EVALUATION OF HEAVY CRUDE OILS PROCESSING WITH ENHANCED HEAT RECOVERY TO OVERCOME CURRENT LIMITATIONS

NIRVANA DELGADO OTÁLVARO

HOCHSCHULE BREMERHAVEN, UNIVERSIDAD EAFIT
ENGINEERING FACULTY
INGOLSTADT
2014

EVALUATION OF HEAVY CRUDE OILS PROCESSING WITH ENHANCED HEAT RECOVERY TO OVERCOME CURRENT LIMITATIONS

NIRVANA DELGADO OTÁLVARO

**For the completion of the study course and honor of:
Bachelor of Science in Sustainable Energy and Environmental Technologies of Bremerhaven University of Applied Sciences and Bachelor of Science in Process Engineering of EAFIT University**

**Advisor:
Prof. Dr -Ing. Wilfried Schütz**

**Co-Advisor:
Dr -Ing. Holger Brust
Santiago Builes, PhD**

**HOCHSCHULE BREMERHAVEN, UNIVERSIDAD EAFIT
ENGINEERING FACULTY
PROCESS ENGINEERING DEPARTMENT
INGOLSTADT
2014**

"Ein Weg entsteht, wenn man ihn geht."
-Chinesische Weisheit.

Acceptation note:

Supervisor

Jury

Jury

,

Abstract

There are two distillation units at the BAYERNOIL facility in Vohburg Germany. One of them processes only light crude oils whereas the other both light and heavy crude oils. The processing capacity of the second is limited by the heater duty which during the last three years and by processing heavy crude oils has often reached the maximal allowed duty. The main subject of this thesis is to evaluate the effect of an enhanced heat recovery capacity, available in the unit that processes only light crude oils by processing heavy crude oils and to determine where or not, the changeover of the distillation units operational mode is a viable option to overcome the current processing capacity limitation.

Processing heavy crude oils in the unit with the enhanced heat recovery achieved an effective decrease on the heater duty of the crude distillation unit. However, the thermal dependency between the crude and the vacuum distillation units, caused an increase in the vacuum unit heater duty and a reduction in the steam generation. This showed that no energetic benefit is accomplished by changing the units operational modes, but rather a shift of the energy requirements in the studied system. Nevertheless, this energy shift reduces in the first instance the heater duty of the crude distillation unit, presenting an option to overcome the current processing capacity limitation by processing heavy crude oils.

Processing heavy crude oils in the unit with the enhanced heat recovery, implies the permanent processing of light crude oils in the other unit. This generates heat losses by the final cool down of the atmospheric residue before it is taken to the storage tanks and presents an argument against a simple changeover of the distillation units operational mode.

CONTENTS

Abstract **i**

page

List of Abbreviations **viii**

Formula Symbols **x**

1 Introduction **1**

2 Theoretical Background **3**

2.1 Heat Transfer . . . 3

2.1.1 Shell and Tube Heat Exchangers . . . 4

2.1.2 Fouling . . . 9

2.1.3 Fired Heaters . . . 12

2.2 Steam generation . . . 13

2.3 Petroleum Refining . . . 14

2.4 Crude Distillation Unit (CDU) . . . 16

2.5 Vacuum Distillation Unit (VDU) . . . 17

3 Units Description and Analysis of the Current State **18**

3.1 Crude Oil Distillation Units at BAYERNOIL . . . 18

3.2 Crude Oil Preheat Train . . . 19

3.2.1 CDU Heater Inlet Temperature and Heater Duty . . . 20

3.2.2 Atmospheric Residue Outlet Temperature from CDU . . . 24

3.3 Fouling of C-1B-107 1/2 (CDU B) . . . 25

3.4 Vacuum Distillation Unit and Steam Generation . . . 26

4 Simulation **30**

4.1 Modeling of the Heat Exchangers C-1A-137 and enlarged C-1A-107 1/2 with Aspen EDR . . . 31

4.2 Simulation Results . . . 31

4.2.1 Simulation 0. Actual State of CDU B . . . 31

4.2.2 Simulation 1. CDU B with the C-1A-137 32
4.2.3 Simulation 2. CDU B with the enlarged C-1A-107 1/2 34
4.2.4 Simulation 3. CDU B with both Exchangers: C-1A-137 and enlarged C-1A-107 1/2 36

5 Test Runs Results Analysis **38**

5.1 CDU Heater Inlet Temperature and Heater Duty 39
5.2 AR outlet Temperature from CDU 42
5.3 Fouling of the C-1B-107 1/2 43
5.4 VDU Heater Duty 46
5.5 Steam Generation in the VDU 48
5.6 Additional Variables considered for the Overall Energy Balance 49
5.6.1 C-1B-132 Heat Flow Rate 49
5.6.2 Stabiliser Energy Consumption 50
5.6.3 Vacuum Residue Outlet Temperature 50
5.6.4 SWD Product Stream Outlet Temperature 50
5.6.5 Additional Product Streams Outlet Temperature 51
5.7 Overall Energy Balance 51

6 Conclusions and Suggestions **55**

BIBLIOGRAPHY **i**

Appendix **iii**

LIST OF TABLES

page

Table 1: Correlations for the calculation of the Nusselt Number (Vette 2014) (E.J. Dittus 1930) 6

Table 2: Correlations for the calculation of C_p 7

Table 3: Thermodynamic Conditions for ES and FS Steam (BAYERNOIL 2006) 14

Table 4: Properties of Light and Heavy Crude Oils 15

Table 5: Equipment for the Petroleum Refining 15

Table 6: Modifications in the Preheat trains 20

Table 7: Units Turnarounds For Cleaning and Technical Inspection. . . . 23

Table 8: Heater Inlet Temperature decrease for the first Six Months after a Unit Turnaround 23

Table 9: Crude Oil type processed in CDU B for the Three Studied Sections 24

Table 10: Actual State of CDU B, important Variables and Simulation Conditions 32

Table 11: Pump Arounds of the atmospheric Distillation Columns 32

Table 12: Mass Flow of Pump Arounds for two Cases of the Simulation . . 34

Table 13: Comparison Actual State of the CDU B and CDU B with enlarged C-1A-107 1/2 35

Table 14: Simulation Results Summary 36

Table 15: Crude Oil Input at maximal Heater Combustion Allowance . . . 37

Table 16: Relevant Data of the analyzed Heavy Crude Oil Batches 38

Table 17: Heater Inlet Temperature and Duty 40

Table 18: Heater Duty and Crude Oil Input 41

Table 19: Heat Losses due to Final Cooling Down of AR (Comparison CDU A and CDU B) 43

Table 20: Heat Losses due to Final Cooling Down of AR (at average AR amount to tank) 43

Table 21: Temperature decrease rate 100 days after each turnaround in CDU B 44

Table 22: Current Fouling factor in C-1A-107 1/2 and C-1B-107 1/2 . . . 45

Table 23: CDU and VDU Heater Duty 46

Table 24: CDU and VDU Heater Duty 48
Table 25: Stabiliser Enery Consumption 50
Table 26: Overall Energy Balance Results Summary 52
Table 27: Combustion Performance Capacity of Fired Heaters (BAYERNOIL 2014b) iii
Table 28: Overall Energy Balance Results Summary iii

LIST OF FIGURES

page

Figure 1: Basic Configuration of a AES Shell and Tubes Heat Exchanger (Sölken 2011) 4

Figure 2: Piping Layout (Modified from (VDI 1997)) 5

Figure 3: Temperature Profiles for parallel and counter flow Heat Exchangers (of Delaware No date given) 8

Figure 4: Correction Factor Charts (NPTEL No date given) 9

Figure 5: Fouling curve (Mueller-Steinhagen 2000) 11

Figure 6: Typical process heater (Baukal 2001) 12

Figure 7: Kettle Boiler (Sölken 2011) 13

Figure 8: Crude Distillation Unit (David S. J. Jones 2006) 16

Figure 9: CDU Heater Duty 18

Figure 10: Heat Exchangers Nomenclature (Example) 19

Figure 11: CDUs Preheat Trains and corresponding Modifications 21

Figure 12: Furnace Inlet Temperature 22

Figure 13: Atmospheric Residue Outlet Temperature 24

Figure 14: Heat Flow Transfer Rate in C-1B-107 1/2 (Fouling Tendency) . 25

Figure 15: CDU and VDU Unit connection 27

Figure 16: VDU Preheat Train, Energy Balance 28

Figure 17: Crude Oil Temperature Profile Comparison: Simulation 0 and 1 33

Figure 18: Atmospheric Residue Bypass 35

Figure 19: Crude Oil Input 39

Figure 20: Heater Inlet Temperature and Bypass around C-1A-107 1/2 . . 40

Figure 21: CDU A Heater Duty 41

Figure 22: Distribution of the Light Crude Oil Atmospheric Residue . . . 42

Figure 23: Changing Frequency of Crude Oil Type 45

Figure 24: VDU Input 48

Figure 25: Steam Generation in the VDU 49

Figure 26: **Reference state CDU B - VDU** 53

Figure 27: **Final state CDU A - VDU** (Test Runs) 54

Figure 28: TEMA Standards iv
Figure 29: Common Types of Baffles (Modified from (Ramesh K. Shah 2003)) v
Figure 30: Temperature Decrease Rate in CDU B 100 days after each turnaround v
Figure 31: Heat Flow Transfer Rate in CA-107 1/2 Heat Exchanger vi
Figure 32: Parent Environment CDU B Simulation vii
Figure 33: Crude Oil Preheat Train, Simulation Sub-Flowsheet Environment viii
Figure 34: VDU, Simulation Sub-Flowsheet Environment ix
Figure 35: CA-107 1/2 EDR Overall Result Summary x
Figure 36: CA-137 EDR Overall Result Summary xi

List of Abbreviations

API	American Petroleum Institute
AR	Atmospheric Residue
approx.	Approximately
avg.	Average
BO	BAYERNOIL Refinery
BORIS	Bayernoil Refinery Information System
BP	British Petroleum
CDU	Crude Oil Distillation Unit
CHD	Catalytic Hydro Desulphuriser
DHT	Distillate Hydro Treater
e.g.	Example given
ENCON	Energy Conservation
FCC	Fluid Catalytic Cracker
HFN	Middle distillate Desulphuriser
HX	Heat Exchanger
ISAR	Initiative for sites safeguarding, plant optimization and profitability increase (translated from german: Initiative zur Standortsicherung, Anlagenverfuegbarkeit und Rentabilitaetssteigerung)

LCO	Light Cycle Oil
LPG	Liquified Petroleum Gas
OZR	Middle pump around (german designation: Oberer Zirkulierender Ruecklauf)
pa	Pump around
P&ID	Piping & Instrumentation Diagram
SWD	Heavy wax distillate (translated from german: Schwer Wax-Destillat)
TAL	Transalpine Pipeline
TEMA	Tubular Exchanger Manufacturers Association
TOP	Upper pump around
TW	Tempered Water
UZR	Bottom pump around (german designation: Unterer Zirkulierender Ruecklauf)
VDU	Vacuum Distillation Unit
VR	Vacuum Residue
VGO	Vacuum Gas Oil

Formula Symbols

$\dot{Q}$	$[\mathrm{W}]$	Heat flow rate
h	$\left[\frac{W}{m^2K}\right]$	Convective heat transfer coefficient
A	$[m^2]$	Heat transfer area
T_s	$[K]$	Solid surface temperature
T_f	$[K]$	Fluid average temperature
q_x	$[W]$	Heat transfer rate in the x direction
k	$\left[\frac{W}{mK}\right]$	Materials thermal conductivity
$\frac{dT}{dx}$	$\left[\frac{K}{m}\right]$	Temperature gradient in the x direction
$\dot{m}$	$\left[\frac{Kg}{s}\right]$	Mass flow
C_p	$\left[\frac{J}{Kgs}\right]$	Specific heat capacity at isobaric conditions
U	$\left[\frac{W}{m^2K}\right]$	Overall heat transfer coefficient
d	$[m]$	Diameter
R_f	$\left[\frac{m^2K}{W}\right]$	Fouling factor
h	$\left[\frac{KJ}{Kg}\right]$	Enthalpy
h_{lv}	$\left[\frac{KJ}{Kg}\right]$	Enthalpy of vaporization
ΔT	$[K]$	Temperature difference

ΔT_{ml}	$[K]$	Logarithmic mean temperature difference
Re	-	Reynolds number
v	$\left[\frac{m}{s}\right]$	Velocity in pipeline
d_h	m	Hydraulic diameter
ρ	$\left[\frac{Kg}{m^3}\right]$	Density
μ	$[Pas]$	Dynamic viscosity
Pr	-	Prandtl number
Nu	-	Nusselt number
ξ	-	Coefficient of adhesion

Subscripts

i	Inner
o	Outer
h	Hot
c	Cold
1	At inlet
2	At outlet

1. Introduction

Crude oil is a complex mixture of hydrocarbons from which many valuable products such as solvents, lubricants and fuels are obtained. The products that can be derived from a crude oil depend mainly on the type of crude. A heavy crude oil is expected to be rich in large hydrocarbons molecules whereas a light crude oil is expected to be richer in smaller molecules from which the light products (LPG/Gasoline) and middle distillates (kerosene, light and heavy heating oil) can be obtained (Favennec 2001).

