water in a desalter

(V-102). Different salts and other impurities present in the oil dissolve in the water and can thereby be removed by separating the water and crude oil. It is crucial to heat the crude oil before it enters the desalter in order for the desalination process to work. The crude oil flow is then preheated further in several shell-and-tube heat exchangers before entering a preflash column (V-103) where around 10 % of the oil evaporates due to the lower pressure in the column. This step is performed to avoid having a two phase flow enter the furnace later on in the process. The light gases leaving the top are lead directly to a distillation column (C-101). The crude oil leaving the bottom is pumped using the pump P-102 and preheated once again in a series of shell-and-tube heat exchangers before entering the furnaces, F-101 A/B. The heated crude oil enters the distillation column (C-101) at around 370^{o}C and different fractions of the oil are obtained. The main product flows from the column are gasoline, kerosene, light gasoil, heavy gasoil and residue. As figure 2.1 shows, the crude oil entering the unit is at around 20^{o}C. After preheating in the heat exchanger train, the temperature of the crude oil before it enters the furnace is approximately 195^{o}C and is then heated to 370^{o}C.

The total thermal input of the furnaces is approximately 26 MW with an efficiency of 92 %. By utilizing the available heat from the product flows and process flows from the TCU, the energy demand of furnace F-101 is reduced significantly. Approximately 27 MW of heat can be recycled and the average fuel consumption is 55 tons/day in F-101. The CO_2 emissions generated in F-101 during one year constitutes of 11 % of the total annual CO_2 emissions for the refinery. As mentioned previously, St1 refinery has experienced problems with fouling within the heat exchanger system leading to a decreased heat transfer efficiency throughout the running cycle. As a result, the fuel consumption in F-101 typically increases by around 12% over 2 years of operations, i.e. between the refinery's major turn-arounds. The fuel used in all the furnaces at the refinery is internally produced fuel gas which is mainly a mixture of hydrogen and light hydrocarbons. Normally there is a deficit of fuel gas and additional fuels has to be added. The additional fuel is either purchased natural gas or LPG that St1 produces and sells as a product. The current market price for natural gas and LPG determines whether it is more profitable to sell LPG and purchase natural gas as fuel in the refinery or to use LPG as fuel instead of selling the product. Therefore it varies which type of fuel is used in F-101.

In figure 2.2 the shell-and-tube heat exchangers used for preheating the crude oil are shown in more detail, including the system boundary.

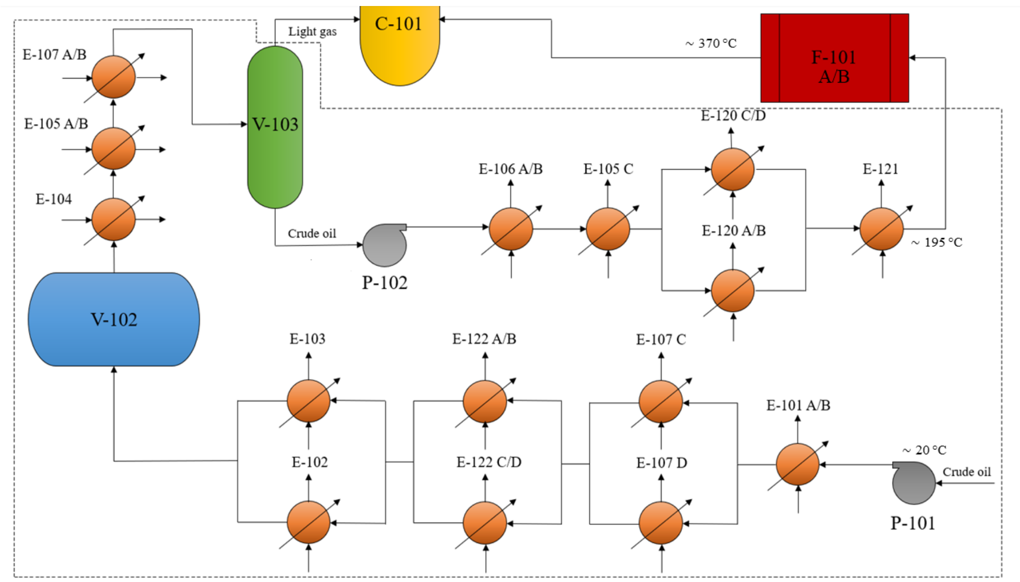


Figure 2.2: A schematic picture of the heat exchanger system with the system boundary

In figure 2.3 a more detailed schematic picture of the preheating heat exchanger system is shown together with the existing temperature sensors, T1-T29.

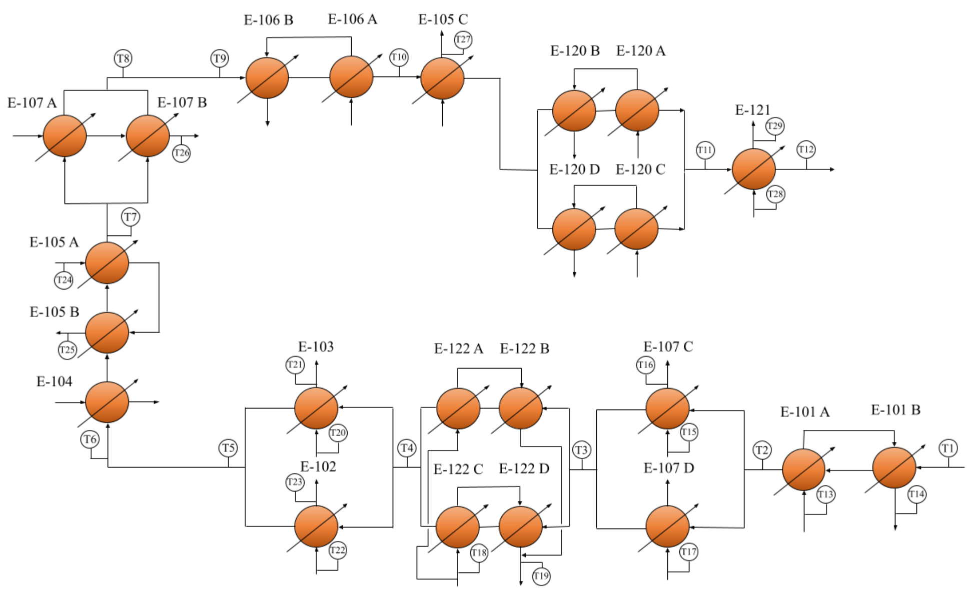


Figure 2.3: A detailed schematic picture of the heat exchanger system

In table 2.1 the hot process streams in the heat exchanger system are described.

Table 2.1: Hot process streams in the system of heat exchangers

Heat Exchanger	Hot Process Flow
E-101 A/B	Light gasoil
E-107 C	Kerosene
E-107 D	Heavy gasoil
E-122 A/B/C/D	Circulating top reflux from C-101
E-103	Heavy gasoil
E-102	Light gasoil
E-104	Residue from thermal cracker
E-105 A/B	Circulating middle reflux from C-101
E-107 A/B	Residue from thermal cracker
E-106 A/B	Residue from thermal cracker
E-105 C	Circulating middle reflux from C-101
E-120 A/B	Residue from thermal cracker
E-120 C/D	Residue from thermal cracker
E-121	Circulating middle reflux from C-1302 (TCU)

2.2 Thermal Cracker Unit

The aforementioned thermal cracker is an adjacent process unit with the purpose of maximizing the total product yield. Residue flows from three different CDU:s are introduced to thermal cracker furnaces and a chemical reaction takes place in which the long hydrocarbons are broken into smaller molecules. The cracking reaction leads to the formation of gas, gasoline and gasoil. There will also be some residue left containing hydrocarbons that are too heavy to be broken at the cracking operating temperature [10]. Figure 2.4 shows the residue flows, thermal tar and visbreaker tar, from the TCU.

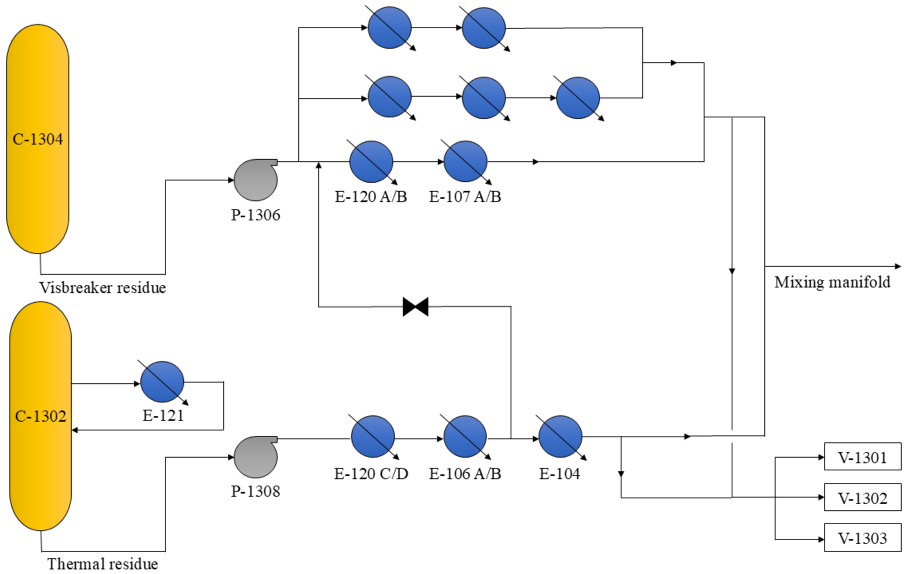


Figure 2.4: A schematic picture of the residue flows from the TCU

C-1302 is a distillation tower that separates the formed gas, gasoline and gasoil. There is a circulating reflux flow at the middle of the tower that is cooled in heat exchanger E-121. The residue stream leaving the bottom of the tower is called thermal residue, which is pumped by pump P-1308 and cooled using the crude oil entering heat exchangers E-120 A/B, E-106 A/B and E-104. C-1304 is a vacuum distillation tower that separates gasoil. The bottom stream that contains the longest and heaviest hydrocarbons is called visbreaker residue and is pumped by pump P-1306. Thereafter the stream splits into 3 streams. One of the streams is cooled by utilizing the colder crude oil in E-120 A/B and E-107 A/B. Note that the thermal residue flow can be redirected to the visbreaker residue stream entering E-120 A/B, but this valve is normally closed. The residue flows are later on mixed in a manifold where it can be further treated and sold as ship fuel. A small part of the residue flows are also used as a cooling medium in V-1301, V-1302, V-1303. These are three separators where the cracked oil from the furnaces is introduced. The oil enters the vessel at high temperatures, the cooling flow is introduced to terminate the cracking reaction to prevent formation of coke, the lighter hydrocarbons exit in the top and the heavier hydrocarbons exit in the bottom.

3
Methodology

In this chapter the different steps and methods used during the project are explained together with relevant equations. Uncertainties associated with the chosen methods, assumptions and simplifications made throughout the project are also discussed.

3.1 Initial Studies and Planning

The project initiated with gathering information about the project together with the supervisors at St1, such as the process layout, the function of the process units and the operability issues. With this information it could be determined what the main scope should be and what tasks should be prioritized during the project, as well as which delimitations had to be made. The start-up phase also included a comprehensive literature search to find relevant information about the different steps of the project. The literature search was mainly performed in available scientific databases provided by Chalmers library. The purpose of the literature search was mainly to research methods used in similar studies to evaluate different approaches when it comes to identifying fouling in heat exchangers. The literature search also included gathering information about the phenomenon of fouling and the underlying processes.

During the initial studies of the project, the heat exchanger system was mapped out by identifying which heat exchangers are used for preheating the crude oil, how they are connected, which heating medium are used and lastly mass flow data were obtained for all of the hot and cold streams.

3.2 Collection and Evaluation of Data

3.2.1 Temperature Data

The second step of the project was to collect temperature data by utilizing online temperature measurements available at the refinery. As figure 2.3 showed in the chapter Process Description, temperature sensors are not available for each stream entering and leaving every heat exchanger within the system. Where instruments for temperature measurement are lacking, the temperature data had to be obtained by manual measurements on site instead. The manual measurements were obtained using an infrared thermometer. The used thermometer was the Fluke 568 Ex IR Thermometer which can measure the temperature of a surface between -40 ^{o}C to

800 °C [11]. The manual data points were acquired to map the temperature profiles within the HEN.

3.2.2 Physical and Chemical Properties

Physical and chemical properties for all the process flows were collected either from heat exchanger design data sheets, simulations, analytical data from St1 laboratory or from literature. The majority of the physical properties for different process flows could be obtained from design data sheets where values for density, viscosity and specific heat at different temperatures were available. With these data points, linear and exponential regressions were made to create equations that represent the dependence of temperature for the physical properties. In figure 3.1 an example of the specific heat for crude oil can be seen.

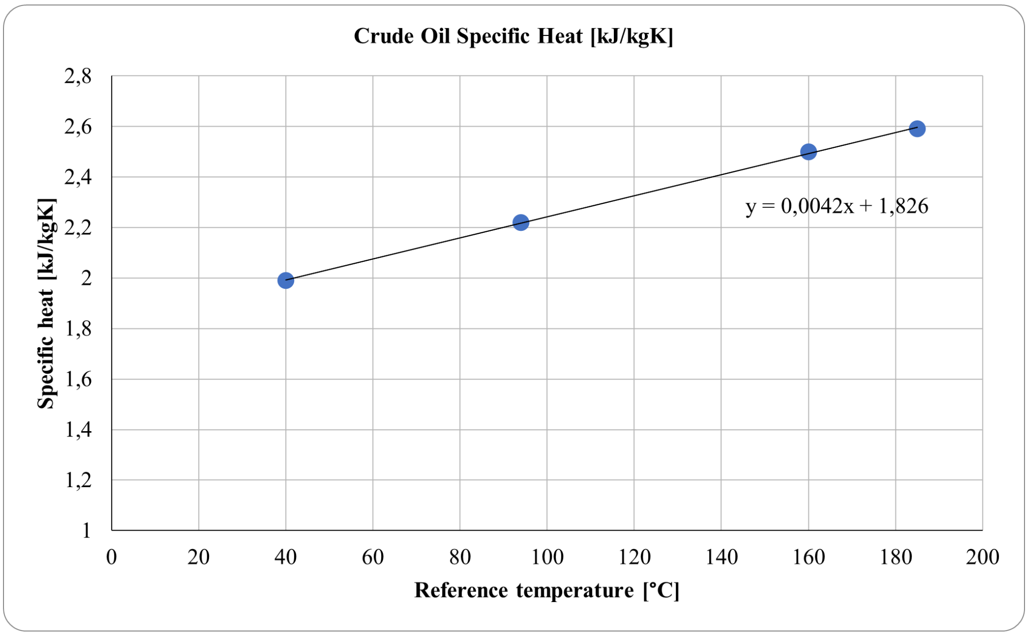


Figure 3.1: A linear regression of the specific heat depending on temperature for crude oil

Physical and chemical properties for the thermal residue and visbreaker residue were obtained using the program *Aspen HYSYS*. The residue process flows were simulated using the tool *Oil Manager* found in the Aspen package where distillation curves for the fluids had to be entered. The distillation curves were retrieved from historical laboratory data. With the given information, Aspen HYSYS could predict multiple properties at a given temperature for the residue fluids. The fluid package used for the simulations was Peng-Robinson. In table 3.1 the distillation curves for thermal and visbreaker residue entered into Aspen HYSYS are presented.