The first processing equipment found in a refinery is the crude oil distillation unit. In this unit there is a distillation column where the different fractions of the crude are separated. The desalter drum, the crude oil preheat train and a fired heater are also part of the crude oil distillation unit. In the desalter the inorganic salts, water and other contaminants are removed from the crude oil. In the preheat train, the temperature of the crude oil is raised by hot product streams and by the side draws of the distillation column. Then the crude oil enters the fired heater where it is heated up to the required distillation column inlet temperature (Jukic 2013) (David S. J. Jones 2006).

This thesis is developed at the BAYERNOIL Vohburg facility where there are two crude oil distillation units. One of them processes only light crude oils while the other processes light and heavy crude oils. These units were initially designed exactly alike. However, the preheat train of the unit where only light crude oils are processed has been enhanced through the years by adding a new heat exchanger and by enlarging an existing one. These heat exchangers use the high temperature of the atmospheric residue to warm up the crude oil before it enters the heater. This additional available heat transfer area provides the unit a better crude oil preheat capacity and a better heat recovery capacity from the atmospheric residue. Due to a lower preheat capacity, the fired heater of the other unit requires more duty to reach the required distillation column inlet temperature. In the last three years the maximal allowed heater duty has often been reached in this unit by the processing of heavy crude oils. This limits the amount of crude that can be heated and so the unit processing capacity. The main subject of this thesis is thus to evaluate the influence of a more efficient preheating of the crude oil on the heater duty. Test runs are conducted where heavy crude oils are processed in the crude distillation unit with the higher preheating capacity.

The atmospheric residue obtained from the bottoms of the distillation column by the processing of heavy crude oils is further processed in the vacuum distillation unit which generates an important thermal dependency between those units. In the vacuum unit there are three steam generators integrated. The aim of those equipments is to use the high temperatures of the streams in this unit to produce low and middle pressure steam. The processing of heavy crude oils in the crude distillation unit with better heat recovery capacity, represents a colder feedstock of the vacuum distillation unit and thus lower temperature levels of the streams in this unit. This is expected to have an influence on the steam generation and on the combustion duty of the unit's fired heater and is also subject of evaluation in this thesis.

The main objectives of this thesis can be summarized as follows:

- Process heavy crude oils in the unit with the enhanced preheat train and evaluate the effect on the heater combustion duty.
- Evaluate the effect caused on the vacuum unit (heater duty and steam generation) by processing heavy crude oils in the crude distillation unit with a larger heat recovery capacity from the atmospheric residue.
- Determine if processing heavy crude oils in the unit with the enhanced preheat train presents an option to overcome the current processing capacity limitation.

2. Theoretical Background

2.1 Heat Transfer

"Heat is a form of energy upon which the majority of all refinery process are based." (Baukal 2001).

The purpose of this chapter is to review basic theoretical concepts, to provide a short overview of the fundamental equations used to calculate the energy balances and of the general estimations regarding heat transfer. Steady state and mass and energy conservation considerations are made for the calculations in this thesis. There are three principal mechanisms of heat transfer: convection, conduction and radiation. Those mechanisms are all involved at some instance in the refining process. Therefore a short introduction is given in this section.

Convection is the energy transport between two different media caused by fluid motion. This motion can be caused by local density differences or due to mechanical forces. Convective heat transfer is for example the energy transport between the tube surface in a heat exchanger and the fluid within.
The convective heat transfer rate is expressed by equation 1.

$$\dot{Q} = hA(T_f - T_s) \tag{1}$$

Where $\dot{Q}$ is the heat flow rate, A is the transfer area, T_s is the temperature of the solid surface, T_f is the average temperature of the fluid and h is the convective transfer coefficient.

Conduction is the energy transport between molecules of the same media caused by a temperature difference e.g. the heat transport trough the width of a pipe in a heat exchanger. The conductive heat transfer rate is defined by Fourier's law for heat conduction in fluids and solids as shown in equation 2.

$$q_x = kA\frac{dT}{dx} \tag{2}$$

where q_x is the heat transfer rate in the x direction, dT/dx is the temperature gradient in the same direction and k the material thermal conductivity.

Radiation is the emission of energy as electromagnetic waves. In the refining process, radiation can be best seen in a fired heater where the energy is transferred from the flames to walls and tubes.

2.1.1 Shell and Tube Heat Exchangers

Shell and tube heat exchangers are the most common type of heat exchangers in refinery processes because their practical construction enables easy cleaning, maintenance and repair, allowing wide temperature and pressure ranges, phase change and gas and liquid fluids (Ke-fa Cen 2009).

Layout and Construction

TEMA (Tubular Exchanger Manufacturers Association) has developed a basic terminology for heat exchanger types of shell and tube where each exchanger is designated by three letters. The first indicates the front head, the second the type of housing, and the third the rear head. A complete table of the TEMA standards is shown in Appendix figure 28. Figure 1 shows the TEMA configuration AES (One shell pass with a removable floating head and a backing device) the most commonly used configuration in oil refineries (Sölken 2011).

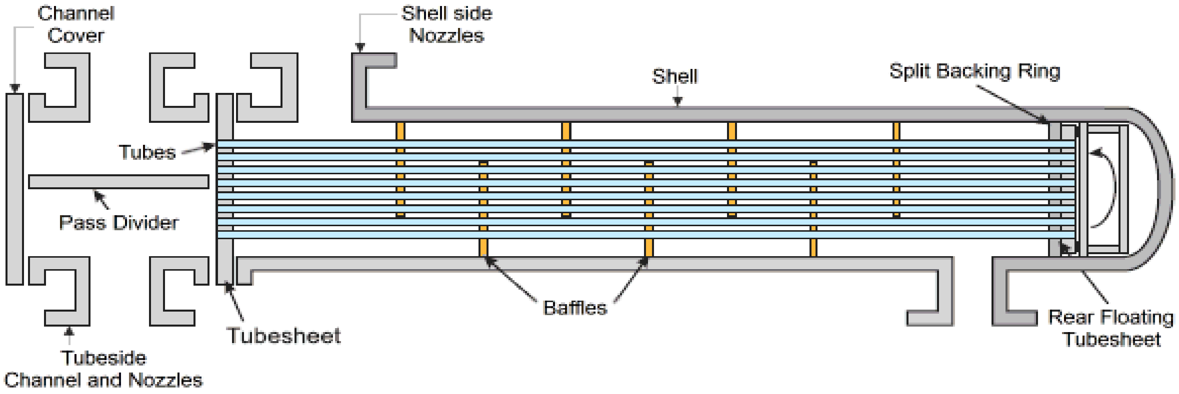


Figure 1: Basic Configuration of a AES Shell and Tubes Heat Exchanger (Sölken 2011)

In shell and tube heat exchangers the heat is transferred between two fluids separated by a wall. Thermodynamics, fluid dynamics, allowable pressure losses and physical and chemical properties of the fluids have to be considered to determine which fluid goes through the tubes and which through the shell. Normally the fluid with corrosive properties is conducted through the tubes to avoid corrosion in the shell side and the fluid with the lower heat transfer coefficient should be conducted through the shell to optimize the heat transfer (VDI 1997).

The geometry of a shell and tube heat exchanger is designed to reach optimal flow rate velocities according to the physical characteristics of the fluids, the spacing and length of the tubes and pressure drop allowances. The arrangement of the pipes is selected to optimize the internal space of the shell. However, the best configuration has to be determined for each case individually. Figure 2 shows three types of piping layout: I: Rotated Squared, II: Squared, III: Triangular with 30° rotation. The triangular arrangement of tubes offers many advantages: the supporting plates are more resistant than in the other arrangements and the turbulence on the shell side is higher increasing the heat transfer rate. However, the triangular layout leads to higher pressure losses and a more difficult mechanical cleaning of the exchanger. The transfer rate in a square arrangement is approx. 1.25 times lower than in the triangular layout but it offers an easier mechanical cleaning (Maria 2013).

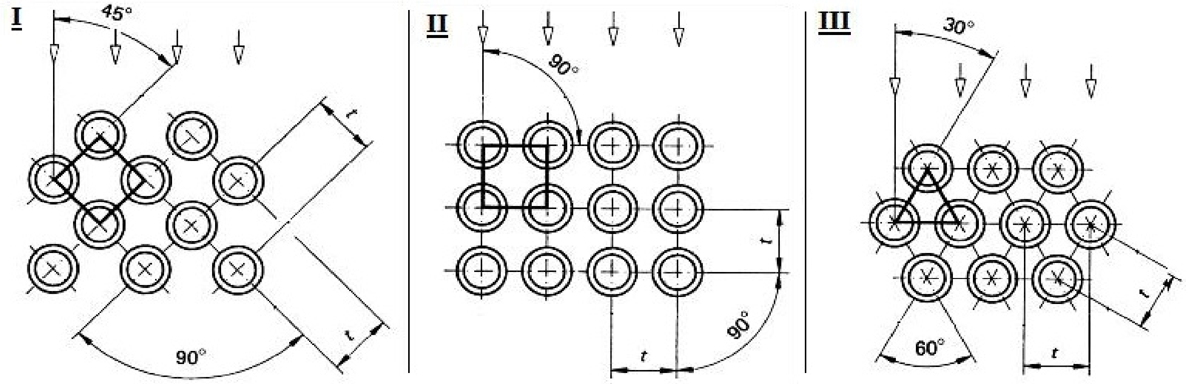


Figure 2: Piping Layout (Modified from (VDI 1997))

Deflection segments, also called support plates or baffles, are arranged in the shell side to establish a cross flow and to induce turbulence on the shell-side fluid. This enhances the heat transfer coefficient and therefor the heat transfer rate. The Baffles support the tubes and minimize fluid-induced vibrations. Single segmental, double segmental, no-tubes-in-window segmental and Disk and doughnut are four common types of Baffles. Those are shown in appendix figure 29 (Chen 1996).

Basic Calculations Methods for the evaluation of heat exchangers

For the study of the single-phase heat transfer in heat exchangers, dimensionless parameters are used. Some of them are described in the following.

The Reynolds number (Re) is a non-dimensional parameter useful for the flow type classification and for many other hydraulic considerations. It is calculated as shown in equation 3 as a function of the velocity in the pipeline (v), the hydraulic diameter (d_h) and the fluid density (ρ) and viscosity (μ). The hydraulic diameter is for circular pipes the normal diameter and for pipes with other geometries, it can be calculated as a function of the cross sectional area and the wetted perimeter (Nam-Trung Nguyen 2009).

$$Re = \frac{vd_h}{\mu} \tag{3}$$

The Prandtl number (Pr) establishes a ratio between heat transfer and flow resistance and it is defined by equation 4 as a function of the fluid dynamic viscosity (μ), the specific heat capacity of the fluid (C_p) and its thermal conductivity (k).

$$Pr = \frac{\mu C_p}{k} \tag{4}$$

The Nusselt number (Nu) is one of the non-dimensional representation of the heat transfer coefficient (h) and it is defined for an internal pipe flow by equation 5.

$$Nu = \frac{hd_h}{k} \tag{5}$$

The Nusselt number is in single-phase forced convection a function of the Reynolds and the Prandtl numbers (mainly dependent on the fluid velocity and viscosity respectively) and is normally calculated through empirical correlations. Table 1 presents three of these correlations and their validity ranges.

	Correlation	Validity Range
Laminar Flow	$Nu = 3.6568$	$Re < 2300$
Gnielinski	$Nu = \frac{(\xi/8)(Re-1000)Pr}{1+12.7\sqrt{\xi/8}(Pr^{2/3}-1)}$ where $\xi = (1.8log(Re) - 1.5)^{-2}$	$2300 < Re < 5.10^6$ ξ:Coefficient of adhesion
Dittus-Boelter	$Nu = 0.023Re^{4/5}Pr^{1/3}$	$Re > 10000$

Table 1: Correlations for the calculation of the Nusselt Number (Vette 2014) (E.J. Dittus 1930)

The simplified steady-flow thermal energy equation (equation 6) describes the sensible heat transfer in moving fluids and is valid for the assumption of incompressible liquids and ideal gases (Incropera 2011).

$$Q = \dot{m} \int_{t_1}^{t_2} C_p(t)dt \tag{6}$$

Where: $\dot{m}$ is the mass flow rate (which can also be expressed in terms of the volume flow and density of the fluid), C_p the specific heat capacity at isobaric conditions expressed as a function of the temperature t, and t_1 and t_2 the fluid temperature at the inlet and outlet of the heat exchanger respectively.

The process modeling program Aspen HYSYS ® is used in this thesis to calculate the heat capacity and other properties of the process streams at different conditions. Mixtures of many crude oil types, origins and compositions are processed in a refinery. A standard basis average composition of each stream (provided by the refinery) is used for the modeling in Aspen HYSYS ®. Temperature-dependent correlations for the calculation of C_p of each mixture were obtained applying linear regression to the simulated data. Table 2 shows the correlations obtained for the crude oil and for the atmospheric residue.

Crude Oil	$C_p = 0.004*T + 1.8943$
Atmospheric Residue	$C_p = 0.0034*T + 1.9884$

Table 2: Correlations for the calculation of C_p

In many practical situation the heat is transferred by a combination of conduction and convection. The heat transfer rate can be estimated by equation 7 where U is the overall heat transfer coefficient and ΔT_{ml} is the logarithmic mean temperature difference.

.

$$Q = UA\Delta T_{ml} \tag{7}$$

The overall heat transfer coefficient based on the outer heat transfer area can be defined as a function of the thermal conductivity of a plane wall (k), the convective transfer coefficient of inner and outer fluids (h_i and h_o respectively) and the inner and outer diameter of the tube (d_i and d_o respectively) as shown in equation 8 (Incropera 2011).

$$\frac{1}{U} = \frac{1}{h_o} + \frac{d_o ln(d_o/d_i)}{2k} + \frac{d_o}{d_i}\frac{1}{h_i} \tag{8}$$

The accurate prediction of the heat transfer coefficient is of great importance for the modeling of heat exchangers. It can also be calculated as a function of the Prandtl, Reynolds and Nusselt numbers using temperature correction factors or estimating it from tables for standard configurations (Incropera 2011). In this thesis the heat exchangers are individually simulated with Aspen HYSYS ® to estimate this coefficient at the defined conditions. For the modeling, the geometry of the heat exchangers is needed along with experimental data of mass flow, temperature, pressure and vapor fraction of the in and outgoing streams. The program calculates a corrected UA factor for the defined conditions. It is important to notice that the heat exchanger performance is affected by fouling, and the calculated data corresponds to a clean state of the apparatus which serves as a reference point and to enable a further analysis of the effect of fouling in the target variables.

The logarithmic mean temperature difference *LMTD*, over the entire length of the heat exchanger ΔT_{ml} is defined as

$$\Delta T_{ml} = \frac{(T_{h1} - T_{c1}) - (T_{h2} - T_{c2})}{ln\frac{(T_{h1}-T_{c1})}{(T_{h2}-T_{c2})}} F_t \tag{9}$$

Where F_t is the temperature correction factor, T is the temperature of the fluid at both ends of the heat exchanger 1 and 2 according to its flow arrangement (see figure 3) and the subscripts c and h represent the cold and hot fluid respectively. figure 3a and 3b illustrate the temperature profiles of two fluids throughout a single pass heat exchanger for both parallel and counter flow configurations respectively. For this configurations the temperature does not have to be corrected and the factor F_t equals 1 (NPTEL No date given).

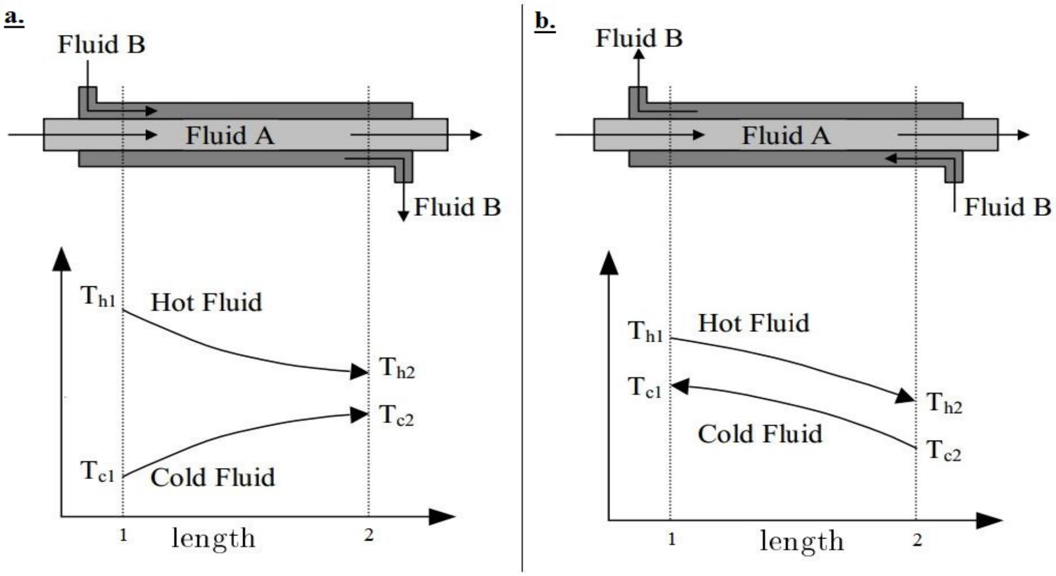


Figure 3: Temperature Profiles for parallel and counter flow Heat Exchangers (of Delaware No date given)

However, for more complex flow conditions such as multipass and cross flow, F_t is calculated using correction charts and the temperature ratios R and P defined in equations 10 and 11 respectively. Correction charts can be found in the literature for many heat exchanger configurations. Figure 4 shows the charts for 1-2 (one shell pass and two tube passes) and 2-4 (two shell passes and four tube passes) heat exchangers.

$$R = \frac{T_1 - T_2}{t_2 - t_1} \tag{10}$$

$$P = \frac{t_2 - t_1}{T_1 - T_2} \tag{11}$$

Where T represents the shell and t the tube temperature and the subscripts 1 and 2 indicate inlet and outlet of the heat exchanger respectively.

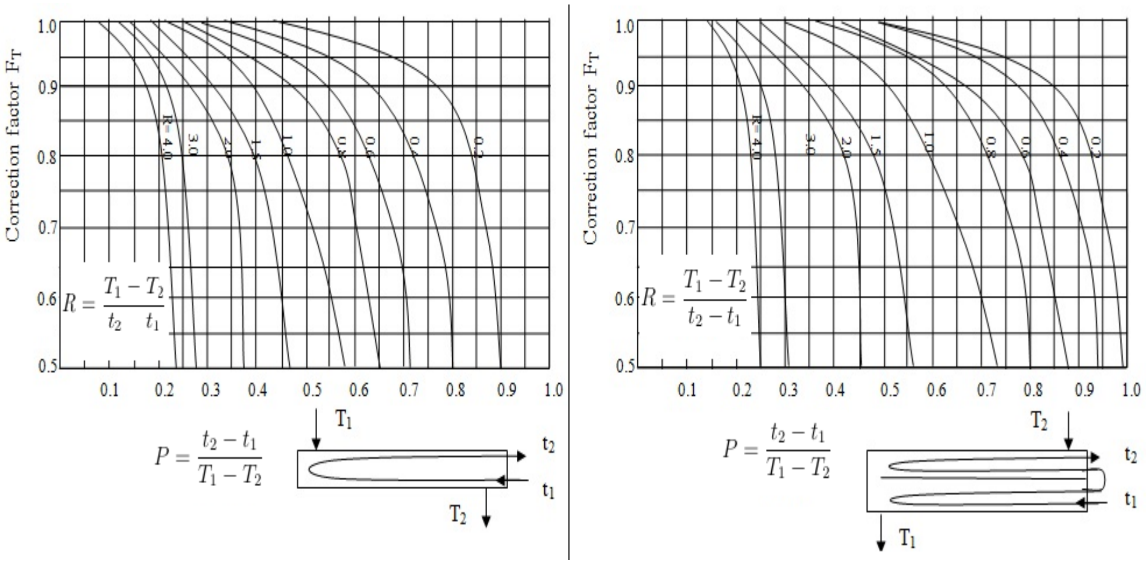


Figure 4: Correction Factor Charts (NPTEL No date given)

2.1.2 Fouling

Fouling is the formation and accumulation of undesired deposits on the surfaces of heat exchangers. The formation of these solid layers generates an additional resistance to the heat transfer process and a thermal efficiency decrease of the fouled unit affecting the whole process profitability. Fouling affects the operating costs not only by generating high maintenance expenses and production interruptions due to regular cleanings but also by requiring additional pumping to recover the great pressure losses. For the applications in which fouling is expected, larger and thus more expensive heat exchangers are designed, increasing the capital expenditure (Awad 2011).

There are several ways to classify the fouling in heat exchangers according to the type of heat exchanger, the industry in which it operates, the type of fluids, etc. The different types of fouling according to its formation mechanisms are ((Awad 2011)):

Particulated Fouling is the accumulation of solid particles suspended in fluids onto the heat transfer surface. These particles can be organic or inorganic and of a wide variety of sizes and shapes. To avoid particulated fouling, the fluid has to be extensively treated to remove the solid contents before it enters the heat exchanger.
Biological Fouling also called *Biofouling* takes place when microorganisms such as bacteria and algae are formed in certain parts of the exchanger, which usually occurs when untreated water is used as fluid in the exchange equipment. Chemical treatment might prevent this form of fouling.
Corrosion Fouling If one of the fluids in the exchanger is corrosive, it might react with the surface of the tubes generating oxide films. The oxidation products can accumulate on the surface of the heat exchanger where they were produced or they can be transported by the fluid to downstream units.
Cristalization Fouling occurs when the salts dissolved in the streams precipitate onto the transfer surface, due to solubility changes caused by evaporation or cooling of the carrier.
Chemical Fouling Undesired chemical reactions like polymerization and cracking may occur during the heat transfer process between reactants contained in the fluid. The products of these reactions accumulate on the surfaces fouling the apparatus. In this fouling mechanism the exchanger surface itself does not react, but it can promote the chemical reaction acting as a catalyst

In the refining processes, fouling is commonly found in heat exchangers as asphaltene deposition, inorganic deposits and corrosion and in the fired heaters of the atmospheric and vacuum distillation units as coke formation. Thus regular shut downs of the units are necessary to restore the efficient operation of the heat exchangers (Wiehe 2008).

The fouling in the units of the refining processes are mainly caused by (List extracted from (Wiehe 2008).):

1. Oil incompatibility on mixing
2. Coke from ever-thermal treating crude oil or residue
3. Insoluble asphaltenes on cooling after conversion
4. Inorganics
5. Polymerization of olefins after thermal conversion
6. Oil-water emulsions.

The additional resistance to the heat transfer generated by the deposits on the wall of the exchanger can be quantified by a fouling factor R_f. As the fouling affects the heat transfer by decreasing the overall heat transfer coefficient, this factor is added to equation 8 to the other thermal resistances resulting in (VDI 1997):

$$\frac{1}{U} = \frac{d_o}{d_i}\left(\frac{1}{h_i} + R_{fi}\right) + \frac{d_o ln(d_o/d_i)}{2k} + \frac{1}{h_o} + R_{fo} \tag{12}$$

Where the new terms in the equation; R_{fi} and R_{fo} are the fouling factors of the inner and outer wall of the tube respectively.

Figure 5 shows four typical fouling curves (Fouling factor R_f vs Time) that represent the behavior of fouling over time. Here t_d is the delay time in which no fouling occurs. This time varies for different processes and equipments and decreases with every cleaning of the exchanger. Linear of fouling (fig. 5a) takes place when the difference between the deposition and removal time is constant or when the deposition time is constant and the removal time is close to zero. In the falling rate fouling (fig. 5b), the deposition rate increases with time but not linearly. In this case the deposition is bigger than the removal time. The asymptotic fouling curve (fig. 5c) represents a case where a steady state and a limit value of deposition is reached and an acceptable operation is possible. The sawtooth line (fig. 5d) is generated when the operating conditions of the apparatus are regularly changed (Mueller-Steinhagen 2000).

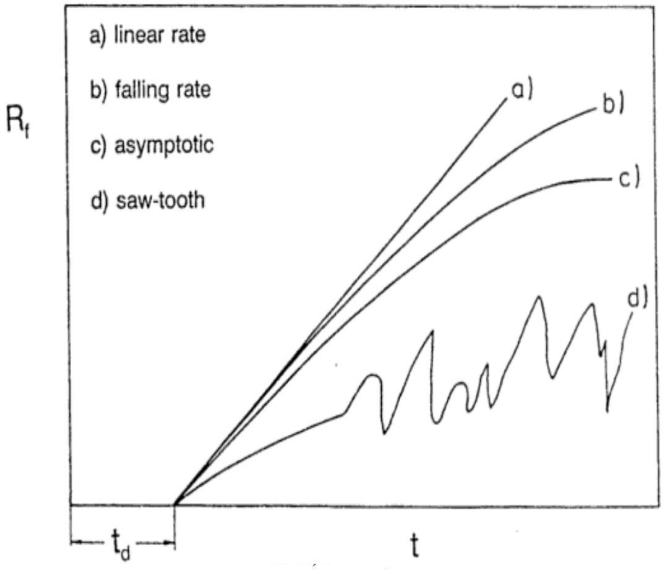


Figure 5: Fouling curve (Mueller-Steinhagen 2000)

2.1.3 Fired Heaters

Fired heaters are direct-fired heat exchangers commonly used in the refining and petrochemical industry to heat up fluids to a predetermined temperature for further processing. Processes like atmospheric and vacuum distillation, thermal cracking, coking, visbreaking or fluidized catalytic cracking require a fired heater to reach the proper feedstock temperature. In a fired heater the fluids flow through a coil of tubes which are direct-fired by burners. These burners are located on the target wall and are fired in the radiant section to heat up the fluids to the desired temperature. Furnaces also have a convection section in which the fluids can be preheated (figure 6). Both the radiant and the convection section are of great importance in the furnace to prevent localized overheating of the fluid which can cause the formation of coke and premature failure of the tubes (Baukal 2001).