Table 3.1: Distillation curves for thermal residue and visbreaker residue

Distillation curve	Thermal residue	Visbreaker residue
IBP	297	373
5 %	368	428
10 %	393	453
20 %	424	491
30 %	446	515
40 %	468	536
50 %	490	555
60 %	511	574
70 %	534	592
80 %	561	613
90 %	593	640
95 %	622	656
FBP %	664	700

3.2.3 Evaluation of Fouling

When all of the relevant data had been collected, it was analyzed systematically. The heating and cooling demands in each heat exchanger were calculated. Outliers in the data were removed by filtering the data for a more clear visualization of trend plots. Thereafter, the heat exchangers with the most severe fouling were identified as follows:

- Examine the temperature gradients over two-year time intervals and note the heat exchangers that experienced a significant decrease in temperature gradient. This enables the list of potential fouling heat exchangers to be narrowed down.
- Investigate if there are specific reasons for the decreased temperature gradient other than fouling, for example process disturbances, new temperature set points or instrument malfunction.
- The temperature data were analyzed over four different running cycles since the fouling behavior should repeat itself. Information about when operations at the CDU was stopped, which heat exchangers were cleaned during this time and if some of the tubes are plugged was required for the analysis as well.

The fact that instruments for online temperature measurements are missing in some places introduced uncertainty in the analysis since these temperatures cannot be trended over time. Manual measurements could be made later on during the project for comparison but it was deemed highly unlikely that the rate of fouling is so high that it would be notable in temperature measurements after such short period of time. For the cases where temperature data were missing, some heat exchangers had to be analyzed as an aggregate. If a decrease in temperature gradient was found for these heat exchangers, a method of exclusion had to be made. St1 has documented the fouling phenomenon for some heat exchangers historically by inspecting internals during the turn-arounds and this information was used to confirm that fouling occurs in the identified heat exchangers.

- Heat transfer calculations for the pinpointed heat exchangers were performed in order to determine how much transfer of energy is lost due to fouling and which heat exchanger has the lowest energy efficiency after a running cycle. The following equations were used, depending which temperature data were available:

$$Q_c = \dot{m}_c C_{p,c}(T_{c,2} - T_{c,1}) \tag{3.1}$$

$$Q_h = \dot{m}_h C_{p,h}(T_{h,2} - T_{h,1}) \tag{3.2}$$

- The linear velocity and Reynolds number were also calculated for the tube side and shell side in the identified heat exchangers. If the velocity and Reynolds number were low, it could be identified as a contributing factor to the fouling processes.

The linear velocity and Reynolds number for the shell-side were calculated using Kern's method which includes the following equations [12]:

$$A_s = \frac{(p_t - d_o)D_s l_B}{p_t} \tag{3.3}$$

$$G_s = \frac{\dot{m}_s}{A_s} \tag{3.4}$$

$$u_s = \frac{G_s}{\rho} \tag{3.5}$$

$$d_e = \frac{1,27}{d_o}(p_t^2 - 0,785 d_o^2) \tag{3.6}$$

$$Re = \frac{G_s d_e}{\mu} \tag{3.7}$$

The following equations were applied to determine the linear velocity and Reynolds number for the tube-side of the heat exchangers [12]:

$$A_t = \frac{\pi * d_i^2}{4} \tag{3.8}$$

$$A_f = A_t * \text{Tubes per pass} \tag{3.9}$$

$$G_t = \frac{\dot{m}_t}{A_f} \tag{3.10}$$

$$u_t = \frac{G_t}{\rho} \tag{3.11}$$

$$Re = \frac{\rho u_t d_i}{\mu} \tag{3.12}$$

- Lastly, the fouling phenomenon that seemed to be occurring in the identified heat exchangers was evaluated by trying to find potential reasons based on information available in the literature.

3.3 Selection of Bypass Configuration

When the fouling issues had been identified it had to be decided which heat exchanger/heat exchangers should be bypassed and by which configuration, in order to find a feasible solution for cleaning while maintaining operations within the process unit. During this step, a qualitative assessment had to be made for the system to determine whether the heat exchanger/heat exchangers could be taken out of operation while maintaining operations for the rest of the unit. It was assumed that while bypassing, 100% redundancy cannot be achieved and therefore the refinery throughput must be reduced by 30% during cleaning. This was based on the refinery's previous experiences with bypassing heat exchangers. In the qualitative assessment, different scenarios were evaluated by discussing possible consequences of bypassing a selected heat exchanger and investigate plausible outcomes downstream, for both the cold and hot process flows.

Assistance from the department of construction at St1 was required to provide guidance for how the bypass pipes and valves could be installed. Several solutions for bypass configurations were found and therefore the reasons behind the selected design had to be motivated. It became a compromise between trying to bypass several heat exchangers at the same time to keep down the material costs and also not lose too much recovery of heat within the system. The selected bypass configurations were also evaluated from a process safety perspective. This was performed by doing a what-if analysis where potential worst case scenarios linked to bypassing a heat exchanger were discussed. Safety data for the fluids present in the pinpointed heat exchangers were obtained to assess potential risks when it comes to leakages and contamination. From the discussed worst case scenarios in the analysis, potential solutions were recommended for decreasing the risk factors and improving the inherent process safety.

3.3.1 E-120 A/B/C/D versus E-105 C

During the identification of fouling in the heat exchangers, E-105 C and E-120 A/B/C/D had to be evaluated as one unit due to the position of temperature instruments, see figure 2.3. It was discovered that a substantial amount of heat was lost in these 5 heat exchangers, but it was unclear if both E-105 C and E-120 A/B/C/D had fouling issues or just E-120 A/B/C/D. It could be concluded that E-120 A/B/C/D had fouling issues since St1 documentation was found confirming this and the large amount of heat loss could not be exclusively from E-105 C due to the small size of the heat exchanger. In order to establish if E-105 C also was a contributing factor, temperature data from the instruments T11 and T27 were examined. By analyzing trends of the outgoing hot temperature from E-105 C together with the outgoing cold temperature from E-105 C + E-120 A/B/C/D, conclusions could be drawn based on the theory that if fouling occurs in E-105 C then the transfer of heat will become less efficient. The outgoing hot temperature T27 should therefore increase significantly together with the decreasing cold temperature T11. To evaluate this further, temperature measurements placed upstream from E-105 C on the hot side can be utilized. Figure 3.2 shows the circulating middle reflux from C-101 before it enters E-105 C, A and B.

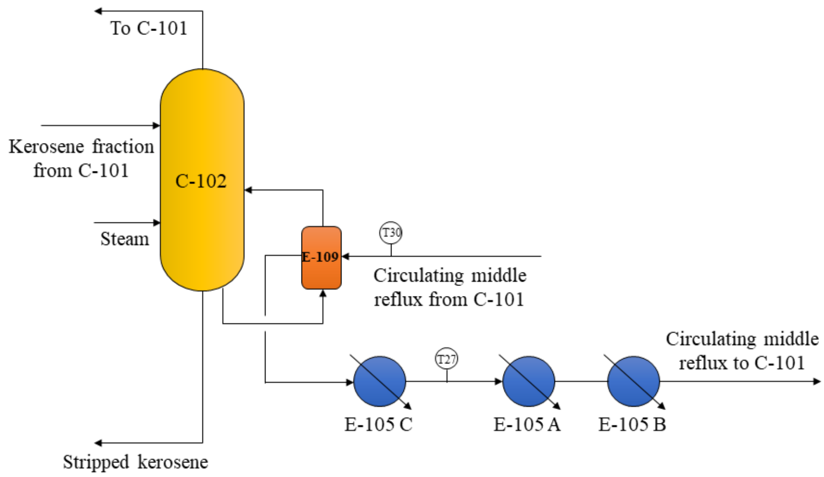


Figure 3.2: A figure visualizing the circulating middle reflux from C-101

As the figure shows, the hot flow entering E-105 C is first cooled in E-109 which is a kerosene reboiler for C-102. Before E-109 there is an online temperature sensor and thus temperature gradient trends could be analyzed for E-109 + E-105 C to note repeated decrease in temperature gradients. A MATLAB script was used to determine the total heat loss in E-105 C over a running cycle by using iterations to calculate the two unknown temperatures T_{c2} and T_{h1} in the beginning and end of a running cycle. The unknown temperatures were iterated based on the criteria that $Q_h \approx Q_c$ should be met. With the calculated temperatures the exchanger load before and after a running cycle could be determined and thus the heat loss. The script is included in Appendix A.1. The calculated load from E-105 C could then be deducted from the total energy demand calculated for E-105 C + E-120 A/B/C/D to obtain the load provided by E-120 A/B/C/D.

3.3.2 Utilizing Existing Bypass Pipes

When designing the bypass for E-120 A/B and E-120 C/D it was discovered that there were two existing pipes bypassing the heat exchangers for the crude oil flow. The diameters of these pipes were however half the size of the regular pipes. To examine the possibility of utilizing these pipes for the bypass solution, various calculations had to be made. Several consequences can arise when the diameter of a pipe is suddenly decreased. The flow velocity will increase to conserve the mass flow rate when the cross-sectional area decreases. This will lead to a pressure drop in the pipe and if the pressure falls below the crude oil vapor pressure, there is risk of cavitation. The increased velocity can also lead to increased turbulence which can cause vibration in the pipe [13]. First the cross-sectional area of the pipes were calculated, together with the initial and final velocities [14]:

$$A_p = \frac{\pi * d_p^2}{4} \tag{3.13}$$

$$v = \frac{\dot{m}}{\rho * A_p} \tag{3.14}$$

The change in Reynolds number and pressure were calculated as follows:

$$Re = \frac{\rho * v * d_p}{\mu} \tag{3.15}$$

$$\Delta P = P_1 - P_2 = \frac{\rho * v_2^2}{2} - \frac{\rho * v_1^2}{2} + \Delta P_{loss} \tag{3.16}$$

$$\Delta P_{loss} = K_c * \frac{\rho * v_2^2}{2} \tag{3.17}$$

$$K_c = (1 - \frac{A_2}{A_1})^2 \tag{3.18}$$

The additional pump work required due to the resulting pressure drop was also calculated:

$$\dot{q} = \frac{\dot{m}}{\rho} \tag{3.19}$$

$$W = \Delta P * \dot{q} \tag{3.20}$$

Lastly, to evaluate the risk of cavitation:

$$P_{min} = P_{static} - \frac{\rho * v^2}{2} \tag{3.21}$$

If $P_{min} > P_{vapor}$ then there is no risk of cavitation within the pipe [14].

3.4 Economic Assessment

The final step of the project was to perform an economic assessment of the bypass solutions. The investment cost, net cost savings and the PBP were calculated. This last step was crucial to determine whether it is a feasible design that is worth the investment for the company [15]. To perform the calculations, it was assumed that the selected heat exchangers should be cleaned once per year. First, the amount of fuel saved due to cleaning was calculated, which depended on the total heat that would normally be lost due to fouling during one year. This is the fuel used in F-101 to compensate for the heat loss within the HEN during one year. Note that the following calculations were performed with both LPG and natural gas as fuel, in order to evaluate the economic performance for two different fuel type scenarios.

$$\dot{m}_{fuel} = \frac{Q_{loss}}{LHV_{fuel} * \eta} \tag{3.22}$$

Thereafter, the cost savings of avoided CO_2 emissions and fuel cost savings could be calculated. Every kg of coal burned in the furnace will produce 3.667 kg of CO_2.

$$\text{Cost savings } CO_2 = \dot{m}_{fuel} * X_{carbon} * 3.667 * \text{Emission rights cost} \tag{3.23}$$

$$\text{Fuel cost savings} = Q_{loss} * \text{Fuel cost} \tag{3.24}$$

During the period of bypassing and cleaning, which was assumed to be 7 days, the transfer of heat occurring in the heat exchanger that is out of service must be compensated for by increasing fuel firing in furnace F-101. Therefore, the cleaning period incurs costs related to increased fuel consumption and CO_2 emissions. As previously stated, the cleaning period would also require a reduced flow of 30 %, which means that there will be a financial loss due to lower net profits for the company during 7 days, i.e. the net loss of revenue associated with the decreased plant throughput.

$$\dot{m}_{fuel} = \frac{Q * 0.7}{LHV_{fuel} * \eta} \tag{3.25}$$

$$\text{Fuel cost}_{\text{cleaning}} = Q * \text{Fuel cost} \tag{3.26}$$

$$\text{Emission cost}_{\text{cleaning}} = \dot{m}_{fuel} * X_{carbon} * 3.667 * 7 * \text{Emission rights cost} \tag{3.27}$$

$$\text{Financial loss}_{\text{-30\% flow}} = \dot{m}_{\text{crude oil}} * 0.3 * 7 * \text{Net profit per ton crude oil} \tag{3.28}$$

$$\text{Total annual costs} = \text{Financial loss}_{\text{-30\% flow}} + \text{Fuel cost}_{\text{cleaning}} + \text{Emission cost}_{\text{cleaning}} \tag{3.29}$$

$$\text{Total annual savings} = \text{Fuel cost savings} * (365 - 7) + \text{Cost savings } CO_2 * (365 - 7) \tag{3.30}$$

$$F = \text{Total annual savings} - \text{Total annual costs} \tag{3.31}$$

The PBP was then calculated by analyzing the cumulative cash flow over several years, see figure 3.2. The total investment cost during year zero, I_0, includes the purchase price for required equipment, shipping and installment costs. During the first year the net annual savings will be negative since no savings can be done until after the first cleaning that happens after one year.

Table 3.2: Calculation of the cumulative cash flow

Year	Cumulative cash flow
0	-I_0
1	Cumulative cash flow year 0 - Total annual costs
2	Cumulative cash flow year 1 + F
3	Cumulative cash flow year 2 + F
4	Cumulative cash flow year 3 + F
n	Cumulative cash flow year n-1 + F

The data were plotted and the year where the cumulative cash flow became positive retained as the PBP. To compensate for additional costs during installment of the bypass equipment that needs to be included in the total investment cost, the Lang factor was included. The Lang factor is a factor that can be used to calculate the contributions from various installment costs to the total capital cost [16].

$$I_0 = C = L(\sum C_e) \tag{3.32}$$

C is the total capital cost including engineering costs, L is the Lang factor, $\sum C_e$ is the total price for purchasing all the equipment, including shipping or delivery costs. The Lang factor is usually used when calculating the investment cost for a whole plant, but it can be used in this case as well to calculate a preliminary installation costs. To determine the Lang factor for installment of a bypass the factors shown in table 3.3 can be used [16].