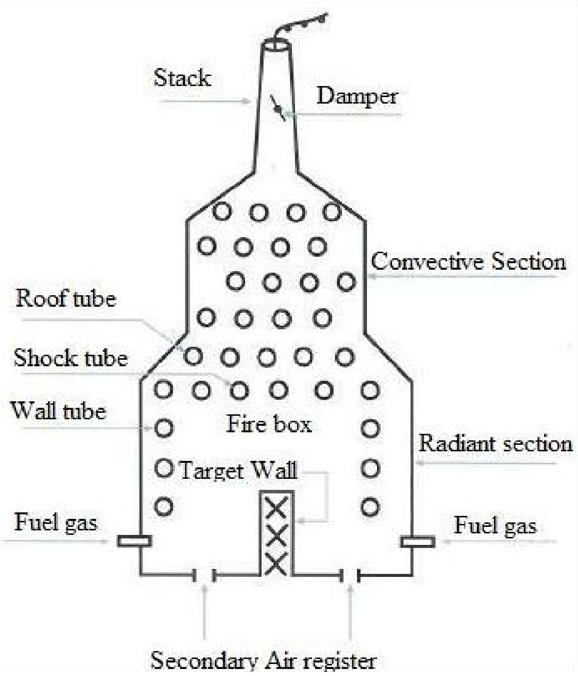


Figure 6: Typical process heater (Baukal 2001)

In the Vohburg facility of BO there are eighteen heaters with a total combustion performance of 232.2 MW (BAYERNOIL 2014b). Of special interest for this thesis are the two crude oil fired heaters B-1A101 and B-1B101 of the two distillation units. These fired heaters are required in the distillation units to accomplish the crude oil final heating to the distillation column inlet temperature also called *transfer temperature*. The fired heaters are provided with 22 burners on the bottom firing vertically upward and have a natural draft which is controlled by a damper flap. The hot ascending gases leaving the furnace generate an unforced flow of air into the heater without any additional mechanical device. Under normal conditions, the heaters of the two distillation units are fired with a combination of fuel and flare gas or with a mixture of top and fuel gas (BAYERNOIL 2001).

2.2 Steam generation

Steam generation systems are designed to use the high temperatures appearing all along the refining processes to increase the energy efficiency. In a steam generator, water is preheated to its boiling temperature and evaporated. The result is the production of saturated steam at different pressure stages which can be used in a wide variety of processes as a heating media or as an energy source (Boege 2007).

Figure 7 shows the heat exchanger TEMA configuration AKT, a kettle boiler. This is a heat exchanger with a horizontal tube bundle at the bottom of an oversized shell which promotes the vapor disengagement from the boiling liquid. The hot fluid flows through the tubes while the vaporizing fluid is on the shell side.

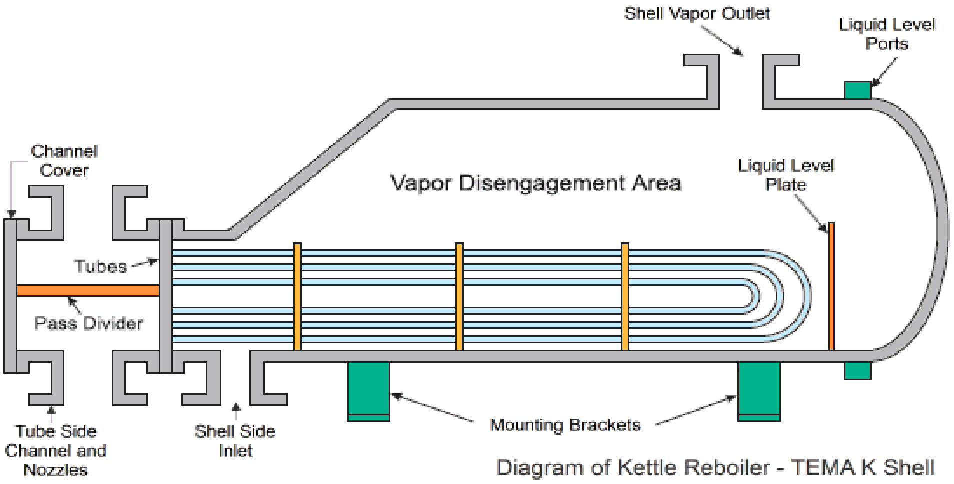


Figure 7: Kettle Boiler (Sölken 2011)

For the energy balance of the steam generators the heat transfer can be rigorously calculated by equation 13 as a function of the amount of water vaporized per unit of time ($\dot{m}$) and the enthalpy difference between the thermodynamic states of the fluid at inlet and outlet of the boiler (Δh).

$$\dot{Q} = \dot{m}\Delta h \tag{13}$$

This equation considers the sensible heat involved in the pre- and overheating of the phase changing fluid and the latent heat of vaporization. This sensible heat transfer takes place in a boiler due to the thermodynamic conditions of the fluid. At the inlet of the apparatus, water is always below the saturation conditions to avoid cavitation in the upstream pumps. At the outlet, the steam is always at least slightly overheated to avoid condensation.

In phase changing fluids, the latent heat accounts for the largest part of the total heat thus the energy flow can be estimated by using the enthalpy of vaporization of the fluid at the specified temperature or pressure (h_{lv}) as shown in equation 14.

$$\dot{Q} = \dot{m} h_{lv} \tag{14}$$

The enthalpy of vaporization (h_{lv}) is reported in the literature for different fluids at several thermodynamic conditions or it can be calculated as the difference between the enthalpy of saturated vapor and saturated liquid.

Steam is used for several industrial purposes and therefore it is available at various thermodynamic conditions. Of interest for this thesis are three steam generators which produce exhausted (ES) and fire steam (FS).

Steam type	Abs. Pressure bar	Temperature °C	Enthalpy KJ/Kg	Entropy KJ/(Kg K)
ES: Exhausted steam	5	165	2778.9	6.892
FS: Fire steam	8	175	2780.0	6.688

Table 3: Thermodynamic Conditions for ES and FS Steam (BAYERNOIL 2006)

At BAYERNOIL ES-Steam is mainly used as a stripping steam, tank heating media and for the so called *heat tracing* (heating of pipelines). This steam is produced in the generators using hot product streams. In some cases this low pressure steam is also used as energy source for reboilers with low temperature requirement. The FS is mainly used for heating tanks with higher temperature level requirement, and for the atomization of the flare gas in the atmospheric distillation furnace. The temperature of this steam (175 °C - 180 °C) makes it more useful as a reboiler heat source.

2.3 Petroleum Refining

Crude oil is a complex mixture of hydrocarbons which also has traces of Water, Salts, Metals (Iron, Vanadium, Nickel, etc), Sulfur, Nitrogen and other compounds (BAYERNOIL 2014b). Crude Oil is obtained from many places in the world and has highly variable chemical and physical properties. The fraction of pure components also varies widely from one crude to another; the gasoline fraction for instance, varies from 37%vol in a Qatar crude to 4.5%vol in a Boscan one. Many valuable products such as solvents, lubricants and fuels are obtained from the crude oil and even asphalt which was seen for many years as a residue, has become a significant product for paving and roofing purposes (Wauquier 1994) (James G. Speight 2001).

There are several ways to classify the crude according to its chemical and physical properties. One of the most widely-used classification is based on the American Petroleum Institute (API) Gravity. This property delivers a comparison between the crude oil relative gravity against water. According to the API Gravity a crude oil is classified as *heavy* or as *light* (heavier or lighter than water) if its API number is greater or smaller than 10 respectively. A heavy crude oil is expected to be rich in large hydrocarbons molecules and very viscous whereas the light crude oil is expected to be richer in smaller molecules from which the light and middle distillates are obtained (Favennec 2001). Table 4 shows some properties of a typical light and heavy crude oil.

	Density (kg/m3)	Sulfur Content (%)	Residue Percentage (%)
Light Crude Oil	808	0.09	29.74
Heavy Crude Oil	890	2.47	52.30

Table 4: Properties of Light and Heavy Crude Oils

The principal process steps in a refinery can be summed up in Separation (Processes that divide crude oil into different fractions), Conversion (Processes that convert heavy fractions into light fractions), Refinement (Processes that upgrade the fractions) and Desulfurization processes. For these operations the equipments listed in table 5 are used.

Separation	Conversion	Refinement
Atmospheric Distillation Unit	Reformer	Hydrofiner
Vacuum Distillation Unit	Catalytic Cracking Unit	Hydrotreater
LPG Separation Unit	Hydrocracker	Claus Unit
Deisopentanizer	Visbreaker	
	Cocker	

Table 5: Equipment for the Petroleum Refining

2.4 Crude Distillation Unit (CDU)

The crude oil distillation unit (CDU) is the first processing unit in an oil refinery. In the distillation column the hydrocarbon compounds contained in the crude oil are separated into various fractions according to their boiling temperatures. The desalter drum, the crude oil preheat train and a fired heater are also part of the crude distillation unit. In the desalter the inorganic salts, water and other contaminants are removed from the crude oil by means of electrostatic precipitationion. In the preheat train the crude is preheated by exchange with the side draws of the distillation column and the product streams. A final heating takes place in a fired heater to achieve the required distillation column inlet temperature. Figure 8 presents a schematic flow diagram of an atmospheric crude distillation unit (Jukic 2013) (David S. J. Jones 2006).

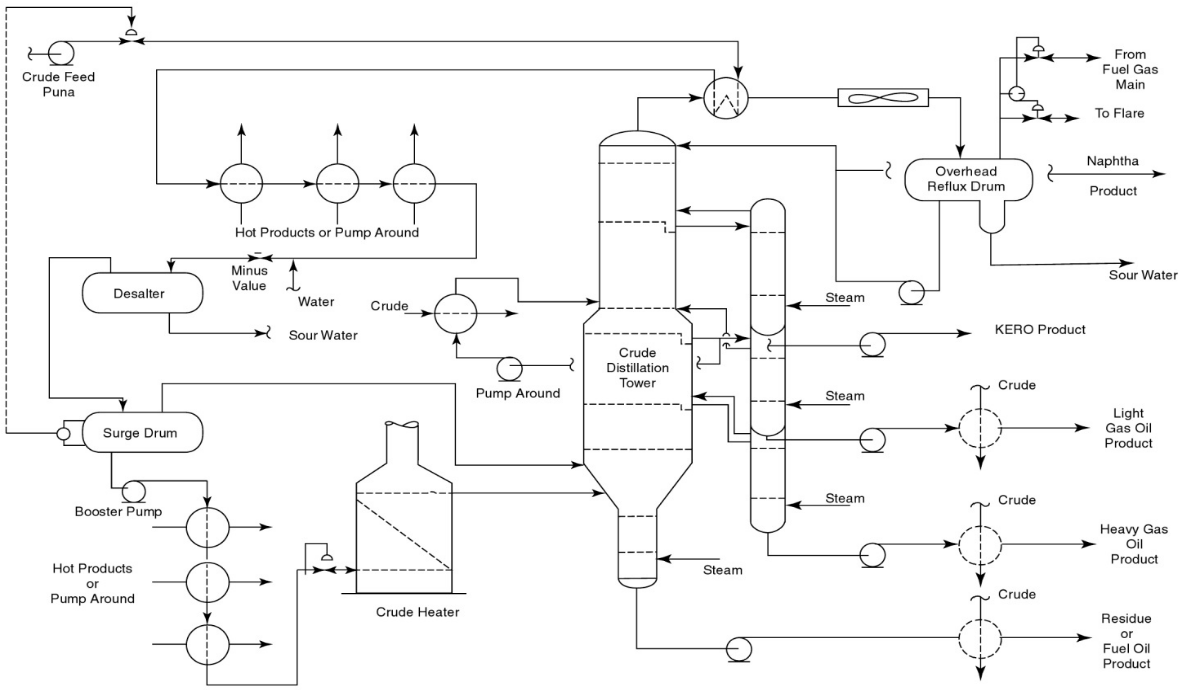


Figure 8: Crude Distillation Unit (David S. J. Jones 2006)

In the oil industry, fractional distillation is performed to obtain fuels from the crude oil. The desired products of the atmospheric distillation are taken off continuously at different heights of the tower according to the trays temperature. This temperature corresponds to the boiling temperature of the specific fraction removed from that tray. Because of this, a constant temperature profile within the tower must be ensured by generating a heat balance between the top and the bottom of the column. A so called ”pump around” is an internal condenser often used to establish this gradient, by returning cooled down refluxes at different heights of the column. This is also conducted to provide better fractionating conditions and to acquire higher concentrations of each fraction along the distillation tower (Ramsden 2000).

From the distillation column the top products (LPG/Benzin), middle distillates (kerosene, light and heavy heating oil) and atmospheric residue are obtained. The different cuts of hydrocarbons taken out are the result of primary separation and undergo further processing before being transformed to end products (ENGGcyclopedia 2011).

2.5 Vacuum Distillation Unit (VDU)

The heavy hydrocarbon residue obtained from the bottom of the atmospheric distillation tower is sent to the vacuum distillation unit (VDU) for further separation under vacuum pressure. This prevents undesired thermal cracking and allows the fractionation of heavy products whose boiling temperatures would be too high at atmospheric pressure. The vacuum pressure lowers the boiling temperature of the individual atmospheric residue components allowing a greater recovery of light fractions. The main products obtained from the vacuum distillation are gas oils, which are transferred to the catalytic cracker; lubricants, which are the feedstock of the Hydrotreater; and the vacuum residue, which has to be further processed in a Deasphalter, Visbreaker, Coker or a Bitumen Plant (OSHA 1999).

3. Units Description and Analysis of the Current State

At BAYERNOIL in Vohburg Germany there are two crude distillation units called CDU A and CDU B. The fired heaters of both units have a maximal allowed combustion capacity of 61,40 MW (BAYERNOIL 2014a). In the previous three years, this boundary has often been reached in CDU B while processing heavy crude oils (figure 9).

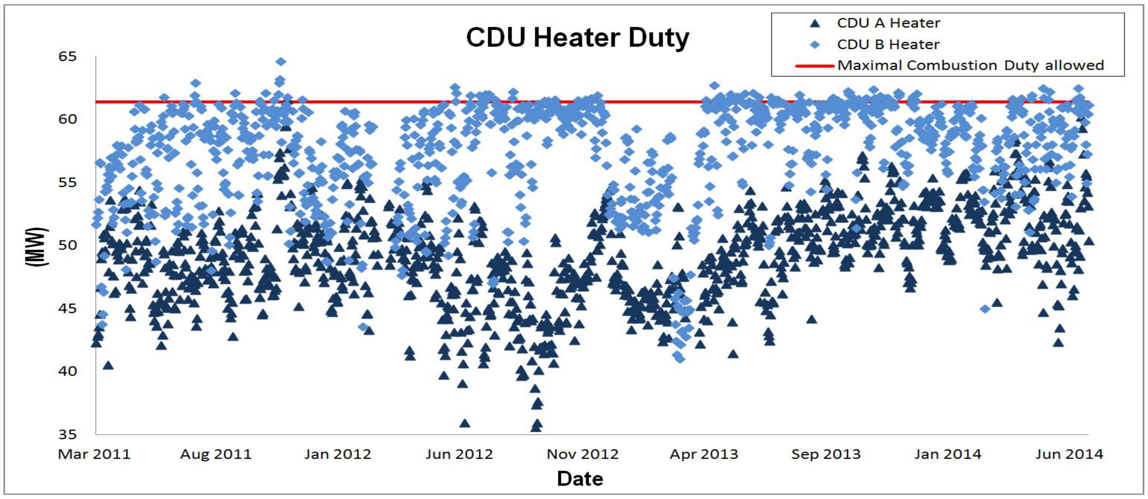


Figure 9: CDU Heater Duty

The findings presented in this thesis are based on test runs where the crude oil type processed in the two distillation units is switched. The aim of this changeover is the evaluation of the better heat recovery configuration of CDU A by the operational mode of CDU B. The aim of this chapter is the description and analysis of the current state in both distillation units, the justification of these test runs and the settlement of the target variables for the evaluation of the tests results.

3.1 Crude Oil Distillation Units at BAYERNOIL

There are two main differences between the two distillation units in the Vohburg site. The first one is the operational mode. Throughout the years, only light crude oils have been distilled in CDU A whereas in CDU B both heavy and light crude oils have been distilled. In the crude distillation unit, the crude oil undergoes a preheating to reach the transfer temperature to the atmospheric distillation column, which is approx. 350 °C - 370 °C in both units (BAYERNOIL 2014b). Heat from the column side draws, pump arounds and other high temperature process streams is recovered, and a final heating takes place in a fired heater. Originally, both distillations units CDU A and CDU B were exactly alike. However some modifications were made over the years in the preheat trains. This is the second factor which distinguishes the two units and will be further discussed.

3.2 Crude Oil Preheat Train

At BO a set of nine heat exchangers composes the preheat train of the crude oil in both distillation units. The name of those heat exchangers is composed of three portions e.g. figure 10. The first section indicates the apparatus and the process unit where it belongs, the second section is composed by three numbers which are the individual designation of the exchanger and the last portion indicates the number of shells of the heat exchanger (when more than one). The shells configuration in series or parallel is not specified in the nomenclature.

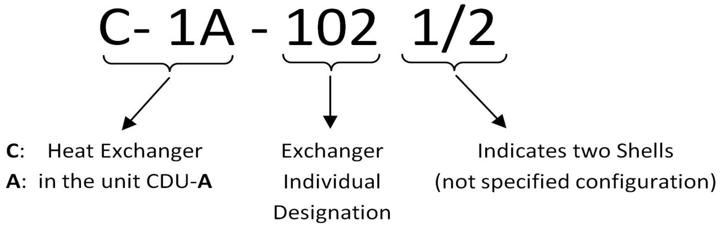


Figure 10: Heat Exchangers Nomenclature (Example)

For heat integration purposes, these heat exchangers use the high temperature of process streams to heat up the crude oil before it enters the fired heater. As a part of ENCON (Energy conservation) projects, the preheat train of both units suffered modifications through the years. Some of these were commonly conducted and some other were conducted according to the conditions generated by each of the operational modes of the units. A summary of all the changes regarding heat transfer are listed in table 6 and the individual modifications are subsequently described.

As shown in table 4 the light crude oils which are mainly distilled in CDU A, have a lower percentage of residue than the heavy crude oils. The atmospheric residue (AR) from light crude oils is used as the FCC (Fluid Catalytic Cracker) feedstock, but the main percentage of this residue (average of the last five years: 48 % (BAYERNOIL 2014b)) is first stored in tanks. To maximize the heat recovery from the atmospheric residue before it is taken to the storage tanks, the preheat train of CDU A was enhanced by adding the heat exchanger C-1A-137 and by enlarging the C-1A-107 A/B. These heat exchangers use the high temperature of the AR to warm up the crude oil before it enters the heater and provide the CDU A a better crude oil preheat capacity and a better heat recover capacity from AR. As the residue from heavy crude oils (which are only

	CDU A	CDU B
C-131	NEW Constructed Area: 315 m^2	NEW Constructed Area: 315 m^2
C-103-1/2	Enlarged Area: 220 m^2	Enlarged Area: 220 m^2
C-1A-137	New Constructed Area: 332 m^2	NA*
C-107-1/2	Enlarged Area: 622.7 m^2	(Unchanged) Area: 316 m^2
C-1B-132	NA*	New Constructed Area: 265 m^2

*NA: Not available in the unit

Table 6: Modifications in the Preheat trains

distilled in the CDU B) is directly taken to the VDU for further processing, it was not necessary to enhance the heat recover capacity on the AR line in the CDU B. In this unit, a connection between the CDU B and the VDU was created by the addition of the heat exchanger C-1B-132 which cools down a VDU product stream by warming up the crude oil. Figure 11 shows an overview of the two CDUs. In this figure, the blue colored heat exchangers underwent modifications as a part of the ENCON project. The specific change of each apparatus is also specified in this figure under its name as ”NEW” when the exchanger was constructed as a part of the project or as ”ENLARGED” when the heat transfer area of an existing apparatus was extended. The stabilisers shown in this diagrams are part of the distillate hydro treating units (DHT). However they are also integrated in the CDUs since the atmospheric residue is the heat source for the reboiler and for the feed preheating in both units. This will be further described in section 3.3.

3.2.1 CDU Heater Inlet Temperature and Heater Duty

As mentioned at the beginning of this chapter, CDU B is limited due to the heater duty. The yield of BO is affected by this limitation, since the amount of crude oil that can be heated to its transfer temperature is restricted, and the maximum processing capacity of the refinery cannot be exploited. Consequently, developing ways to reduce the consumption of the heater could enable the increase of the unit input and the refinery yield. In order to provide upgrade ideas that remove that limitation in CDU B, the greater heat recovery capacity of CDU A is evaluated in this thesis by processing heavy crude oils.

The main variable for this evaluation is the heater inlet temperature. Figure 12a presents the heater inlet temperature for the last five years in both distillation units. Turnarounds of the units for cleaning and technical inspection were conducted within

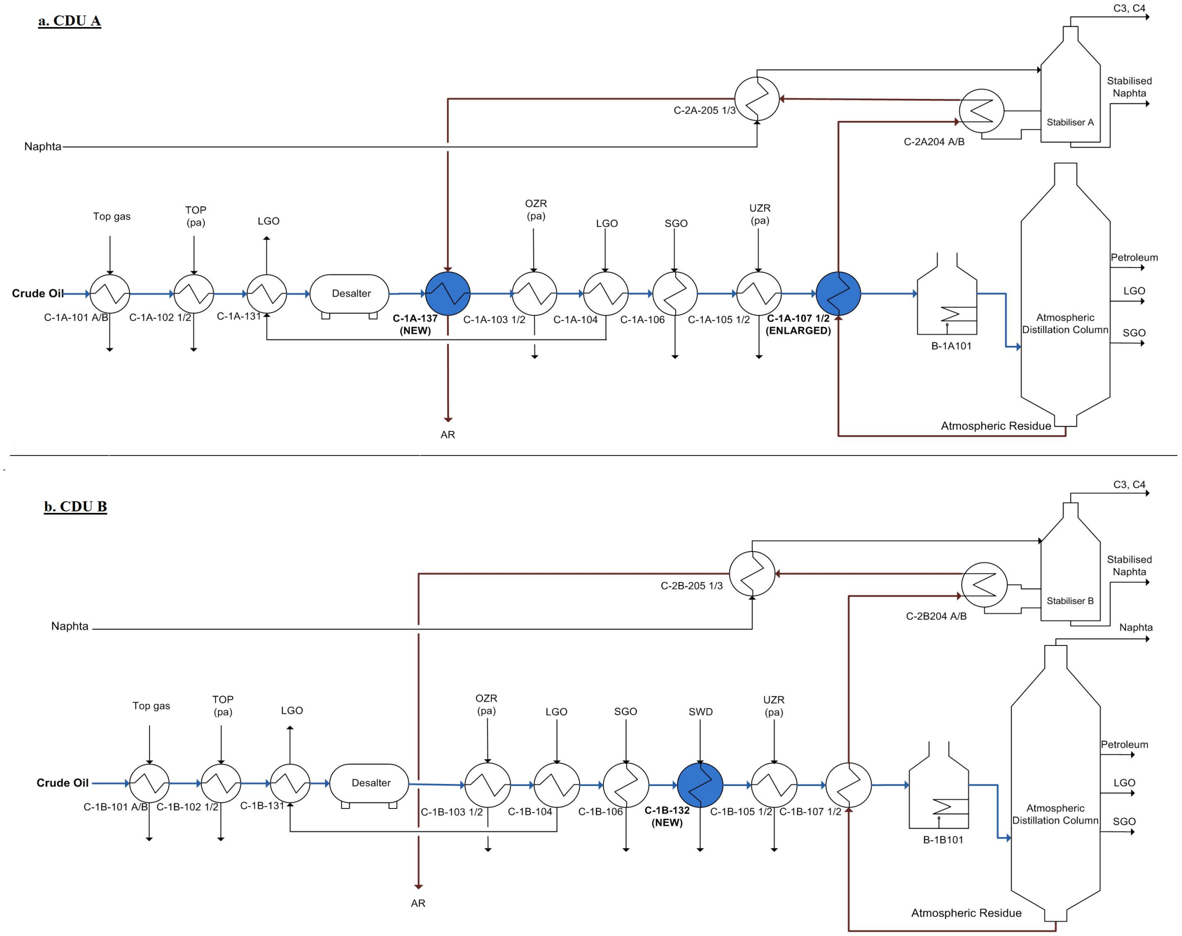


Figure 11: CDUs Preheat Trains and corresponding Modifications

this time interval. These turnarounds can be recognized by peaks going all the way down the diagram followed by a temperature increase and are listed in table 7.
Figure 12b zooms the marked areas in figure 12a and shows the fired heater inlet temperature for both units, starting from the second turnaround of each unit and for a period of sixteen months. The cleanings of both units were placed at the beginning of the diagram for a more accurate analysis of the temperature behavior starting from a similar cleanliness degree. The linear trend lines and their equations are also shown in this diagram. The slope of each equation represents the progressive temperature change in °C/day for each section.