Table 3.3: Typical factors for estimation of fixed capital costs

Item	Factor
f1 Equipment erection	0.3
f2 Piping	0.8
f3 Structures and buildings	0.2
f4 Design and engineering	0.3
f5 Contingency	0.1

The Lang factor can be calculated using equation 3.33:

$$L = 1 + \sum_{i=1}^{5} f_i \tag{3.33}$$

The PBP values were compared for the different bypass designs and the preferred option was the bypass scenario with the lowest PBP when using both LPG and natural gas as fuel. The PBP is a useful tool to determine if an investment is profitable or not. However, it does not consider the time value of money and it usually favors short-term investments [15]. Public market data for fuel gas price, cost for CO_2 emissions permits were used for these calculations since the data for the refinery's internal investment assessments is classified. The values for net profit per ton of crude oil feed used were general data specific for the refinery.

3.4.1 Sensitivity Analysis

A sensitivity analysis was also performed for different scenarios since the economic assessment does not take into account the variability and fluctuation of the economical data. Namely, the fuel gas prices, CO_2 emission permits cost and net profit per barrel crude oil. Therefore, an analysis for the influence of fluctuations in these parameters were made. The interval for the variation of each parameter is given in table 3.4. Note that in reality, all parameters fluctuates simultaneously. However, this analysis is limited to the variation of one parameter at a time, together with scenarios where all the parameters are high and low respectively.

Table 3.4: Variation intervals of economic parameters

Parameter	Normal value	Deviation interval
LPG price	0.17 EUR/kWh	[-25% ; +25%]
Natural gas price	0.1 EUR/kWh	[-50% ; +50%]
CO_2 emission permits cost	83 EUR/ton CO_2	[-25% ; +25%]
Net profit per barrel crude oil	4 $/barrel	[-50% ; +50%]

3.5 Workflow Diagram

Figure 3.3 shows a workflow diagram including the main steps of the project.

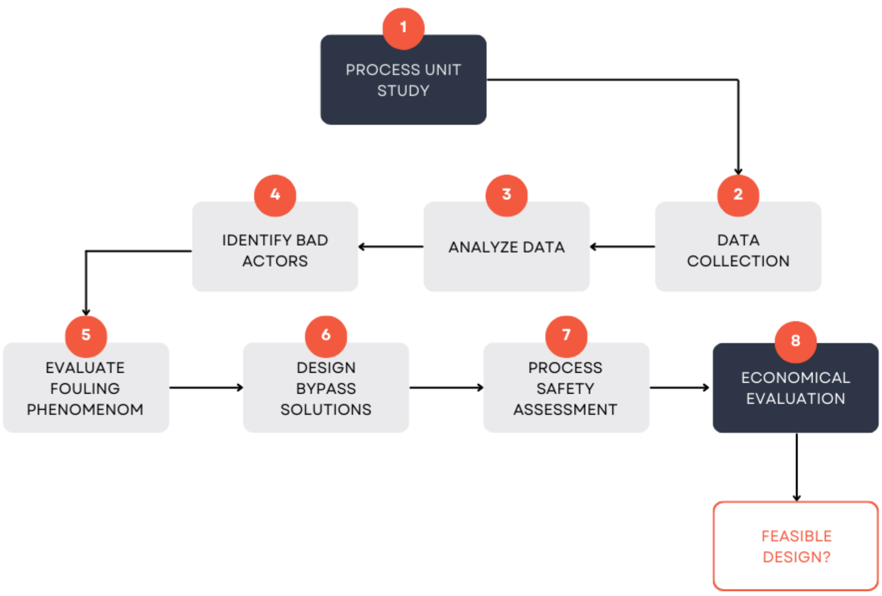


Figure 3.3: Workflow diagram containing the main steps of the project

3.6 Uncertainties

The described methods used during this project have certain uncertainties which could have different effects on the outcome.

3.6.1 Data collection

The collection of data for temperatures and mass flows were important during this project since it was needed to be able to identify fouling by trending the temperature gradients over time and calculating the heat transfer in the heat exchangers. The mass flow data were collected by flow sensors and the temperature data were a mix of online instruments and manual measurements using an infrared thermometer. St1 has a variety of online sensors at the refinery with different accuracies. In general, the accuracy is between 1 % - 5 %. St1 has experienced instruments that sometimes generates inaccurate data, which is discovered by operators and process engineers. This is usually solved by performing a manual reset of the instrument. The obtained inconsistent data were identified as outliers and removed by filtering the data in Excel.

When it comes to the manual temperature data, the accuracy is lower and the uncertainty is much higher. The infrared thermometer can have an accuracy of 1 % at best, but it only measures the temperature of a surface by detecting infrared wavelengths that an object emits [11]. The surface temperature of a pipe does not reflect the real temperature of the process flow, but it can give a general idea of how the temperature fluctuates within the system of heat exchangers. Another uncertainty with these measurements is the way they were performed. In some cases the heat exchangers were located on top of each other making it difficult to come close to the pipes connected to the heat exchangers. The longer the distance between the thermometer and pipe, the lower the measurement accuracy becomes.

3.6.2 Assumptions and Simplifications

To be able to perform certain calculations different assumptions had to be made:

- Physical and chemical data for the fluid circulating middle reflux from C-101 were unavailable and therefore an assumption had to be made that the fluid has the same properties as heavy gasoil.
- Physical and chemical data for the fluid circulating top reflux from C-101 were unavailable and therefore an assumption had to be made that the fluid has the same properties as gasoline.
- Physical and chemical data for the fluid circulating middle reflux from C-1302 were unavailable and therefore an assumption had to be made that the fluid has the same properties as the gasoil produced in the TCU.
- During the preheating process of the crude oil vaporization will occur to some extent. In which heat exchangers the vaporization will take place and to what extent will vary depending on the composition of the crude oil mixture and the amount of heat delivered from the warm process flows. Since there is no

way to obtain information about the present two-phase flows an assumption has to be made that a single-phase flow of liquid is constant within the system.
- When performing heat transfer calculations it is assumed that $Q_c = Q_h$. This is not the case in reality since there will be some heat loss and the total heat transferred will also include the latent heat of vaporization for the crude oil.
- There are several uncertainties for the economical evaluation since it is only an estimate of the potential net value based on public market data for costs and prices. The public data are used instead of specific economical data for St1 refinery since it is classified information.
- The total time required for taking a heat exchanger out of service, clean it and then put it back into operation was assumed to be 7 days based on the refinery's previous experiences.
- It was assumed that the heat exchangers experiencing fouling should be cleaned once per year to recover heat within the system.
- During the economic calculations it was assumed that the fouling process is linear and that the effect is divided equally between E-120 A/B/C/D since the heat exchanger designs are the same.

4

Results

4.1 Fluid Properties and Energy Streams

Table 4.1 presents the collected physical and chemical properties of the process flows at atmospheric conditions. It can be noted that the hot process flows *circulating top reflux from C-101*, *circulating middle reflux from C-101* and *circulating middle reflux from C-1302* are not included in the table. As mentioned previously, physical and chemical data were unavailable for these process flows. It can also be noted that the visbreaker- and thermal tar have significantly high viscosity compared to the other process flows within the HEN.

Table 4.1: Physical and chemical properties of process streams at 20°C and 1 atm

Fluid	Boiling range [°C]	Flash point [°C]	Auto-ignition tempera-ture [°C]	Viscosity [cP]	Density [kg/m^3]	Specific heat [kJ/kgK]
Crude oil	10-400	23	220	6.58	832	1.91
Gasoline	45-166	-43	246-280	0.43	694	2.1
Kerosene	174-239	59	210	0.56	750	2.2
Light gasoil	179-302	55	200	1.50	780	1.90
Heavy gasoil	237-376	100	225	1.70	800	1.93
Visbreaker tar	>373	100	250	380	1016	1.82
Thermal tar	297-664	100	250	380	1013	1.78
Gasoil (thermal cracker)	252-414	100	233	1.58	840	1.91

The calculated energy streams using manual temperature measurements are presented in figure 2.3. The total energy demand for heating the cold streams is 27 066 kW and the total need for cooling the hot streams is 32 390 kW. The calculated heating demand is lower than the calculated cooling demand, which can be explained by non-accurate manual temperature measurements and since the heat of vaporization of crude oil is not accounted for.

Table 4.2: Energy streams in the process

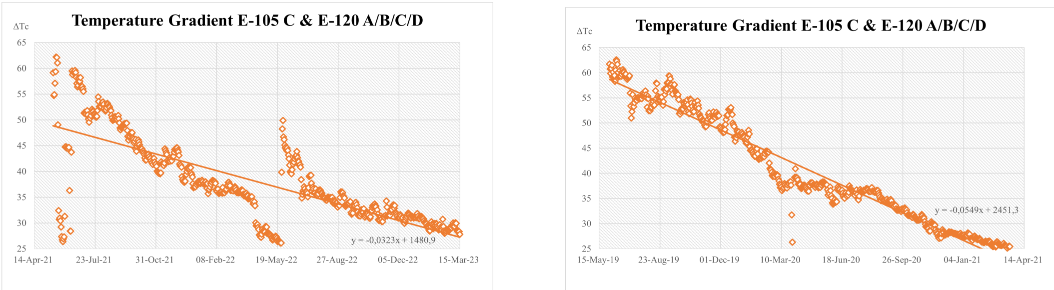
Stream	Location	Hot/Cold	Inlet temperature [°C]	Outlet temperature [°C]	MCp [kJ/h°C]	Enthalpy [kW]
1	E-101 AB	Hot	68	21.6	47630	613.4
2	E-101 AB	Cold	23.1	27.4	477588.7	565.1
3	E-102	Hot	249.5	120.6	62560	2240
4	E-102	Cold	98.1	102	277272.9	301.2
5	E-103	Hot	297.7	120.6	82010	4035
6	E-103	Cold	98.1	126.4	283550.1	2230
7	E-104	Hot	150.5	130	89290	508.4
8	E-104	Cold	126.3	129.4	584869.2	508.4
9	E-105 AB	Hot	206	158.5	191500	2526
10	E-105 AB	Cold	123.5	139.1	584869.2	2526
11	E-105 C	Hot	234	206	203200	1583
12	E-105 C	Cold	161.3	190	571550.6	4555
13	E-106 AB	Hot	186	153.8	93820	839.2
14	E-106 AB	Cold	154	161.3	554799.5	1130
15	E-107 AB	Hot	252	216.4	78760	779.4
16	E-107 AB	Cold	139.1	154.5	602638.2	2588
17	E-107 C	Hot	81.8	39.3	57810	683
18	E-107 C	Cold	27.5	35.6	242025.6	546
19	E-107 D	Hot	84.2	42.9	63420	727.1
20	E-107 D	Cold	27.5	39.2	242951.7	791
21	E-120 AB	Hot	310	213	83790	1443
22	E-120 AB	Cold	153	160	276867.2	538.5
23	E-120 CD	Hot	279	237	107300	1252
24	E-120 CD	Cold	153	170	279192.5	1318.5
25	E-121	Hot	311.5	187.9	183500	6302
26	E-121	Cold	186.5	191	583716.3	734.5
27	E-122 ABCD	Hot	170.6	95	421900	8858
28	E-122 ABCD	Cold	37.8	98.1	521513.5	8734

4.2 Identification of Fouling within the Heat Exchanger Network

During this project, temperature- and heat transfer trends were analyzed for every heat exchanger over four different running cycles. However, in this section of the results only graphs indicating potential fouling phenomenon will be presented. The heat exchangers within the system that showed declining heat transfer over time were E-102, E-103, E-105 C, E-120 A/B/C/D, and E-122 A/B/C/D. However, the heat exchangers showing repeated fouling behavior for each running cycle were E-105 C, E-120 A/B/C/D. Therefore results will only be shown for these five heat exchangers, the rest of the temperature and heat transfer trends can be seen in Appendix A.2.

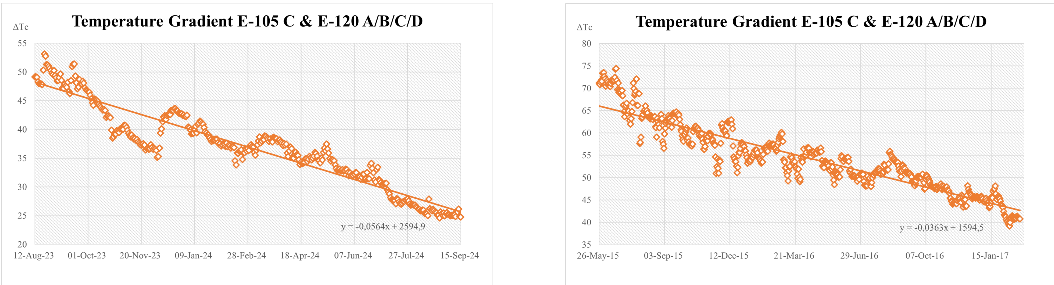
4.2.1 Data Analysis for E-105 C and E-120 A/B/C/D

In figure 4.1 and 4.2 the change in temperature gradient over E-105 C and E-120 A/B/C/D can be seen for four running cycles. The graphs show that there is a decrease in temperature gradient over the five heat exchangers for every chosen time period. The temperature drop is around 20-30 ^{o}C over time.



(a) 2021-2023 **(b)** 2019-2021

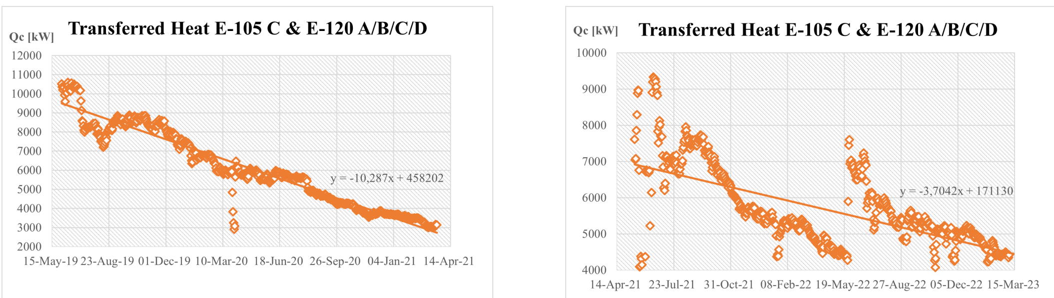
Figure 4.1: Temperature gradients over E-105 C and E-120 A/B/C/D for two running cycles



(a) 2023-2024 **(b)** 2015-2017

Figure 4.2: Temperature gradients over E-105 C and E-120 A/B/C/D for two running cycles

In figure 4.3 the heat transferred over time in E-105 C and E-120 A/B/C/D is shown for two different running cycles. Heat losses are detected in every running cycle with losses between 3000-7000 kW.



(a) 2019-2021 **(b)** 2021-2023

Figure 4.3: E-105 C and E-120 A/B/C/D Transferred heat trends for two running cycles

4.2.2 Confirming Fouling in E-105 C

In figure 4.4 it can be seen that the outgoing hot temperature from E-105 C increases with 9 % more over time than what the outgoing cold temperature from E-120 A/B/C/D decreases. This confirms that fouling seems to be happening in E-105 C.