The most important insight of this diagram is the temperature levels in both units. It can be seen that the temperature reached in CDU A is most of the time higher than in the CDU B. There is a difference between the heater inlet temperature in both units around 10 °C even at the beginning of the diagram where the exchangers of both units were clean. The few exceptions when the temperatures were alike or higher in CDU B,

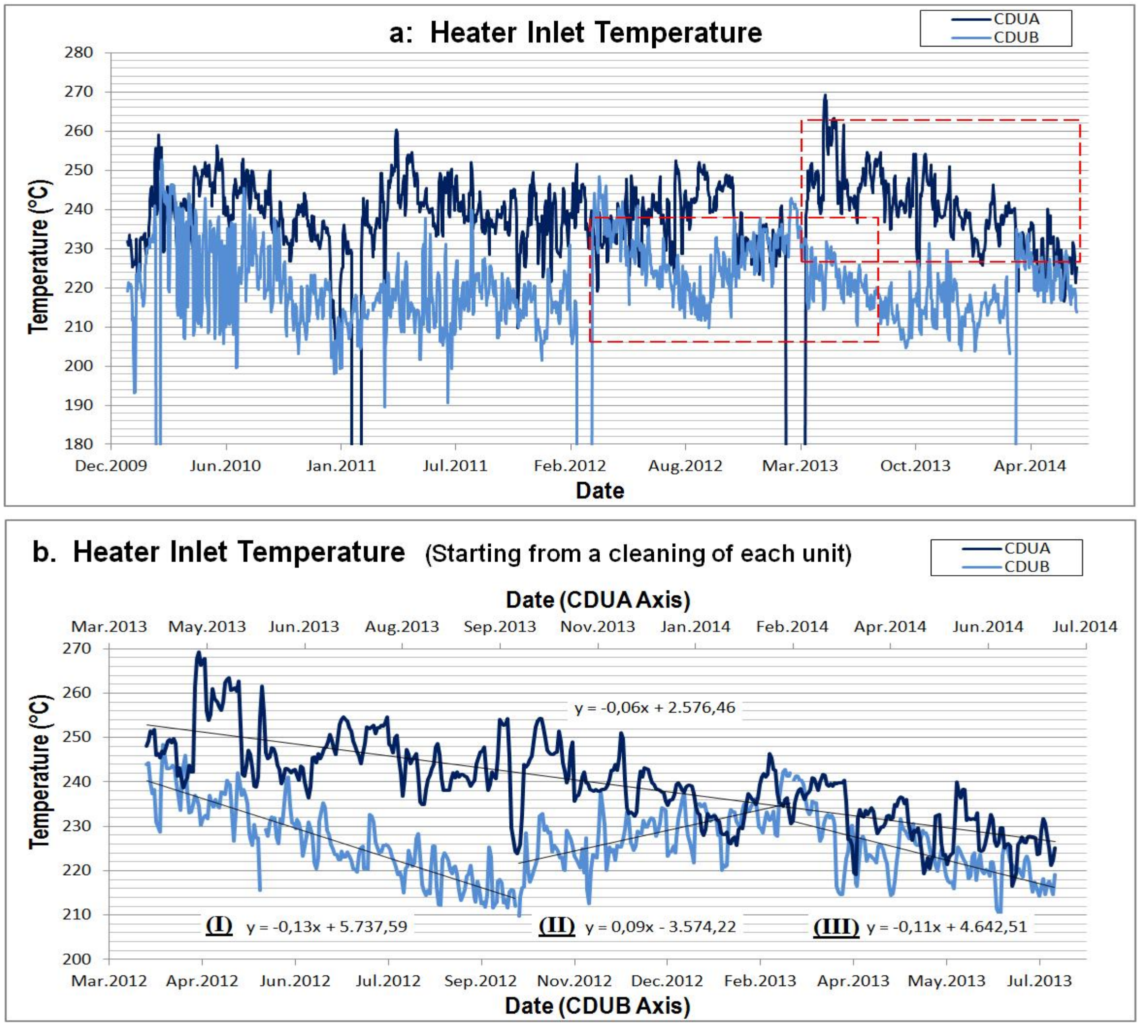


Figure 12: Furnace Inlet Temperature

occurred only when the CDU A was fouled **and** the CDU B was clean. Due to the higher heater inlet temperature reached in CDU A caused by the enhanced preheat train, a lower heater combustion duty is needed to reach the required distillation column inlet temperature. A quantitative evaluation is calculated as a part of this thesis to determine the effect of a better preheat capacity on the fired heater duty.

It can be observed in figure 12b that a unique trend line can be drawn to describe the general temperature pattern in CDU A during the entire period of time considered. The CDU B graph in the other hand, has to be divided in three sections (I, II, and III). The trend line of CDU A and of the sections I and III of CDU B, describe the expected behavior: A negative slope representing a progressive temperature decrease caused by fouling of the heat exchangers in the units. Comparing those slopes it can be concluded that the temperature decrease is around two times faster in CDU B. Approx.

Unit	1st. Turnaround	2nd. Turnaround	3rd. Turnaround
CDU A	Feb. 2011	Mar. 2013	
CDU B	Mar. 2010	Mar. 2012	Mar. 2014

Table 7: Units Turnarounds For Cleaning and Technical Inspection.

6.6 months after the cleaning of CDU B (exact length of section I: 198 days) the heater inlet temperature was already 26 °C lower than the initial temperature requiring individual cleanings of the critically fouled heat exchangers in this unit. In CDU A on the other hand, no individual or intermediate cleaning were needed because of a less severe temperature decrease. The comparison of both units six months after the cleaning is shown in table 8.

	CDUB Section I	CDUA (first 198 days)
Temp. Decrease rate (°C/day)	-0,13	-0,06
Aprox. initial Temp. (°C)	238	253
Aprox. final Temp. (°C)	212	241
ΔT after 198 days	26	12
Difference	**14**	

Table 8: Heater Inlet Temperature decrease for the first Six Months after a Unit Turnaround

Section II of the CDU B graph starts with the individual cleaning of the fouled heat exchanger. This section represents a peculiar period where the heater inlet temperature increases. One reason for this behavior might be the crude oil type processed in this time. Section II takes place in Winter between Oct. 2012 and Feb. 2013 when there is a low Bitumen demand, and mainly light crude oils are processed in the refinery (reported in table 9). The processing of light crude oils generate less fouling in the units and their composition and operating conditions might have a cleaning effect on the heat exchangers. The processing of mainly light crude oils combined with regular individual cleanings of the fouled heat exchangers had a positive effect on the heater inlet temperature, improving the heat transfer rate in the exchangers of the preheat train. Section III begins when the percentage of heavy crude oil batches is again increased (summer) after march 2013.

CDUB	Section I	Section II	Section III
Total Batches	67	46	42
Heavy Crude Oil Batches	44	12	24
% Heavy Crude Oil Batches	66%	26%	57%

Table 9: Crude Oil type processed in CDU B for the Three Studied Sections

3.2.2 Atmospheric Residue Outlet Temperature from CDU

Another important variable for the analysis is the atmospheric residue (AR) outlet temperature of the distillation unit. The AR leaves the distillation column at approx. 348 °C in both units (BAYERNOIL 2014b). The heat from this hot stream is recovered before it leaves the CDU. The AR is thus used as the energy source of the stabiliser reboiler and as heating media to warm up the crude oil and the stabiliser feed. Figure 13 shows the ARs temperature after the heat recovery. This temperature is in average 70 °C lower in CDUA due to the heat exchangers C-1A-137 and the enlarged C-1A-107 A/B (CDU A) which provide the unit a better heat recovery capacity from the AR to warm up the crude oil.

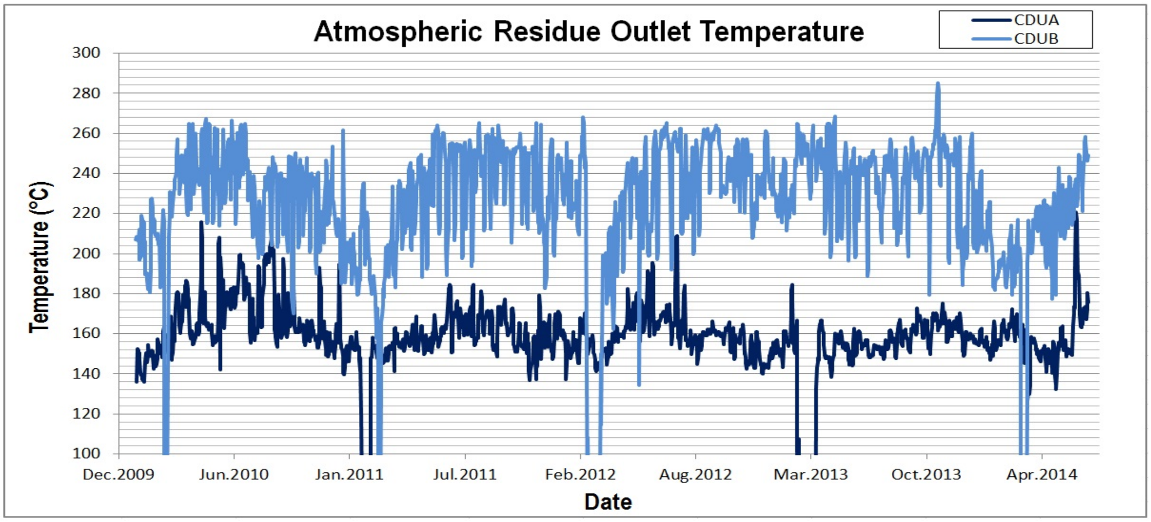


Figure 13: Atmospheric Residue Outlet Temperature

Figure 13 also shows that the temperature variation range is wider in CDU B. As mentioned in section 2.1, heavy crude oils are expected to have a higher proportion of heavy hydrocarbon fractions generating a greater amount of atmospheric residue than light crude oils. In BO approximately **110 tons/hour** of atmospheric residue are produced by the processing of light crude oils and **165 tons/hour** by the processing of heavy crude oils (average January-April 2014 (BAYERNOIL 2014b)). The alternating change of the crude oil type in CDU B (from light to heavy and vice versa) causes the variation of the mass flow of residue and thus of the heat transferred by the exchangers on the AR line. In CDU A on the contrary, only similar light crude oils are distilled, generating a more stable behavior.

3.3 Fouling of C-1B-107 1/2 (CDU B)

An energy balance of all heat exchangers of the preheat train of both units was calculated to determine which of them are more affected by fouling and have more influence in the crude oil temperature at the end of the preheat train. The heat transfer rate of each heat exchanger was plotted to facilitate the behavior analysis of the heat transfer rate over time. Fouling was recognized in several units but an extremely strong fouling rate was identified in the C-1B-107 1/2 (Figure 14). The location of this exchanger at the end of the preheat train of CDU B showed an important influence on the final temperature of the crude oil.

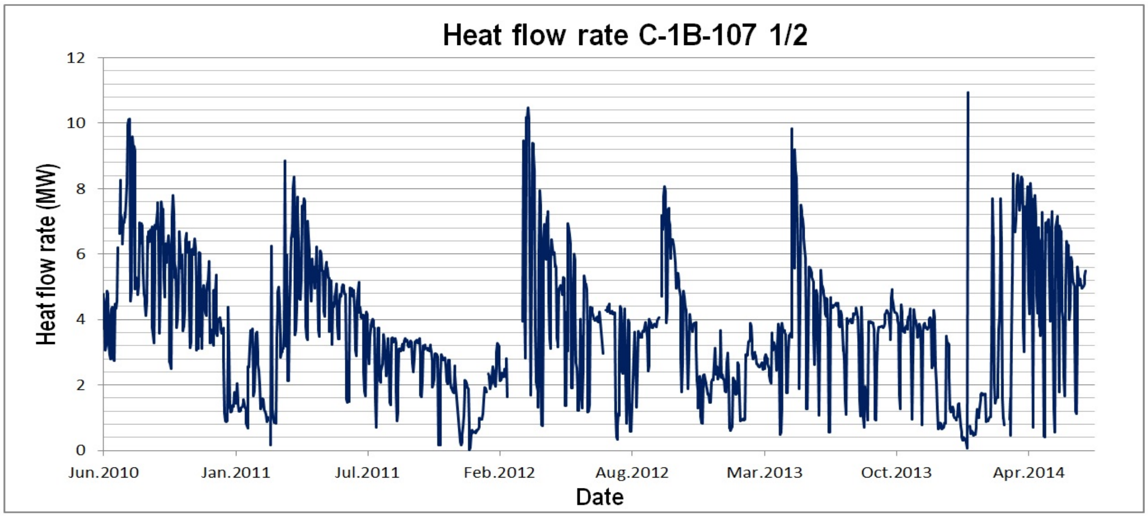


Figure 14: Heat Flow Transfer Rate in C-1B-107 1/2 (Fouling Tendency)

The AR is the heat source of the stabiliser reboiler (C-204 A/B) as shown in figure 11. When processing light crude oils the amount of atmospheric residue might be too low to keep the required duty in the C-204 A/B. Therefore the ARs mass flow is controlled via bypass in the heat exchanger C-107 1/2 in both units, to maintain the AR temperature high enough. Low mass flows of atmospheric residue generated by the processing of light crude oils, can lead to a complete opening of the bypass valve to guarantee a high temperature of the AR at the inlet of the stabilizer reboiler. Due to the alternating operational mode of the CDU B, the opening of this valve oscillates between 0 % and 100 %, increasing and decreasing abruptly the mass flow through the exchanger and thereby the fluid velocity. As mentioned in section 2.1.2, low velocities lead to longer residence time of the fouling agent in the tubes promoting the accumulation of unwanted material on the heat transfer surface. Figure 14 shows how the heat flow transfer rate reaches its maximum after a cleaning of the equipment and decreases at a high rate shortly afterwards evidencing a strong fouling rate in the C-1B-107 1/2. Through the period shown in this figure, a regular opening and closing of the bypass valve took place. Since in CDU A only light crude oils are processed, the valve opening does not oscillate so drastically and less severe fouling is evidenced. The heat flow transfer rate of C-1A 107 1/2 (CDU A) is presented in appendix figure 31.

Cleanings of C-1B-107 1/2 have to be regularly conducted in CDU B to reduce the heat transfer limitation. In the past four years these cleanings were performed with an average frequency of approx. 8 months. This represents large direct and indirect expenses for the refinery. The cost of each one of these cleanings is estimated in approx. US$ 50.000, not to mention the throughput losses during the cleanings and the high risk of failure after reassembling the equipment.

3.4 Vacuum Distillation Unit and Steam Generation

The main feedstock of the VDU is the atmospheric residue obtained from the processing of heavy crude oils. The heavy atmospheric residue is further processed under vacuum to gain vacuum gas oils (VGO) which are the feedstock of the Mild Hydro-cracker where diesel is produced. The AR leaves the CDU and enters the VDU, which creates an important thermal dependency between these units.

Figure 15 is included for illustration purposes. This basic process flow diagram shows how CDU B and VDU are connected and illustrates the flow of the crude oil and the atmospheric residue throughout the whole CDU - VDU system. It can be observed in this figure that the preheat train in the VDU is composed by the heat exchangers C-403 1/3 and the C-410 A/B. The VDU also integrates three steam generators: C-417 (FS), and C-418 1 and 2 (ES). Steam is generated in this unit to enhance the thermal efficiency of the process, transforming the heat contained in the high temperature streams into an useable form of energy.

The steam demand in the refinery fluctuates according to the the time of the year since less steam is needed for tanks and pipelines heating when the ambient temperature is higher. For estimation purposes the ES-steam (pressure: 5 bar abs.) is considered in the refinery as a valuable product only half of the year (winter time). Measures are taken to use the additional steam generated in summer e.g. feeding more steam to the tank farm or to reduce its production e.g. turning the energy source of turbines to

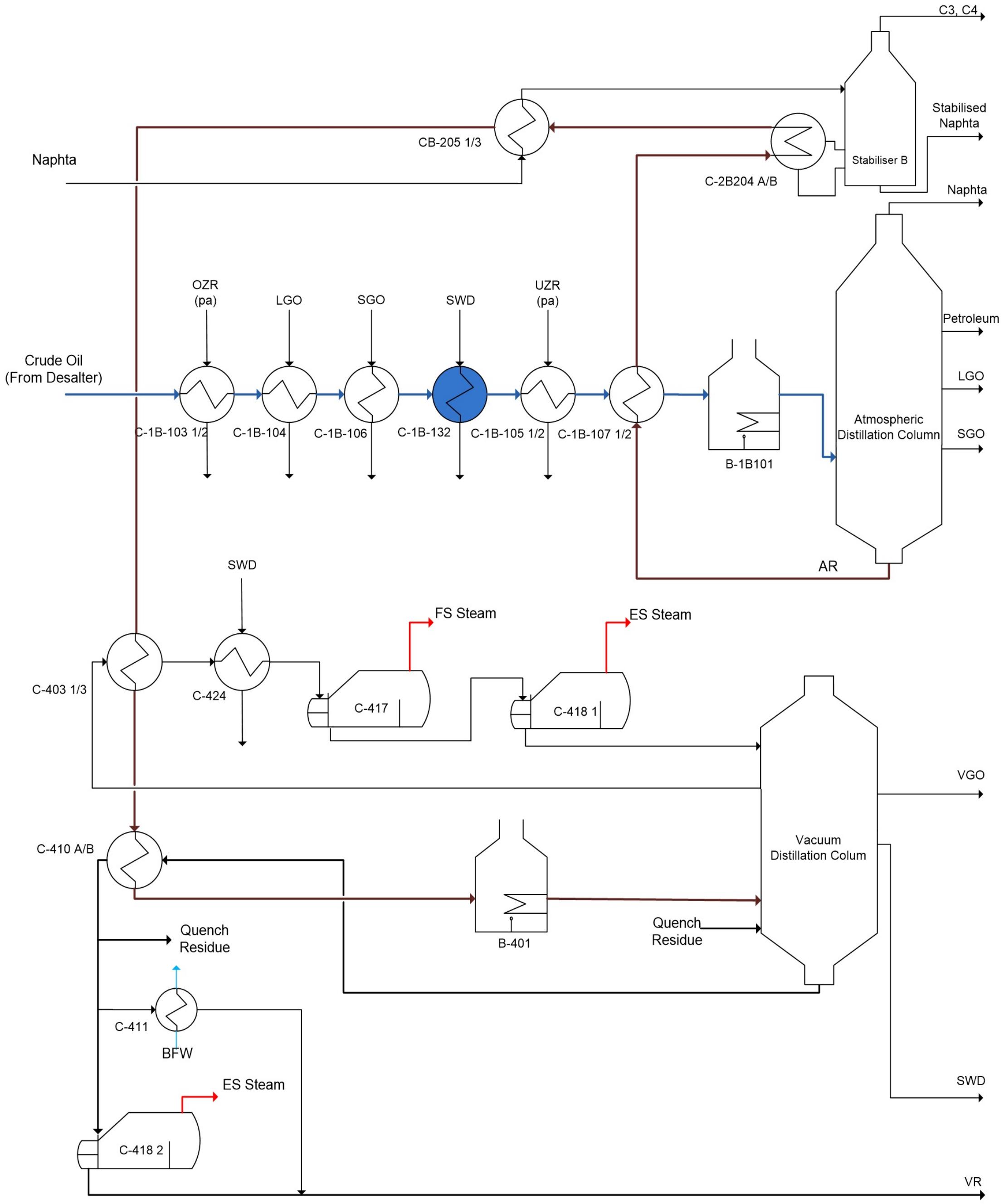


Figure 15: CDU and VDU Unit connection

electricity, and in extreme cases the ES-steam is even discharged to the atmosphere. Therefore, measures that reduce the steam production in the summer time are desirable.

The thermal dependency between CDU and VDU provides an option to reduce the total steam generated in the VDU.As shown in figure 13, the outlet temperature of the

AR is lower in CDU A than in CDU B. This plays an important role in the test runs, where heavy crude oils are processed in the CDU A and this temperature becomes the inlet temperature of the VDU feedstock. This temperature decrease also affects the exchangers C-403 1/3 and C-410 A/B of the VDU preheat train. The AR has to be preheated before entering the vacuum distillation column and it is therefore the energy sink of these exchangers. This analysis presents a difficulty due to the lack of an intermediate temperature reading between the exchangers. Thus an energy balance was set up in Excel to estimate the missing temperature using the heat flow rate of both exchangers.

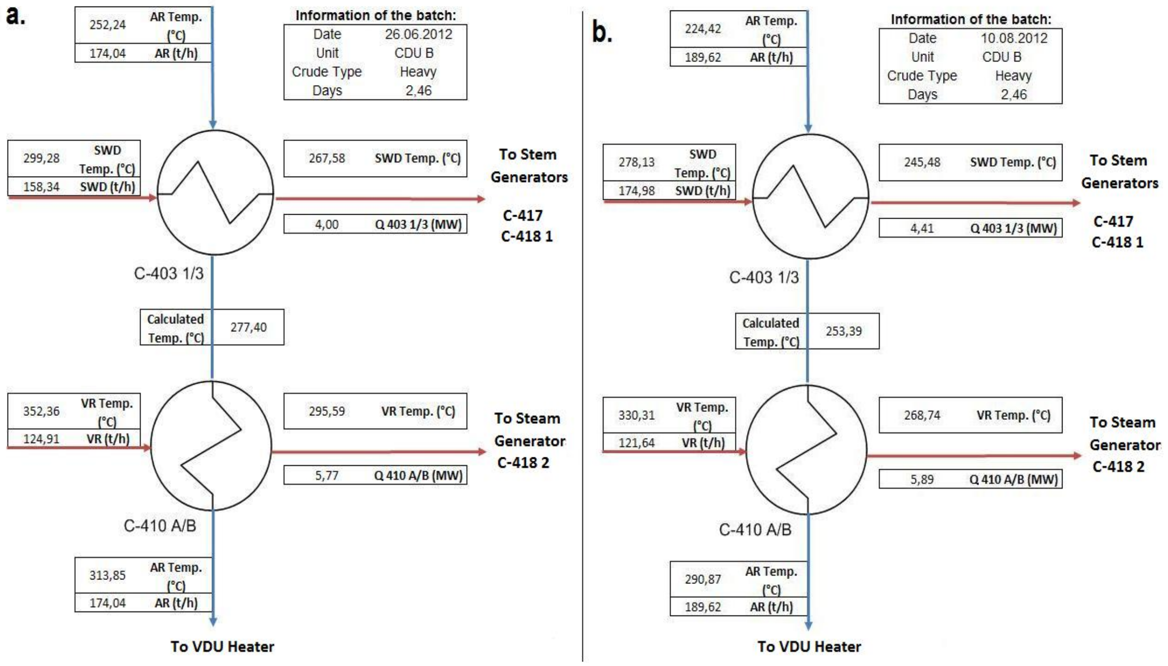


Figure 16: VDU Preheat Train, Energy Balance

This energy balance was calculated and compared for two heavy crude oil batches to obtain a basic notion about the behavior of the VDU by the test runs where the AR inlet temperature will decrease. Figure 16a shows a batch in which the AR inlet temperature was higher than in b. The aim of this comparison is to illustrate the changes in the operation of the system caused by a lower AR inlet temperature into the unit. Although both cases cannot be directly compared, it can be recognized that the decrease in the AR inlet temperature shifts the temperature level in the subsequent streams generating two main consequences:

- The inlet temperature in the steam generator decreases. Given that the outlet temperature of the steam generators is fixed (approx. 5 °C higher than the water boiling temperature at the corresponding pressure), the steam generation is also reduced in the boilers of the unit.

- A lower temperature at the end of the preheat train of the VDU is reached. Since the inlet temperature of the vacuum distillation column is fixed, this shifting represents more combustion duty of the VDU fired heater. This increase will be evaluated during the test runs where the AR proceeds from the CDU A and enters the VDU at a colder temperature. However, as it was shown in table 27 in appendix this furnace has a large underexploited capacity and this should not generate any operational problems.

4. Simulation

Aspen HYSYS® is the program used for simulation purposes at BAYERNOIL. There are several models for different equipments and processes of the refinery, which are mainly used for planing of new equipments, for rating the existing ones and for evaluation of optimization possibilities. For the evaluation of some of the target variables described in chapter 3, a model of CDU B developed for BO by FLUOR® is used.

This simulation is made-up of a parent environment of the distillation unit CDU B and three additional sub-flowsheet environments the VDU, DHT, and the crude oil preheat train. Those sub-flowsheets can be accessed from the parent environment. The sketches of the simulation are shown in appendixes 32, 33 and 34 to provide a general overview of the simulation. Each sub-flowsheet environment is individually simulated and then integrated with the parent and the other sub-environments. This separate structure helps not only to maintain an overview but also to avoid computational problems generated by the simultaneous solving of this complex simulation.

This model was generated in 2006 for the planning and evaluation of the energy conservation project ISAR (initiative for sites safeguarding, plant optimization and profitability increase) and some of the information contained is obsolete. Therefore, first the data is updated to match the actual state of the unit and to obtain realistic results. The specified stream data in the simulation was compared with the data found in BORIS (Bayernoil Oil Refinery Information System) and corrected to match the actual mass and energy balances of the unit. The configuration of the units was also updated; Heat exchangers were removed or built and others were relocated or changed to represent the actual configuration of CDU B.

The model of CDU B was modified to evaluate some of the target variables of this thesis. Three new versions of the simulation were built from the basis model: *current state of CDU B*. For these new versions of the simulation (listed bellow), the heat exchangers that enhance the crude oil preheat train in CDU A (C-1A-137 and enlarged C-1A-107 1/2) were added to the model of CDU B to evaluate their influence on the heater duty. For an easier determination of the effects that each of those heat exchangers generate in the process, they were first individually integrated to the model of CDU B and a final version of the simulation with both heat exchangers was afterwards created and analyzed.

Simulation 0: Models the actual configuration of CDU B.
Simulation 1: Integrates the C-1A-137 from CDU A to the actual configuration of CDU B.
Simulation 2: Integrates the enlarged C-1A-107 1/2 from CDU A to the actual configuration of CDU B.
Simulation 3: Integrates both C-1A-137 and C-1A-107 1/2 from CDU A to the actual

configuration of CDU B.