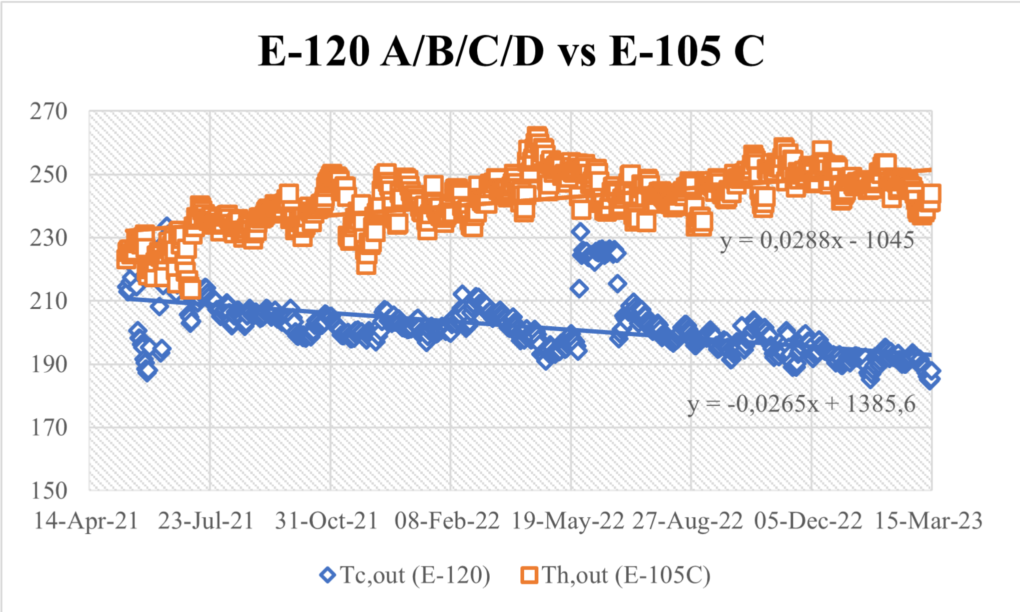
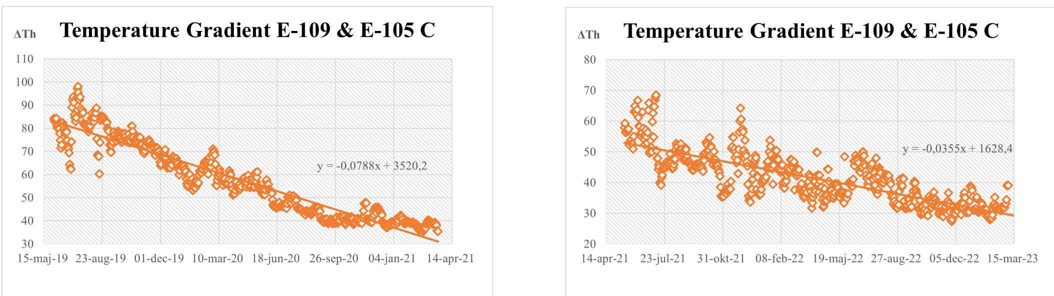


Figure 4.4: Outgoing hot temperature E-105 C compared outgoing cold temperature E-120 A/B/C/D

In figure 4.5 the temperature gradients over E-109 and E-105 C for two different running cycles are shown. It can be seen that the temperature gradient decreases over time during all running cycles, implying that fouling occurs in E-105 C.



(a) 2019-2021 **(b)** 2021-2023

Figure 4.5: Temperature gradients over E-109 and E-105 C for two running cycles

4.3 Potential Reasons for Fouling

As the results show, it seems that the most severe fouling occurs in heat exchangers E-105 C and E-120 A/B/C/D. In this section potential contributing factors behind the fouling will be presented. Other theories behind the fouling phenomenon will be discussed in section 5.2.

4.3.1 E-105 C

In table 4.3 calculations for the flow on both tube- and shell-side in E-105 C using equations 3.3 - 3.12 are presented. When designing shell-and-tube heat exchanger a good rule of thumb is to have a shell-side velocity between 0.3 m/s - 1 m/s and a tube-side velocity around 2 m/s, to ensure efficient transfer of heat between the fluids and to minimize fouling [12]. It can be seen that the velocity in the tubes is a bit low, which creates a higher residence time in the tubes and could enable fouling happening on the surface. The Reynolds number will also have an effect on the fouling rate. The flow should be turbulent to minimize fouling since the viscous shear stress in the fluid is higher near the surfaces in turbulent flows. If the flow is laminar, the wall friction is lower and this could enable dirt and scales to accumulate onto the surface. It can be seen that the flow is turbulent for both tube- and shell-side in this case.

Table 4.3: E-105 C

	Shell-side	Tube-side
Temperature in [°C]	148.8	234
Temperature out [°C]	153.5	205.96
Average temperature [°C]	151.2	219.98
Density [kg/m^3]	755.3	702.5
Viscosity [Pas]	0.001006	0.00032
Mass flow [kg/s]	30.98	20.34
Tube pitch [m]	0.032	-
Tube outside diameter [m]	-	0.025
Tube inside diameter [m]	-	0.020
Shell inside diameter [m]	0.99	-
Baffle spacing [m]	0.37	-
Cross-flow area [m^2]	0.073	-
Tube cross-sectional area [m^2]	-	0.00032
Number of tubes	-	616
Tube passes	-	2
Tubes per pass	-	308
Total flow area [m^2]	-	0.099
Mass velocity [kg/m^{2}s]	424.55	203.69
Linear velocity [m/s]	0.56	0.29
Hydraulic diameter [m]	0.025	-
Reynolds number	10581.9	12849.3
Turbulent/Laminar	Turbulent	Turbulent

4.3.2 E-120 A/B/C/D

In table 4.4 and 4.5 calculations for the flow on both tube- and shell-side in E-120 A/B/C/D using equations 3.3 - 3.12 are presented. The velocity is relatively low for both tube- and shell-side in all four heat exchangers, which could be a reasons behind the fouling. It can also be noted that the flow is either laminar or in the transition regime on the shell-side. This could be due to the highly viscous fluids visbreaker and thermal reside. The low Reynolds numbers could be contributing factors for the high rate of fouling in the heat exchangers E-120 A/B/C/D.

Table 4.4: E-120 A/B

	E-120 A Shell-side	E-120 B Shell-side	E-120 A Tube-side	E-120 B Tube-side
Temperature in [°C]	309	289	156	153
Temperature out [°C]	289	250	160	156
Average temperature [°C]	299	269.5	158	154.5
Density [kg/m^3]	840.08	859.31	750.47	752.94
Viscosity [Pas]	0.0055	0.0060	0.00090	0.00095
Mass flow [kg/s]	11.09	11.09	30.98	30.98
Tube pitch [m]	0.032	0.032	-	-
Tube outside diameter [m]	-	-	0.025	0.025
Tube inside diameter [m]	-	-	0.020	0.020
Shell inside diameter [m]	0.91	0.91	-	-
Baffle spacing [m]	0.18	0.18	-	-
Cross-flow area [m^2]	0.032	0.032	-	-
Tube cross-sectional area [m^2]	-	-	0.00032	0.00032
Number of tubes	-	-	496	501
Tube passes	-	-	4	4
Tubes per pass	-	-	124	126
Total flow area [m^2]	-	-	0.04	0.04
Mass velocity [kg/m^{2}s]	346.41	346.41	770.40	758.17
Linear velocity [m/s]	0.41	0.40	1.03	1.01
Hydraulic diameter [m]	0.025	0.025	-	-
Reynolds number	1571.36	1443.61	17359.36	16153.42
Turbulent/Laminar	Laminar	Laminar	Turbulent	Turbulent

Table 4.5: E-120 C/D

	E-120 C Shell-side	E-120 D Shell-side	E-120 C Tube-side	E-120 D Tube-side
Temperature in [°C]	279	262	153	149
Temperature out [°C]	262	237	170	153
Average temperature [°C]	270.5	249.5	161.5	151
Density [kg/m^3]	856.26	869.99	747.99	755.41
Viscosity [Pas]	0.0036	0.0033	0.00085	0.0010
Mass flow [kg/s]	11.09	11.09	30.98	30.98
Tube pitch [m]	0.032	0.032	-	-
Tube outside diameter [m]	-	-	0.025	0.025
Tube inside diameter [m]	-	-	0.020	0.020
Shell inside diameter [m]	0.91	0.91	-	-
Baffle spacing [m]	0.18	0.18	-	-
Cross-flow area [m^2]	0.032	0.032	-	-
Tube cross-sectional area [m^2]	-	-	0.00032	0.00032
Number of tubes	-	-	501	501
Tube passes	-	-	4	4
Tubes per pass	-	-	126	126
Total flow area [m^2]	-	-	0.041	0.041
Mass velocity [kg/m^{2}s]	346.41	346.41	758.17	758.17
Linear velocity [m/s]	0.40	0.40	1.01	1.00
Hydraulic diameter [m]	0.025	0.025	-	-
Reynolds number	2388.48	2672.95	18359.22	15273.69
Turbulent/Laminar	Transition	Transition	Turbulent	Turbulent

4.4 Bypass Solutions

For the bypass configurations it was decided to use double block and bleed valves for the ingoing and outgoing flows to increase safety and minimize leakage through the valves. See section 4.5.3 for more information about double block and bleed valves. To be able to monitor the fouling processes more accurate in the future, new online temperature instruments should be installed in the places where they are currently missing.

4.4.1 E-105 C Bypass Design

The new equipment required for implementing a bypass over E-105 C are presented in table 4.6.

Table 4.6: Equipment required for bypass design E-105C

10" Valve	3
6" Valve	3
Drainage valve	2
Thermometer	2
Online temperature instrument	2

In figure 4.6 the proposed bypass design for E-105 C can be seen. The equipment shown in blue color is new equipment that needs purchasing and installment and the black equipment are already present on site. There are already existing pipes available for bypassing the heat exchanger that can be utilized. Two online temperature sensors should also be installed for the outgoing cold flow and ingoing hot flow to ensure reliable monitoring of the fouling rate.

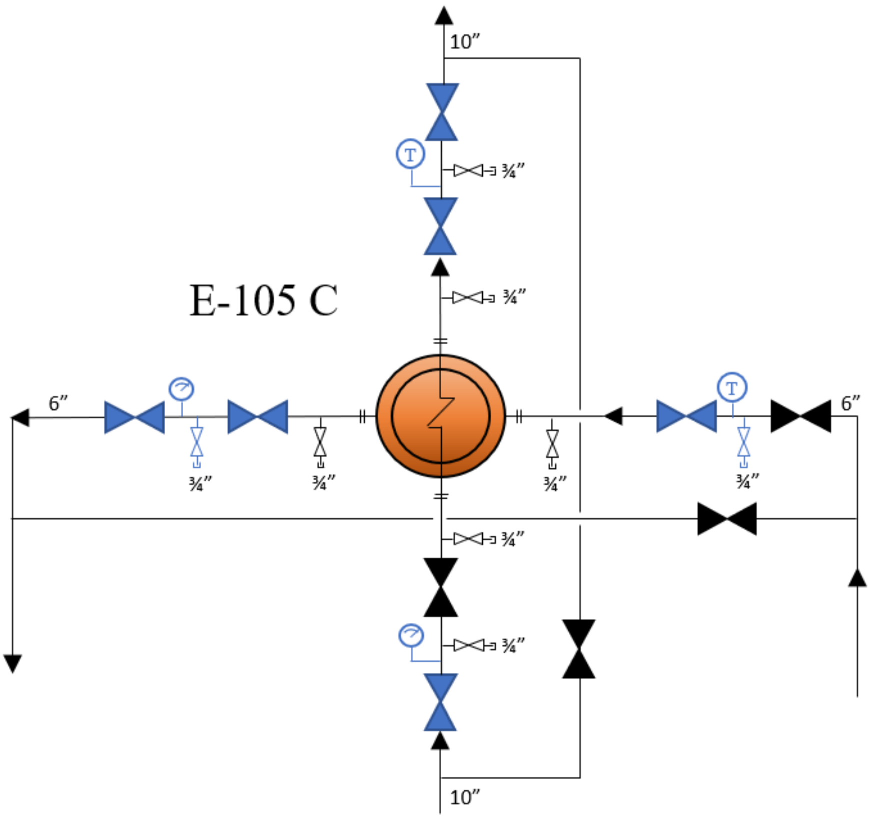


Figure 4.6: Bypass design E-105 C

4.4.2 E-120 AB/CD Bypass Design

The new equipment required for implementing a bypass over E-120 A/B or C/D are presented in table 4.7. Note that if a bypass were to be installed for either E-120 A/B or C/D, a platform above the ground has to be installed. This is due to restricted space in between the heat exchangers and to be able to accommodate for all the new equipment and to maneuver the valves they have to be placed above the ground using a platform. The investment cost for a platform was compensated for using factor f3 for structures and buildings found in table 3.3.

Table 4.7: Equipment required for bypass design E-120 AB/CD

8" Valve	4
6" Valve	5
2" Valve	2
Drainage valve	6
8" Pipe	12 m
6" Pipe	18 m
2" Pipe	30 m
Insulation	21 m^2
Thermometer	1
Online temperature instrument	4
Platform	1

In figure 4.7 the proposed bypass design for E-120 A/B and E-120 C/D can be seen. The equipment shown in blue color is new equipment that needs purchasing and installment and the black equipment are already present on site. The red equipment represents new pipes and valves that needs to be attached to the heat exchanger in order to introduce flush oil. Flush oil is a fluid used at the refinery that has to be introduced to heat exchangers where visbreaker- and thermal residue flows exist before the equipment is taken out of operation. The reason is because if the residue were to stand still inside the heat exchanger and cool down there is high risk of coke formation. Therefore the residue has to be flushed out using the much lighter flush oil fluid before the heat exchanger can be opened up and cleaned. Online temperature sensors should be installed for all the outgoing and ingoing flows to ensure reliable monitoring of the fouling rate in the four heat exchangers.

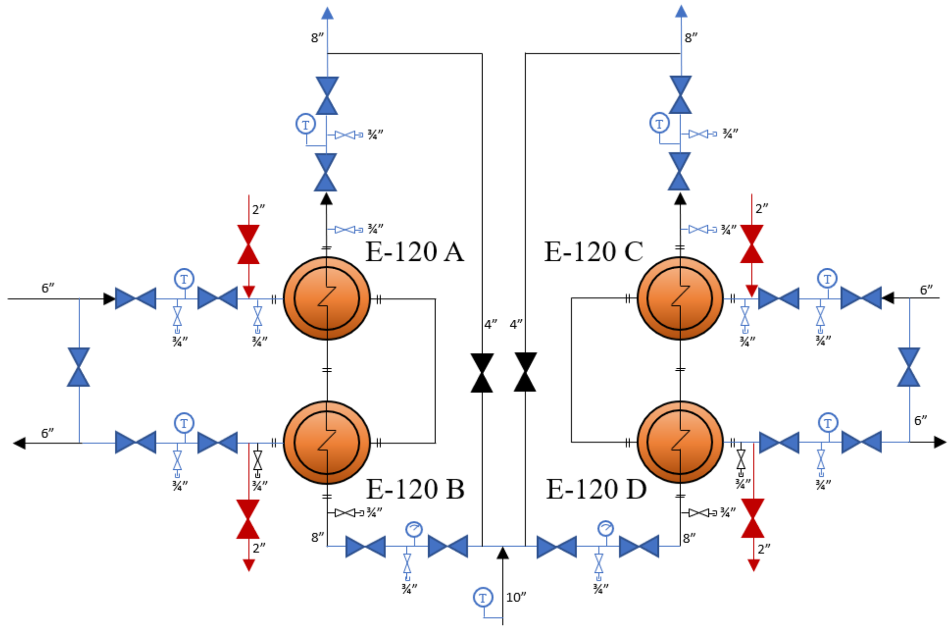


Figure 4.7: Bypass design E-120 A/B/C/D

As the figure shows there are already existing pipes available for bypassing the heat exchangers that can be utilized, however the dimension is half the size of the original pipes which could lead to complications. In table 4.8 the values calculated using equations 3.13 - 3.21 are presented to determine whether the change in pipe dimension will cause issues. It can be seen that the Reynolds number doubles when the pipe diameter is halved which significantly increases turbulence. This could lead to increased vibrations and structural damages to the bypass pipes. In terms of cavitation risk within the pipe, if P_{vapor} for the crude oil is larger than 2 390.29 kPa cavitation would occur. The vapor pressure for crude oil varies depending on the current composition, but the chance of it exceeding P_{min} is very low.

Table 4.8: Flow calculations for change in pipe diameter in E-120 A/B/C/D bypass

Diameter 1 [m]	0.2032
Diameter 2 [m]	0.1016
Mass flow [kg/s]	30.98
Area 1 [m]	0.032
Area 2 [m]	0.008
Density [kg/m^3]	751.7
Viscosity [Pas]	0.0009
Velocity 1 [m/s]	1.27
Velocity 2 [m/s]	5.08
Reynolds number 1	209224.4
Reynolds number 2	418448.8
K_c	0.5625
ΔP_{loss} [Pa]	5462.8
ΔP_{tot} [Pa]	14567.5
Volumetric flow [m^3/s]	0.041
Pump work [W]	600.34
P_{static} [Pa]	2400000
P_{min} [Pa]	2390288.36

4.5 Process Safety Analysis

Process safety analyses are a crucial step when designing and implementing process equipment and should be performed in order to [17]:

- Prevent incidents by identifying potential hazards
- Protect the environment by minimizing toxic contamination
- Ensure safety for personnel and nearby communities
- Follow regulatory safety standards within the industry
- Reducing financial risk

For this project, a "what-if" analysis has been performed and is presented below.

4.5.1 Safety Data

In table 4.9 safety data from SDS:s for the process flows present in heat exchangers E-105 C, E-120 A/B and E-120 C/D are shown to get an understanding of the dangers and risks connected to contamination, exposure and spillage.

Table 4.9: Safety data from SDS:s

Substance	Hazards	Precautions
Crude oil	• Extremely flammable liquid and vapor • Carcinogenic • Fatal if swallowed and enters airways • Serious eye irritation • Drowsiness or dizziness if inhaled • Damage to organs through long or repeated exposure • Toxic to aquatic life • Skin dryness or cracking	• Keep away from heat and ignition sources • No smoking • Wear protective gloves and clothing • Use eye protection • Use in a well-ventilated area • Manage leakages
Heavy gasoil	• Flammable liquid and vapor • Fatal if swallowed and enters airways • Harmful if inhaled • Suspected of causing cancer • Damage to organs through long or repeated exposure • Toxic to aquatic life • Skin irritation	• Keep away from heat and ignition sources • Wear protective gloves and clothing • Use eye protection • Use in a well-ventilated area • Manage leakages • Do not inhale fumes
Residue	• Flammable liquid and vapor • Carcinogenic • Harmful if inhaled • Possibly toxic to reproduction • Damage to organs through long or repeated exposure • Very toxic to aquatic life • Skin dryness or cracking	• Keep away from heat and ignition sources • Wear protective gloves and clothing • Use eye protection • Use in a well-ventilated area • Manage leakages • Do not inhale fumes

4.5.2 What-if Process Safety Analysis

To assess different worst case scenarios that could happen for bypass and heat exchanger equipment, a qualitative "what-if" analysis has been made. It is shown in table 4.10. P stands for probability, S stands for safety, E stands for environment and F stands for financial. A what-if analysis is a useful tool to identify potential risks and hazards, and can improve safety connected to implementing new process equipment [17]. However, the project requires a more thorough process safety assessment and mitigation strategies should be created to prevent accidents as well as ensuring protection against negative environmental impacts and the safety of personnel.

Table 4.10: What-if process safety analysis

Nº	Equipment	What-if	Causes	Consequences	Existing barriers	P	S	E	F	Recommendations
1	Bypass	Leakage during disassembly of heat exchanger	Process stream leakage due to flange leakage, valve leakage or human error	Fire, Injuries, fatalities, shut down, human exposure to toxic substances	Double block and bleed valves, standardized work instructions	3	4	2	4	Gas detection systems, shutdown procedures, fire extinguishing procedures
2	Pipeline	Pressure build-up	Malfunction of valves/pumps, human error	Broken equipment, temporary shut down, leakage, human exposure to toxic substances, fire	Normally closed/open valves and back-up pump	2	4	2	4	Regular maintenance and shut down the process if pressure anomalies occur
3	Pipes	Reduction of the wall thickness	Improper material selection, chemical attack, insufficient coating, lack of monitoring and inspection	Compromise the structural integrity of the equipment	Proper material selection and coatings, regular inspection	2	3	2	2	Corrosion monitoring

Continued on the next page

Table 4.10 Continued from previous page

Nº	Equipment	What-if	Causes	Consequences	Existing barriers	P	S	E	F	Recommendations
4	Heat exchanger	Contamination of the heat exchanger streams	Leaks in the heat exchanger internals (like tubes), poor maintenance	Reduction in heat transfer efficiency altering the consecutive steps of the process, premature equipment failure	Maintenance of the heat exchanger internals	3	2	2	3	Advance monitoring to detect early signs of contamination/leakage
5	Pipes	Damage from hot pipes	Hot surfaces are created by high temperatures	Injuries, fire	Insulation	1	3	2	3	Heat shields to protect personnel
6	Heat exchanger	Heat exchanger internals collapse	Internal corrosion, defective material, poor mantainance	Pipe burst, loss of containment, fire	Regular inspection	1	4	2	4	Include ultrasonic testing in the maintenance procedures

4.5.3 Double Block and Bleed Valves

In figure 4.8 a double block and bleed valve is shown. It is typically used in situations where the fluids are dangerous in different ways and the process safety has to be increased. The configuration enhances safety by creating two isolation barriers and the fluid trapped in the cavity between the barriers bleeds out. The two valves are to be closed to isolate the heat exchanger and between the valves there is a bleed valve that releases the enclosed fluid. With this design the risk of leakage between different pipeline sections is reduced significantly [18]. As an extra tool to minimize the risk of opening the heat exchanger while there are leakages occurring, a thermometer should also be included between the valves to ensure that the temperature decreases between the barriers.

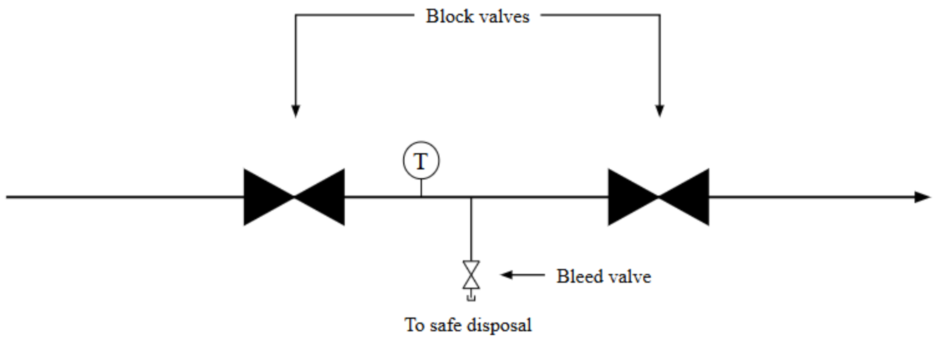


Figure 4.8: Double block and bleed valves

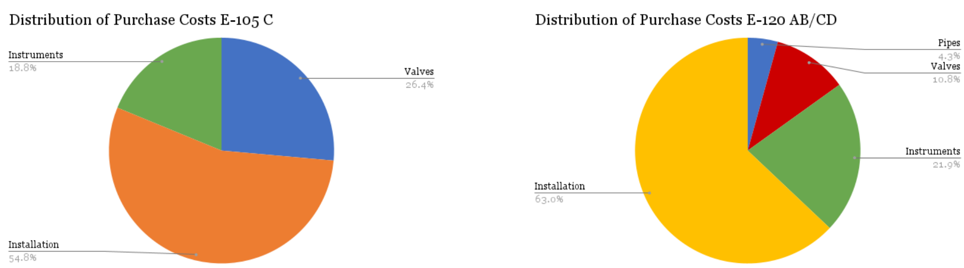
4.6 Economical Evaluation

The economical evaluation results shown in this section for the bypass solutions of heat exchangers E-120 A/B and E-120 C/D are shown together. The reason behind this is due to the fact that the bypass designs are identical for E-120 A/B and E-120 C/D and since it was assumed that the heat losses were divided equally between the four heat exchangers. Therefore the economical feasibility will be identical for both bypass designs. In table 4.11 the purchase prices for different equipment required for the bypass design are shown. The pipe material is carbon steel.

Table 4.11: Purchase costs of bypass equipment

Equipment	Purchase price
6" Pipe design pressure 30 barg	1200 SEK/m
6" Pipe design pressure 8 barg	950 SEK/m
8" Pipe design pressure 30 barg	1100 SEK/m
10" Pipe design pressure 26 barg	1520 SEK/m
4" Pipe design pressure 26 barg	385 SEK/m
2" Pipe design pressure 15 barg	160 SEK/m
1" Pipe design pressure 15 barg	120 SEK/m
4" Valve	6400 SEK
6" Valve	10800 SEK
8" Valve	14400 SEK
10" Valve	19800 SEK
2" Valve	2700 SEK
1" Valve	1500 SEK
3/4" Drain valve	1500 SEK
Thermometer	1042 SEK
Insulation material	330 SEK/m^2
Insulation plate	125 SEK/m^2
Online temperature instrument (including installment)	50000 SEK

In figure 4.9 the distribution of purchase costs for the different bypass designs are shown. For both cases it is the installation costs that constitutes the majority of the total expenses.



(a) E-105 C

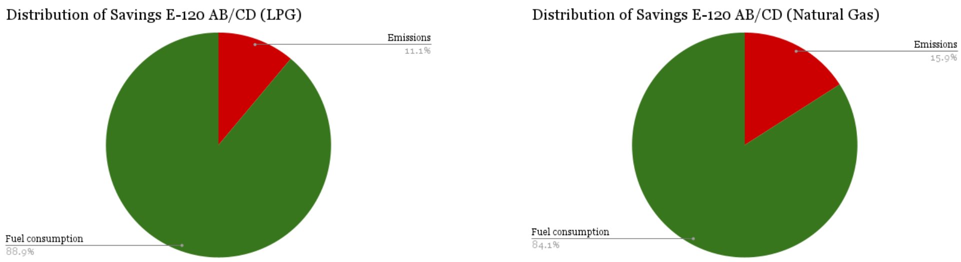
(b) E-120 AB/CD

Figure 4.9: Distribution of purchase costs for E-105 C and E-120 AB/CD bypass

In figure 4.10 and 4.11 the distribution of savings generated by cleaning the heat exchangers are shown for E-105 C and E-120 AB/CD with different fuel scenarios. With these figures it becomes clear that the savings in fuel consumption due to the lowered heat loss over one year are the majority of the total savings per year.

(a) LPG as fuel **(b)** Natural gas as fuel

Figure 4.10: Distribution of savings for E-105 C bypass



(a) LPG as fuel **(b)** Natural gas as fuel

Figure 4.11: Distribution of savings for E-120 AB/CD bypass

In figure 4.12 and 4.13 the distribution of costs linked to the cleaning of heat exchangers during one week are presented. The figures reveals that the major cost in all scenarios is the financial loss due to a reduced crude oil flow of 30 %.

(a) LPG as fuel **(b)** Natural gas as fuel

Figure 4.12: Distribution of costs during cleaning of E-105 C

(a) LPG as fuel **(b)** Natural gas as fuel

Figure 4.13: Distribution of costs during cleaning of E-120 AB/CD

The annual net savings that can be done for bypassing and cleaning E-105 C using LPG or natural gas as fuel i F-101 is 2.1 MSEK and -0.27 MSEK. The annual net savings that can be done for bypassing and cleaning E-120 A/B or C/D using LPG or natural gas as fuel i F-101 is 11 MSEK and 5.2 MSEK.

4.6.1 E-105 C with Different Fuel Options

In figure 4.14 the cumulative cash flow in MSEK is shown over 5 years with the PBP highlighted at 3.28 years for the bypass scenario of E-105 C using LPG as fuel.

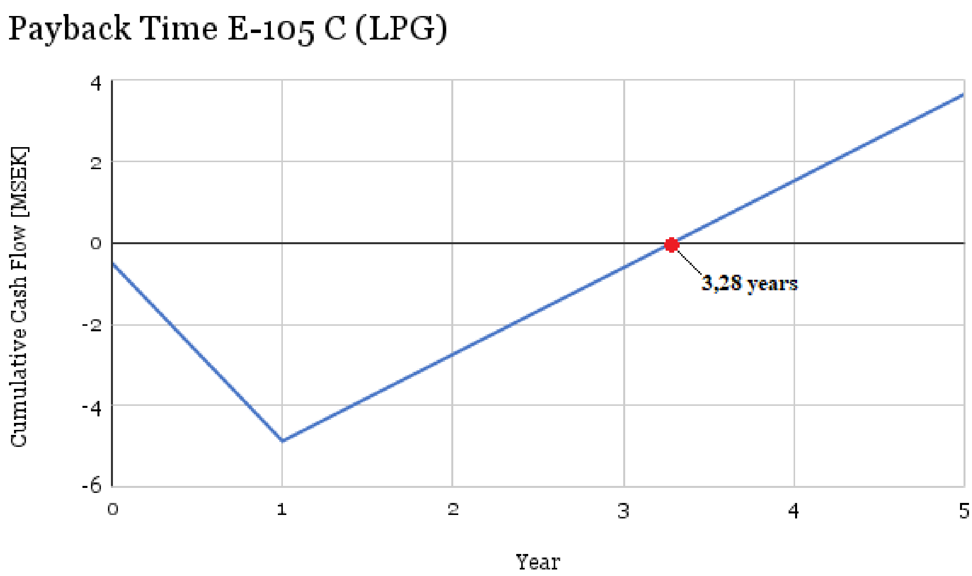


Figure 4.14: PBP for E-105 C bypass with LPG as fuel

In figure 4.15 it can be seen that the total net annual savings are negative for the case of E-105 C bypass using natural gas as fuel. The costs caused by cleaning the heat exchanger are greater than the annual savings, meaning that the investment cost will never be paid off.

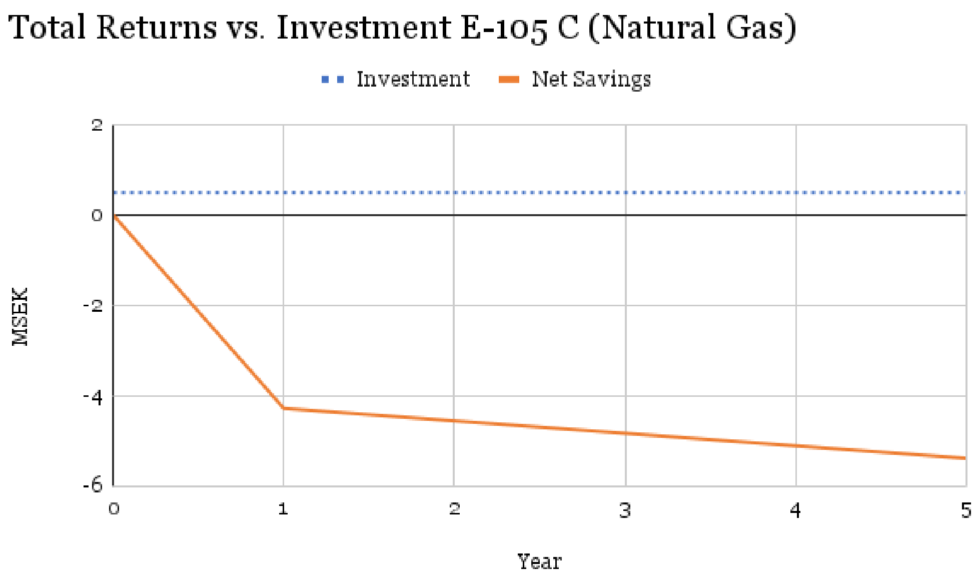
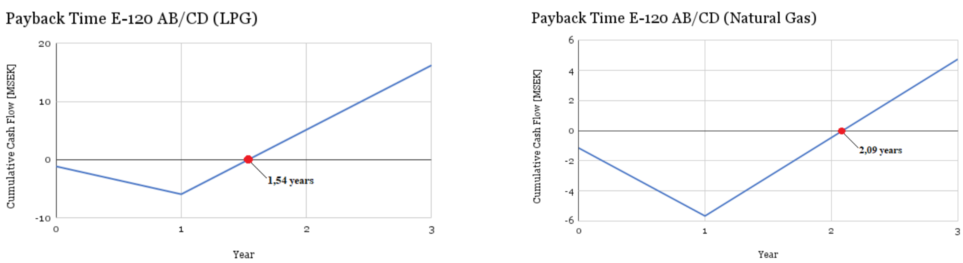


Figure 4.15: Total returns and investment for E-105 C bypass with natural gas as fuel

4.6.2 E-120 AB/CD with Different Fuel Options

In figure 4.16 the cumulative cash flow in MSEK is shown over 3 years with the PBP:s highlighted at 1.54 years for the bypass scenario of E-120 A/B or C/D using LPG as fuel and 2.09 years for the bypass scenario of E-120 A/B or C/D using natural gas as fuel.



(a) LPG as fuel

(b) Natural gas as fuel

Figure 4.16: PBP for E-120 AB/CD bypass with different fuel options

4.7 Sensitivity Analysis

4.7.1 E-105 C All Economic Parameters

In figure 4.17 the calculated PBP:s for the E-105 C bypass using LPG as fuel in a sensitivity analysis where all the economic parameters are fluctuating are shown. It can be seen that the PBP is mostly sensitive to higher values for all economic parameters.

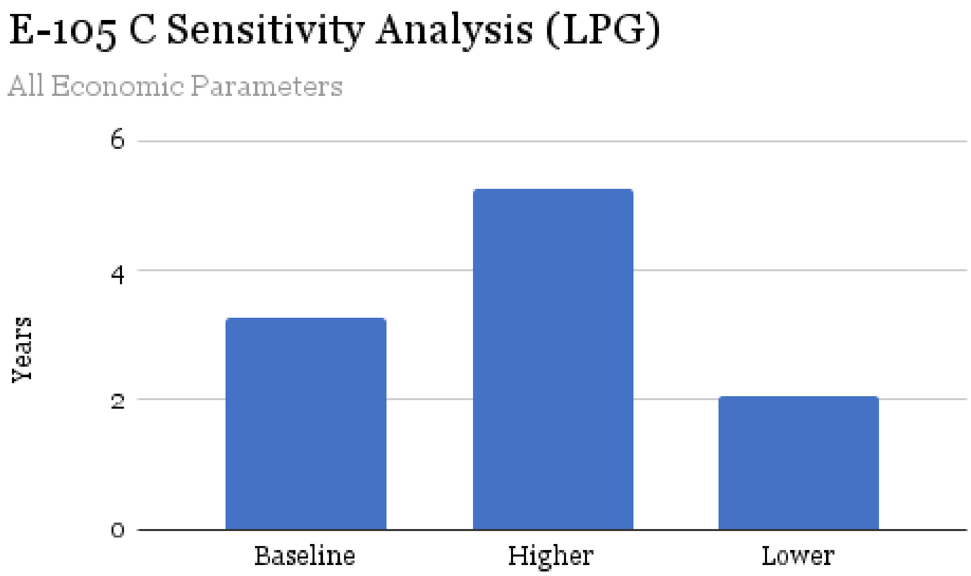
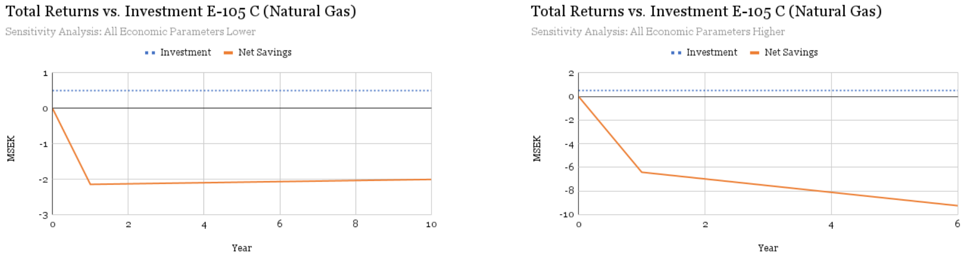


Figure 4.17: Sensitivity analysis for all economic parameters E-105 C bypass with LPG as fuel

Figure 4.18 shows results from the sensitivity analysis where all economic data are fluctuating for E-105 C bypass using natural gas as fuel. It can be seen that the investment is not profitable for either lower or higher economic parameters.



(a) Lower parameters

(b) Higher parameters

Figure 4.18: Sensitivity analysis for all economic parameters E-105 C bypass with natural gas as fuel

4.7.2 E-105 C CO_2 Emission Rights Cost

Figure 4.19 shows the calculated PBP:s for the E-105 C bypass using LPG as fuel in a sensitivity analysis where the emission rights cost varies. It can be seen that the PBP is relatively stable when the cost for emission rights fluctuates.

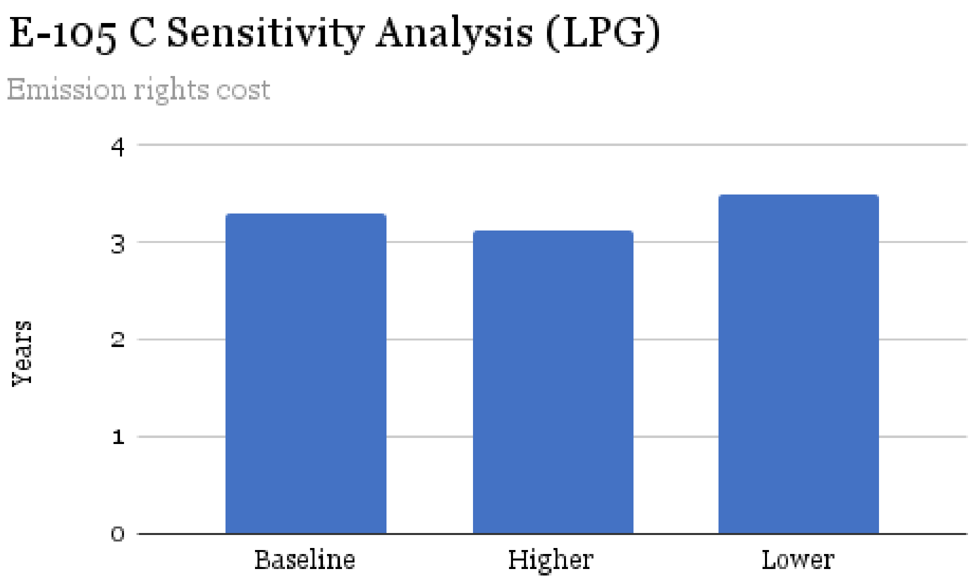
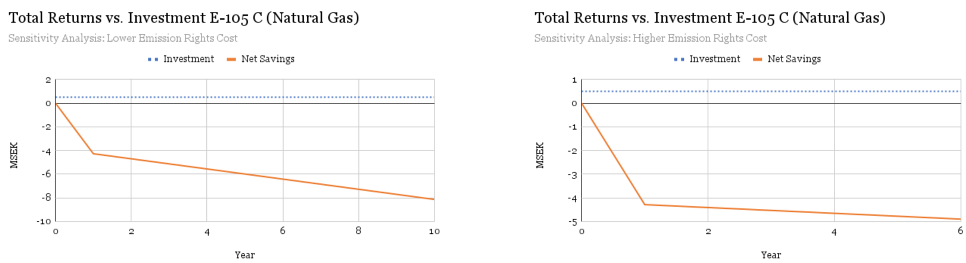


Figure 4.19: Sensitivity analysis for CO_2 emission rights cost E-105 C bypass with LPG as fuel

Figure 4.20 presents results from the sensitivity analysis for variations of the emission rights cost for E-105 C bypass using natural gas as fuel. It can be seen that the investment is not profitable for either lower or higher emission rights cost.



(a) Lower parameters   **(b)** Higher parameters

Figure 4.20: Sensitivity analysis for CO_2 emission rights cost E-105 C bypass with natural gas as fuel

4.7.3 E-105 C Net Profit per Barrel Crude Oil

In figure 4.21 the calculated PBP:s are shown for the E-105 C bypass using LPG as fuel in a sensitivity analysis where the net profit per barrel crude oil varies. It can be seen that the PBP is very sensitive to increasing changes in net profit per barrel crude oil.

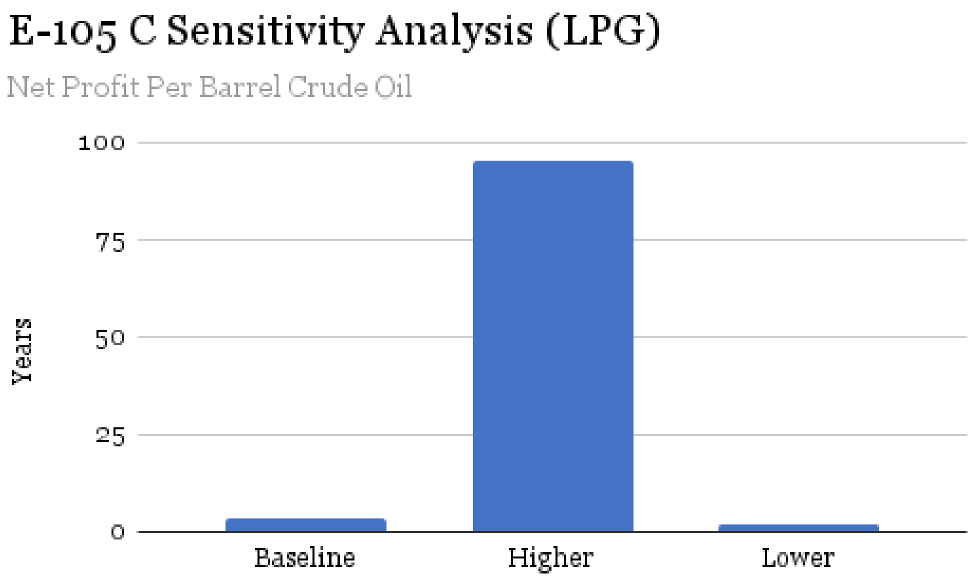
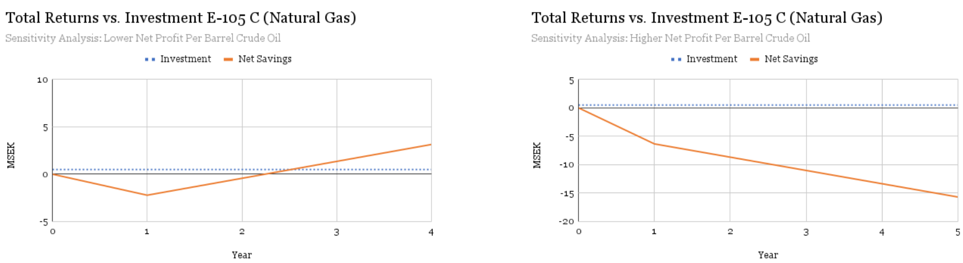


Figure 4.21: Sensitivity analysis for net profit per barrel crude oil E-105 C bypass with LPG as fuel

In figure 4.22 it can be seen that the bypass scenario for E-105 C when using natural gas as fuel becomes profitable if the net profit per barrel crude oil decreases by 50 %.



(a) Lower parameters

(b) Higher parameters

Figure 4.22: Sensitivity analysis for net profit per barrel crude oil E-105 C bypass with natural gas as fuel

4.7.4 E-105 C LPG Price

Figure 4.23 presents the calculated PBP:s for the E-105 C bypass using LPG as fuel in a sensitivity analysis where the LPG price varies. It can be seen that the PBP is sensitive to lower prices for LPG.

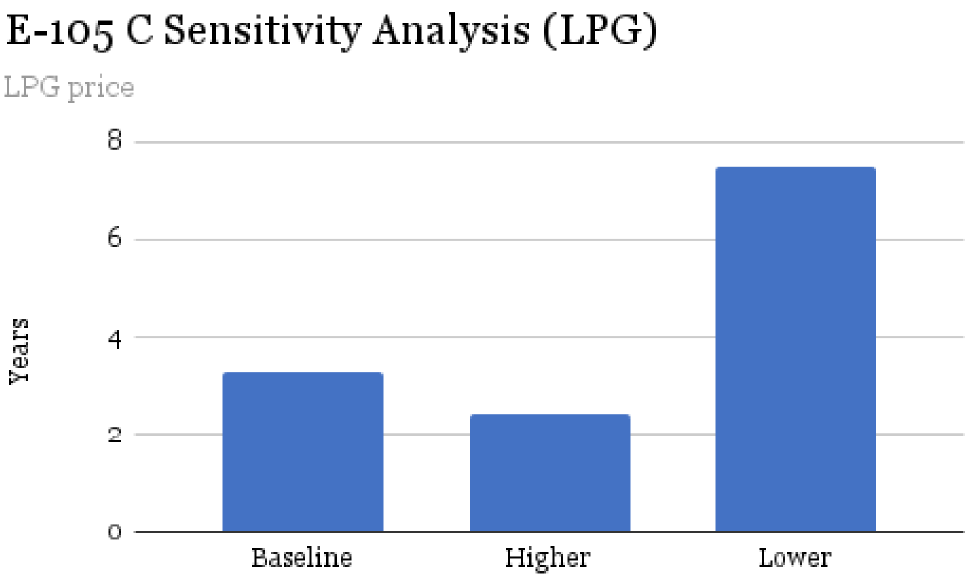


Figure 4.23: Sensitivity analysis for LPG prices E-105 C bypass with LPG as fuel

4.7.5 E-105 C Natural Gas Price

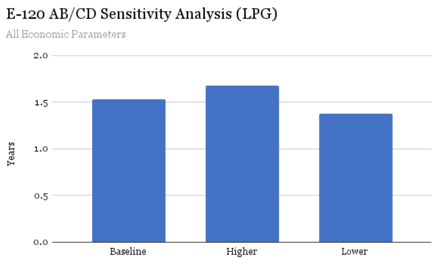
In figure 4.24 it can be seen that the bypass scenario for E-105 C when using natural gas as fuel becomes profitable if the price for natural gas increases by 50 %.

(a) Lower parameters **(b)** Higher parameters

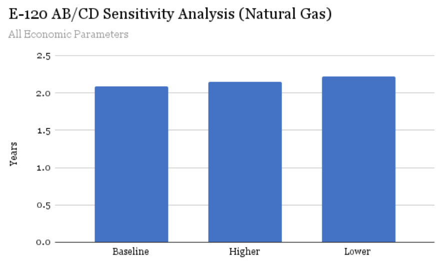
Figure 4.24: Sensitivity analysis for natural gas prices E-105 C bypass with natural gas as fuel

4.7.6 E-120 AB/CD All Economic Parameters

Figure 4.25 shows the calculated PBP:s for the E-120 A/B or C/D bypass using LPG and natural gas as fuel in a sensitivity analysis where all the economic parameters are fluctuating. It can be seen that the PBP barely changes when the economic parameters changes.



(a) LPG as fuel

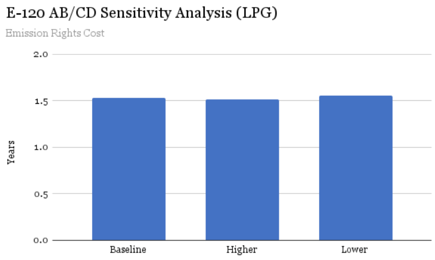


(b) Natural gas as fuel

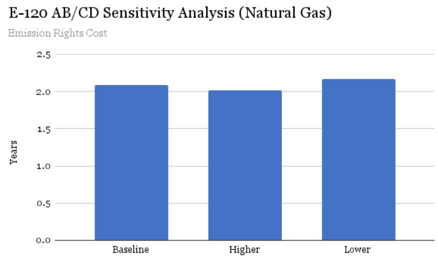
Figure 4.25: Sensitivity analysis for all economic parameters E-120 AB/CD bypass with different fuel options

4.7.7 E-120 AB/CD CO_2 Emission Rights Cost

In figure 4.26 the calculated PBP:s are shown for the E-120 A/B or C/D bypass using LPG and natural gas as fuel in a sensitivity analysis where the emission rights cost fluctuates. It can be seen that the PBP barely changes when the economic parameter changes.



(a) LPG as fuel

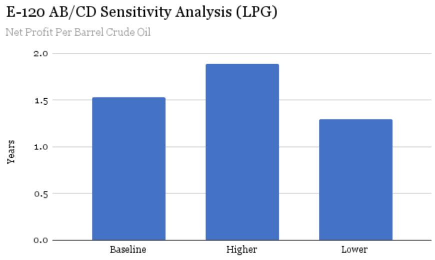


(b) Natural gas as fuel

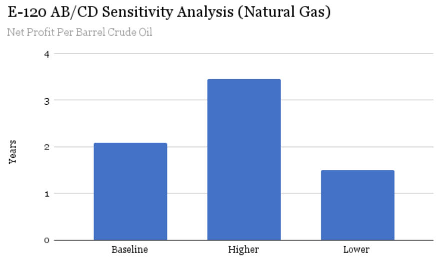
Figure 4.26: Sensitivity analysis for CO_2 emission rights cost E-120 AB/CD bypass with different fuel options

4.7.8 E-120 AB/CD Net Profit per Barrel Crude Oil

In figure 4.27 the calculated PBP:s are shown for the E-120 A/B or C/D bypass using LPG and natural gas as fuel in a sensitivity analysis where the net profit per barrel crude oil fluctuates. It can be seen that the PBP is sensitive to changes in the net profit per barrel crude oil.



(a) LPG as fuel



(b) Natural gas as fuel

Figure 4.27: Sensitivity analysis for net profit per barrel crude oil E-120 AB/CD bypass with different fuel options

4.7.9 E-120 AB/CD LPG Price

In figure 4.28 the calculated PBP:s are shown for the E-120 A/B or C/D bypass using LPG as fuel in a sensitivity analysis where the LPG price fluctuates. It can be seen that the PBP is mostly sensitive to lower LPG prices.

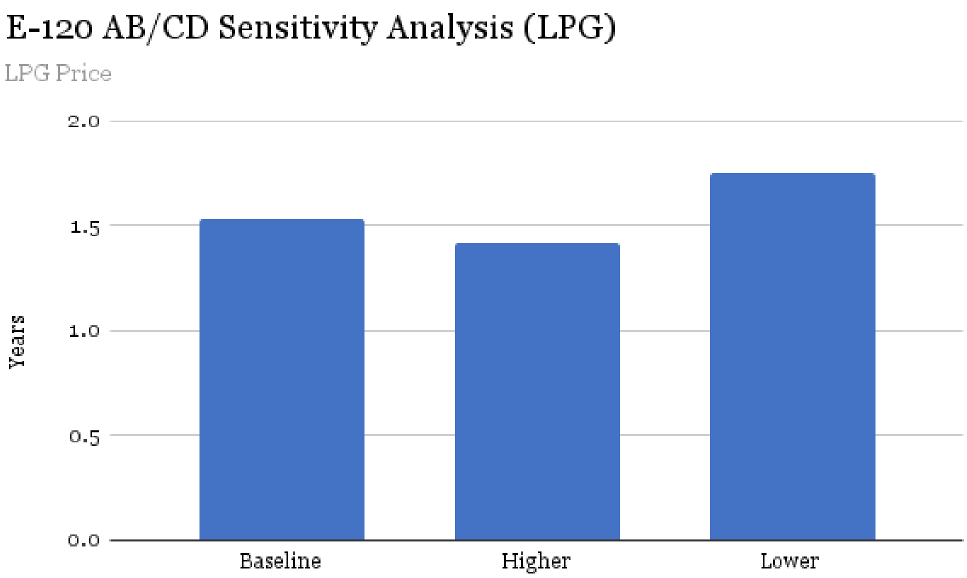


Figure 4.28: Sensitivity analysis for LPG prices E-120 AB/CD bypass with LPG as fuel

4.7.10 E-120 AB/CD Natural Gas Price

In figure 4.29 the calculated PBP:s are shown for the E-120 A/B or C/D bypass using natural gas as fuel in a sensitivity analysis where the price for natural gas fluctuates. It can be seen that the PBP is extremely sensitive to lower natural gas prices.

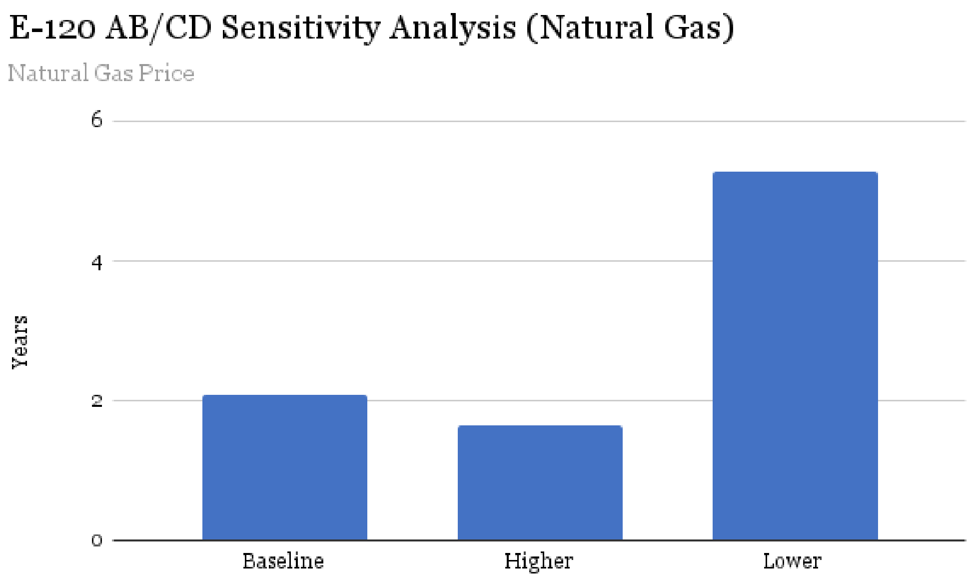


Figure 4.29: Sensitivity analysis for natural gas prices E-120 AB/CD bypass with natural gas as fuel

5

Discussion

5.1 Potential Sources of Errors

Different assumptions made during this project together with uncertainties in the used methods has had an effect on the outcome for the presented results. In this section, the main contributing sources of errors are discussed.

- A delimitation and assumption were made to not consider variations of composition in the crude oil and to assume single-phase flows in all heat exchangers. In reality the mixture of different crude oils varies on a weekly basis and vaporization of the light components in the crude oil occurs within the heat exchangers. This means that the composition of different hydrocarbons will never be constant and the locations in the HEN where vaporization of the lighter hydrocarbons occur will vary over time. This could result in misleading trends when examining the plots for heat transfer since the heat transfer calculation did not include the contributing heat of vaporization. If vaporization suddenly happens in a heat exchanger to a large extent, it can be seen as a decrease in the calculated heat transfer which can be misinterpreted as fouling phenomenon.
- The used physical and chemical data are not 100 % accurate since they are not fully based on laboratory data and the fluid properties will vary over time due to changes in process conditions and product specifications. This will probably not have such a large effect on the results. The main source of error could be when calculating the heat losses using the specific heat capacity values that the financial assessment was based on. The variation in specific heat capacity could lead to smaller or larger recovery of heat done by bypassing and cleaning a heat exchanger which also effects the calculated annual net savings and PBP.
- The level of accuracy in the mass flow and temperature data will also have an effect on the calculated heat transfer which can lead to inaccurate results for heat recovery per year and calculated PBP:s for bypass designs.
- There are other uncertainties when it comes to the economic calculations. It was noticed during the sensitivity analysis that the fuel price had a large impact on the feasibility of the investment. The fuel prices were based on public market data in Sweden but the real prices used for the refinery will be different which will influence the outcome of the financial evaluation. The fuel prices fluctuate frequently and the choice between LPG and natural gas varies on a weekly basis. In the economic calculations only one type of fuel is used which decreases the reliability of the results. In reality there will be a mixture

of different types of fuel used in the furnace.
- A simplification was made for the heat transfer calculations in E-120 A/B/C/D. It was assumed that the transferred heat was the same in each heat exchanger leading to identical results for bypassing E-120 A/B or C/D. This is not the case in reality and the potential net annual savings that can be made with the bypass solutions will differ from each other.

5.2 Reasons behind Fouling Phenomenon

Based on the theory behind different fouling mechanisms, such as crystallization and particulate fouling, it could be expected that high rates of fouling should occur in heat exchangers E-101 A/B, E-107 C/D, E-122 A/B/C/D, E-103 and E-102 since the crude oil is heated before entering the desalter where salts and particles are removed. If more salts and particles are present in the crude oil, there should be a higher chance of fouling occurring. The results showed trends for temperature gradients and transferred heat indicating fouling phenomenon, but the declining tendencies were not repeated for each running cycle and were therefore excluded. Another theory was that fouling could occur in E-106 A/B, E-105 C, E-120 A/B/C/D and E-121 since the crude oil flow is decreased by 10 % after the preflash column, decreasing the velocity, and since the crude oil has higher temperatures in these locations. Fouling behavior was observed in E-105 C and E-120 A/B/C/D, but none were detected in E-106 A/B and E-121. Coke formation fouling were to be expected in the heat exchangers using residue as heating medium, which are E-104, E-106 A/B, E-107 A/B and E-120 A/B/C/D. This theory was only confirmed for the case with E-120 A/B/C/D.

5.3 Consequences of Bypass Scenarios

During the time required for bypassing and cleaning a heat exchanger it was assumed that the flow of crude oil had to be reduced by 30 %. However, cleaning of heat exchanged could be performed at the same time as the burnout of the furnaces in the thermal cracker. The purpose of a burnout is to remove fouling and coke formation that builds up over time in the thermal cracker furnaces and this is usually performed approximately 4 times per year. During this time the total flow of crude oil introduced to the refinery is normally reduced and the operating temperature in the TCU is lowered. Co-scheduling of the heat exchanger cleaning and burnout of the furnaces would clearly improve the economic performance of the heat exchanger cleaning, since the costs due to reduced throughput can be allocated to the furnace burnout.

5.3.1 Bypass of E-120 AB/CD

Figure 2.4 shows the hot process flows present in the heat exchangers E-120 A/B and C/D. Figure 2.2 shows the layout of the HEN. If E-120 A/B or C/D are by-passed the crude oil flow will be colder going in to E-121, affecting the heat transfer between crude oil and circulating middle reflux from C-1302. The crude oil will not be heated to 195^{o}C as it normally would which has to be compensated for by increasing the fuel consumption in F-101 A/B. The outgoing hot temperature from E-121 could become lower than usual since the cold medium will have a lower ingoing temperature, increasing the driving forces for exchange of heat. This could possibly have a negative affect on the distillation process in C-1302 since the temperature of the middle reflux flow changes.

The consequences of bypassing E-120 A/B or C/D for the hot process flows could be as follows. The visbreaker residue flow enters E-107 A/B at an elevated temperature and the thermal residue flow enters E-106 A/B and E-104 at elevated temperatures. This would temporarily change the temperature profiles within the whole system of heat exchangers. The residue flows will later on create a mixture that also have a higher temperature than normal. After the mixing manifold there are several district heating heat exchangers that can be used to cool the mixture further. A small part of the mixture flow is lead to the separators V-1301/V-1302/V-1303 at a higher temperature. The design temperature for the equipment is 450^{o}C which is marginally higher than what the temperature for the residue mixture should be. However, the higher ingoing temperature to the separators could lead to a less efficient termination of the cracking reaction happening, which could lead to coke formation within the TCU. It is recommended to combine the bypassing and cleaning of E-120 A/B/C/D with the burnout of the thermal cracker. By combining these processes the consequences of bypassing E-120 A/B/C/D will be less negative.

5.4 Suggestions for Further Work

Recommendations for further work to implement the proposed bypass solutions for E-120 A/B and E-120 C/D would be to calculate how the strength and durability of the existing pipes and structures will change when installing the bypass. More thorough design and planning has to be done for installing the platform as well, along with more detailed design drawings of the bypass configurations. It is also suggested that a more comprehensive investigation of the consequences of bypassing E-120 A/B and C/D is performed. It was recommended that new temperature sensors should be installed for E-105 C and E-120 A/B/C/D to be able to monitor the fouling rate more accurately. It would be a good idea to install other online temperature instruments within the HEN for future monitoring as well, for example in between E-104 and E-105 B for the crude oil flow. In figure 5.1 all the recommended additional temperature sensors are shown within the HEN as blue temperature instruments.

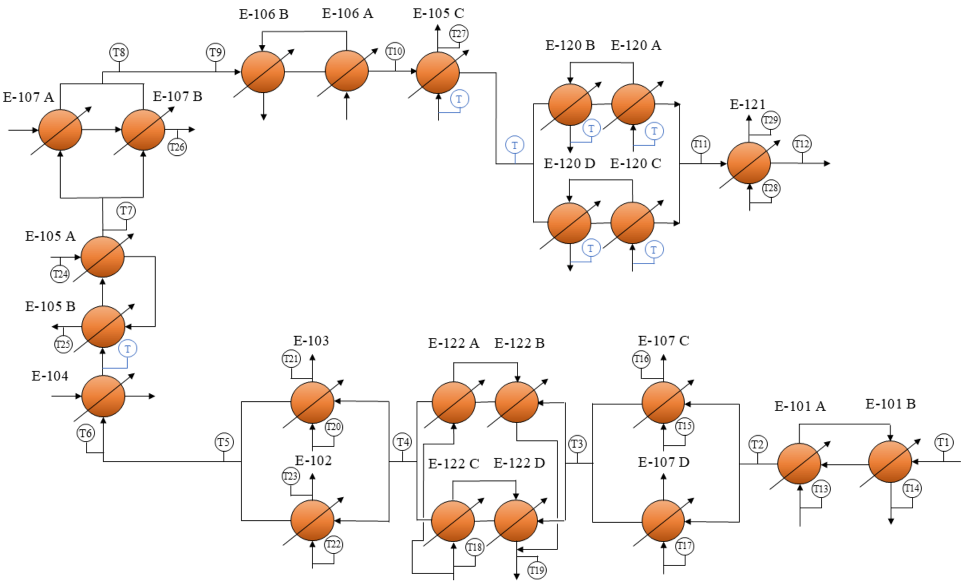


Figure 5.1: A schematic picture of the heat exchanger system with new temperature instruments

Other potential future projects could be to perform a retrofit study of the HEN to increase the heat recovery further. It would also be interesting to investigate different possibilities for online cleaning for heat exchangers, such as shockwave cleaning methods where a precise shockwave with high velocity is used to dislodge deposits and accumulations of dirt on equipment [19].

6
Conclusions

The aim of this project was to evaluate and identify up to three heat exchangers with severe fouling issues within a large system of shell-and-tube heat exchangers. The average heat losses per year due to fouling in the pinpointed heat exchangers were calculated and bypass configurations for cleaning opportunities during operations were suggested. A techno-economic assessment of the proposed bypass designs was performed to determine the feasibility of the investment. The main conclusions for this project were as follows:

- The total heating demand for preheating the crude oil feed in the HEN is 27 066 kW and the total cooling demand is 32 390 kW.
- The heat exchangers experiencing the most fouling within the HEN are E-105 C and E-120 A/B/C/D.
- Fouling appears to occur within the heat exchangers due to elevated temperatures, low fluid velocities and coke formation together with wax deposits on the surfaces.
- It is recommended to implement two bypass solutions, one for E-120 A+B and one for E-120 C+D, to use for cleaning the four heat exchangers once per year.
- For each proposed bypass design an average heat load of 829 kW can be saved every year resulting in annual net savings of 11 MSEK if LPG is the used fuel in F-101, or 5.2 MSEK if natural gas is used.
- The PBP for each bypass solution is 1.52 years or 2.06 years depending on whether LPG or natural gas is used as fuel option.
- The PBP for the recommended bypass solutions are mostly sensitive to changes in fuel prices and the net profit per crude oil.

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A

Appendix 1

A.1 MATLAB script

A MATLAB script used for iteration of two unknown temperatures, Tc_2 and Th_1, in heat exchanger E-105 C and calculation of the effect, Q, in the beginning and end of a running cycle.

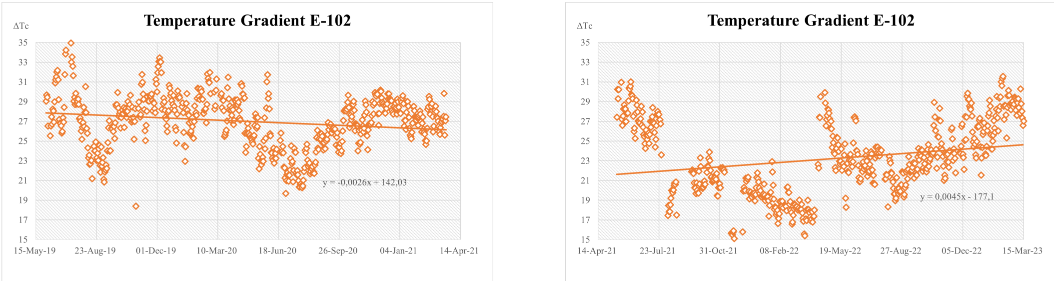
```
%% Beginning of running cycle
mc = (5390.65*1000)/(24*3600); % [kg/s]
mh = (1816.45*1000)/(24*3600); % [kg/s]
Tc1 = 147.5; % [Celcius]
Th2 = 195; % [Celcius]

% While loop to get Tc2 and Th1
Tc2 = 148.5; % initial guess [Celcius]
Th1 = 196; % initial guess [Celcius]
while true
Cpc = (((4.17*10^(-3)*Tc1)+1.83)+
((4.17*10^(-3)*Tc2)+1.83))/2 % [kJ/kgK]
Cph = (((4.25*10^(-3)*206)+1.84)+
((4.25*10^(-3)*234)+1.84))/2 % [kJ/kgK]
Qc = mc*Cpc*(Tc2-Tc1) % [kW]
Qh = mh*Cph*(Th1-Th2) % [kW]

    if Tc2 >= 160
        break;
    if Th1 >= 280
        break;
    if (abs(Qc-Qh)) < 100
        break;
    end
    end
    end
    Tc2=Tc2+0.01;
    Th1=Th1+0.01;
end

Q = (Qc+Qh)/2
```

```
%% End of running cycle
mc = (5448.3*1000)/(24*3600); % [kg/s]
mh = (1812.7*1000)/(24*3600); % [kg/s]
Tc1 = 154; % [Celcius]
Th2 = 227; % [Celcius]

% While loop to get Tc2 and Th1
Tc2 = 155; % initial guess [Celcius]
Th1 = 228; % initial guess [Celcius]
while true
Cpc = (((4.17*10^(-3)*Tc1)+1.83)+
((4.17*10^(-3)*Tc2)+1.83))/2 % [kJ/kgK]
Cph = (((4.25*10^(-3)*206)+1.84)+
((4.25*10^(-3)*234)+1.84))/2 % [kJ/kgK]
Qc = mc*Cpc*(Tc2-Tc1) % [kW]
Qh = mh*Cph*(Th1-Th2) % [kW]


    if Tc2 >= 160
        break;
    if Th1 >= 280
        break;
    if (abs(Qc-Qh)) < 100
        break;
    end
    end
    end
    Tc2=Tc2+0.01;
    Th1=Th1+0.01;
end

Q = (Qc+Qh)/2
```

A.2 Trends for Temperature Gradients and Transferred Heat

A.2.1 Data Analysis for E-102

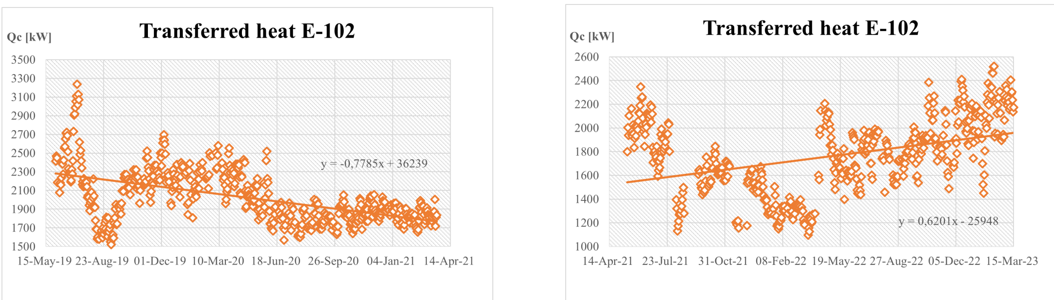
In figure A.1 the changes in temperature gradient over E-102 can be seen for two running cycles. It can be seen that the temperature gradient fluctuates throughout the running cycles, but no clear descending trends can be observed.



(a) 2019-2021 **(b)** 2021-2023

Figure A.1: Temperature gradients over E-102 for two running cycles

In figure A.2 the heat transferred over time in E-102 is shown for two different running cycles. A heat loss of approximately 600 kW can be observed during 2019-2021, but this behavior does not repeat itself during other running cycles.

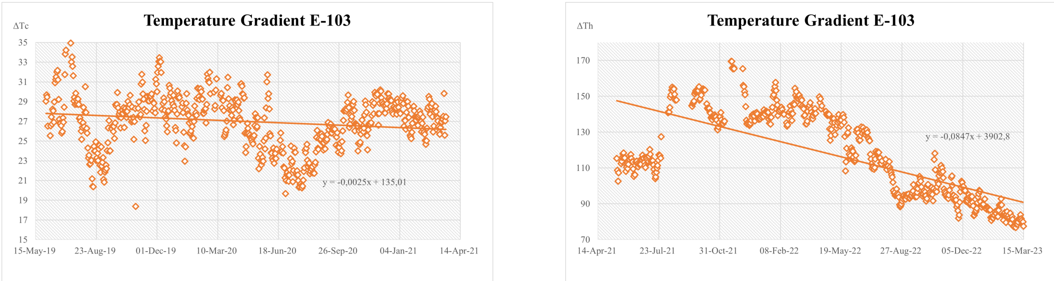


(a) 2019-2021 **(b)** 2021-2023

Figure A.2: E-102 Transferred heat trends for two running cycles

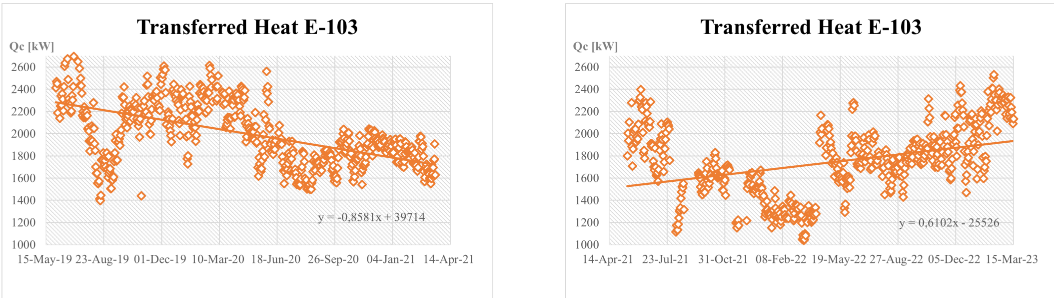
A.2.2 Data Analysis for E-103

In figure A.3 the changes in temperature gradient over E-103 can be seen for two running cycles and in figure A.4 the heat transferred over time in E-103 is shown for two different running cycles as well. In these four plots decreasing tendencies can be observed for both temperature profiles and transferred heat. However, the declining trends are not repeated for all time intervals.



(a) 2019-2021 **(b)** 2021-2023

Figure A.3: Temperature gradients over E-103 for two running cycles

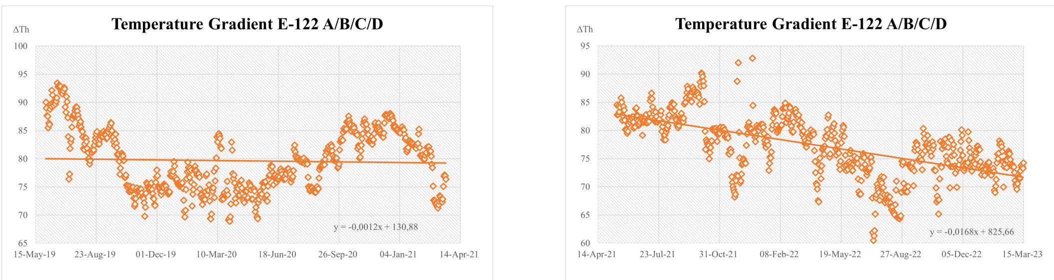


(a) 2019-2021 **(b)** 2021-2023

Figure A.4: E-103 Transferred heat trends for two running cycles

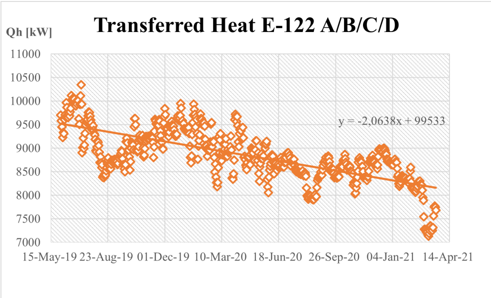
A.2.3 Data Analysis for E-122 A/B/C/D

In figure A.5 the change in temperature gradient over E-122 A/B/C/D can be seen for two running cycles. For these four heat exchangers decreasing trends in temperature gradient are noted but not repeated every time. In figure A.6, where the heat transferred over time in E-122 A/B/C/D is shown for two different running cycles, the same tendencies are found.

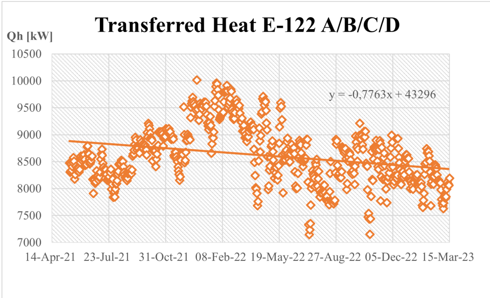


(a) 2019-2021 **(b)** 2021-2023

Figure A.5: Temperature gradients over E-122 A/B/C/D for two running cycles



(a) 2019-2021



(b) 2021-2023

Figure A.6: E-122 A/B/C/D Transferred heat trends for two running cycles

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