4.1 Modeling of the Heat Exchangers C-1A-137 and enlarged C-1A-107 1/2 with Aspen EDR

The HYSYS integrated functionality *Aspen EDR (Exchanger Design and Rating)* is employed in this thesis for the rigorously modeling of the exchangers based on their geometry and actal operating conditions. This data is extracted from the exchangers design documents in DMS (Document Management System) and from the piping and instrumentation drawings (P&ID).

The first step for modeling the heat exchangers, after creating a new EDR case, is the definition of the process and property data. This information is imported from the case file in HYSYS where the fluid compositions and the stream data are already defined. Necessary for the design are the temperature, pressure and mass flow of the ingoing streams. Furthermore the geometry of the exchangers has to be defined. It is necessary to select the TEMA type, the position, the number of shells, the arrangement of the shells, the specifications of the tubes, baffles and bundle. After defining the parameters for the modeling of the exchangers, the Aspen EDR delivers a bank of data in which several information such as input, result, thermal/hydraulic and mechanical summaries are contained. Appendixes 35 and 36 show the summary of the overall results generated by EDR.

The results from Aspen EDR are exported to HYSYS and integrated in the simulation. It is noticed that the temperatures of the cold media are in both cases higher in the simulation than the actual temperatures reached in the plant. This is due to fouling in the heat exchangers. Although the data was taken from a ”clean” state of the unit, it is impossible to return the exchangers to its initial condition after years of operation. The fouling factor of the exchangers is manually adjusted to fit their current performance.

4.2 Simulation Results

4.2.1 Simulation 0. Actual State of CDU B

This simulation represents the current state of CDU B. The conditions for this simulation are reported in table 10 along with other important variables which will be mentioned in the subsequent sections for comparison purposes. Data from a heavy crude oil batch was considered fort this set of simulations.

Variable	Value	Units
Crude Oil Input	367.1	(t/h)
Heater Inlet Temperature	228.2	(°C)
Heater Duty	58.9	(MW)
AR from CDU	188.0	(t/h)
AR Bypass (around C-1B-107 1/2)	0	(t/h)
OZR Mass Flow (C-1B-103 1/2)	208.5	(t/h)
UZR Mass Flow (C-1B-105 1/2)	97.45	(t/h)
Stabi. Temp. Requirement	290	(°C)

Table 10: Actual State of CDU B, important Variables and Simulation Conditions

The stabiliser reboiler temperature requirement was fixed at 290 °C. However, with the simulated configuration, the minimum the residue can be cooled down is 297.5 °C. This indicates that the available heat transfer area is not enough to cool down the AR to the allowed temperature.

The pump arounds in the atmospheric distillation columns at the Vohburg site are called TOP (upper pump around), OZR (middle pump around) and UZR (bottom pump around). The aim of those pump arounds is to remove heat from the distillation column to maintain a constant temperature gradient within. A fraction of hot liquid is withdrawn from the column and cooled down in a heat exchanger of the crude oil preheat train. The pump arounds and their corresponding heat exchangers are listed in table 11.

Name	Pump Around	Heat Exchanger
TOP	Upper	C-102 1/2
OZR	Middle	C-103 1/2
UZR	Bottom	C-105 1/2

Table 11: Pump Arounds of the atmospheric Distillation Columns

4.2.2 Simulation 1. CDU B with the C-1A-137

Figure 17 shows the crude oil temperature profile through the preheat train for two sets of the simulations: Simulation 0 and Simulation 1. Aim of this comparison is to determine the influence of CA-137 in the temperature of the crude oil at the end of the preheat train.

C-1A-137 was modeled and integrated in the simulation of the CDU B at the same position it is located in CDU A. As shown in figure 17, C-1A-137 raises the crude oil temperature by 27 °C. However at the end of the preheat train, the temperature of the crude oil is only 8 °C higher than the temperature achieved with the actual configuration of the unit. A temperature shift of the subsequent streams is caused, leading to a reduction of the heat transfer potential of the downstream heat exchangers and reducing the temperature difference between the two sets of simulations.

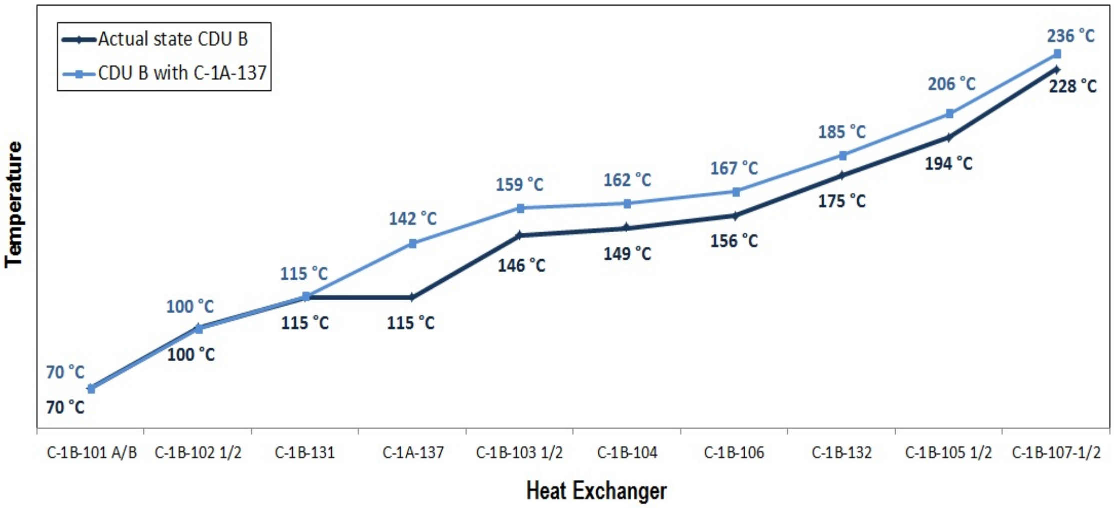


Figure 17: Crude Oil Temperature Profile Comparison: Simulation 0 and 1

Furthermore, the location of C-1A-137 could present additional effects on the refining process. The temperature shift caused by this exchanger decreases the heat transfer potential of the column's middle and lower pump arounds by rising the temperature of their heat sink (the crude oil). This could adversely influence the heat removal from the distillation column and increase the temperature levels within the tower. As a consequence, heavy vapors could rise up reducing the quality of the side-stream and top products. The total heat removal from the column has to be controlled to avoid the deterioration of the qualities. This is achieved both in the simulation as in the actual plant by increasing or reducing the mass flow through the heat exchangers of the pump arounds.

C-1B 103 1/2 (the middle pump around) is the most affected heat exchanger in the preheat train because of its location right after the C-1A-137. To transfer the same heat amount that is transferred without the influence of the C-1A-137, the mass flow through this exchanger has to be increased. This is limited by the quantity of OZR available in the column which might not be enough to maintain the specified heat removal from the column. In this case, the heat exchangers of the upper and bottom pump arounds have to achieve the total heat removal.

This restriction was recognized in Simulation 1 by difficulties for the convergence of the adjust function that controls the OZR flow in C-1B-103 1/2. For the simulation to converge, the amount of liquid withdrawn from the column was manually increased until a solution was found, values are reported in table 12 for the two versions of the simulation.

	C-1B-102 1/2 TOP (t/h)	C-1B-103 1/2 OZR (t/h)	C-1B-105 1/2 UZR (t/h)
Actual state CDU B	273.0	208.5	97.4
CDU B with C-1A-137	273.0	230.5	142.1
Difference (t/h)	0	22	44.7

Table 12: Mass Flow of Pump Arounds for two Cases of the Simulation

The addition of C-1A-137 to the preheat train also has an effect on the AR temperature. In Simulation 1 the AR reaches the stabiliser reboiler at 302.3 °C, which is 12.3 °C higher than the temperature required by the reboiler. This indicates that the AR is fed to the stabiliser at a temperature higher than required and a larger heat transfer area would be necessary to recover more heat from the AR to warm up the crude oil.

4.2.3 Simulation 2. CDU B with the enlarged C-1A-107 1/2

Similarly to C-1A-137, the location of C-1A-107 1/2 plays a decisive role. This exchanger is right before the fired heater and any change at this stage of the preheat has a direct impact on the final temperature of the crude oil. This exchanger does not affect the performance of other heat exchangers and its effect is directly reflected in the heater duty. However, this heat exchanger is limited: as mentioned in section 3.2.2, the AR temperature has to be controlled to meet the energy requirement of the stabiliser reboiler, which causes the regular opening and closing of the bypass valve to maintain the AR temperature above the specified value. This is also modeled in the simulation sets where an adjust function fixes the stabiliser reboiler ingoing temperature at 290 °C by regulating the mass flow of AR through C-1A-107 1/2 (see figure 18). This function calculates the amount of AR that has to be bypassed to maintain the temperature at the required level.

This restriction is reflected in results from Simulation 2 (reported in table 13). Since C-1A-107 1/2 has a larger heat transfer area than C-1B-107 1/2, a larger amount of AR has to be bypassed to maintain its temperature above the requirement of the stabiliser reboiler. Due to this limitation, the crude oil is heated up to 233 °C (5 °C higher than the temperature reached in Simulation 0 with the actual configuration of the unit). By-

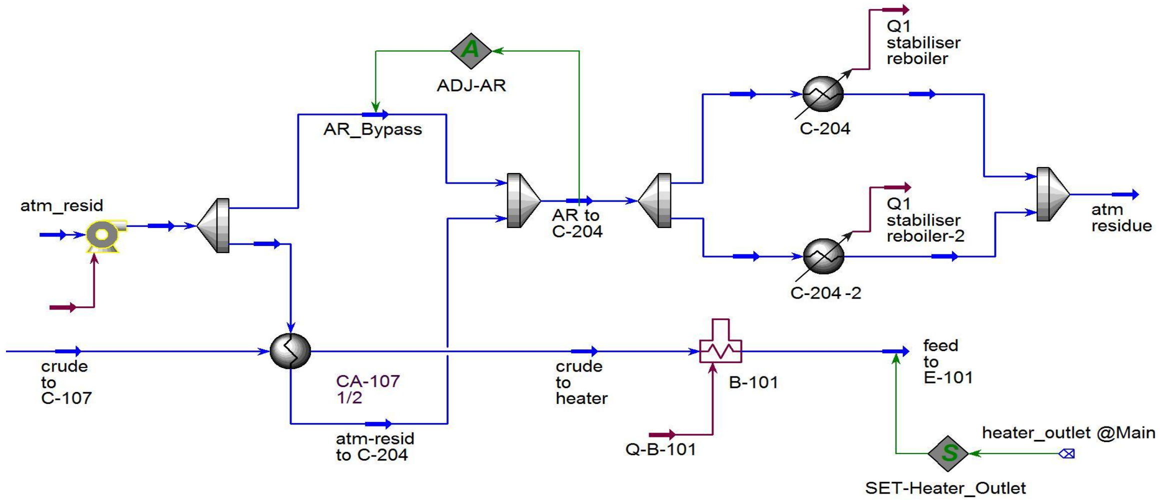


Figure 18: Atmospheric Residue Bypass

passing this heat exchanger represents great losses not only because it promotes fouling (as mentioned in section 3.2.2) but also due to sub-utilization of the available energy levels. C-1A-107 1/2 was simulated at the same conditions but ignoring the stabiliser requirement to calculate the temperature increase that this exchanger could achieve in the crude oil without this limitation. In this case the crude oil reached a temperature of 236 °C, which is 8 °C higher than the temperature reached in Simulation 0. This increase represents a reduction of 2.6 MW in the heater duty but it cools the AR to 284 °C, which is not enough to supply the stabiliser reboiler. Increasing the size of C-1B-107 1/2 can be considered as a possibility to decrease the CDU B heater duty only when there is another heat source available to supply the stabiliser reboiler.

	Heater Inlet Temp (°C)	AR Bypass (t/h)	Effect on the Heater Duty (MW)
Actual state CDU B	228	0	
CDU B with C-1A-107 1/2	233.2	41.1	-1.6
CDU B with C-1A-107 1/2*	236.1	0	-2.6

* Closed Bypass around C-1A-107 1/2

Table 13: Comparison Actual State of the CDU B and CDU B with enlarged C-1A-107 1/2

4.2.4 Simulation 3. CDU B with both Exchangers: C-1A-137 and enlarged C-1A-107 1/2

This simulation set models the CDU B with the heat recovery configuration (from AR) of the CDU A and provides a prediction about the outcome of the test runs where heavy crude oils are processed in this unit. The restrictions described in sections 4.2.2 and 4.2.3 generated by the addition of the C-1A-137 and C-1A-107 1/2 respectively, are also identified in this set of simulations where both heat exchangers are added to the configuration of CDU B. Table 14 shows a summary of the results of the different sets of simulations. Simulation 3 achieves the highest temperature (238.7 °C) at the heater inlet. This temperature is 10.5 °C higher than the temperature reached in Simulation 0 by the actual configuration of the unit and represents a reduction of 3.7 MW in the heater duty.

Version of the Simulation	Heater Inlet Temp. (°C)	Δ T (°C)	Heater Duty (MW)	Difference (MW)	AR Temp. to Stabi. (°C)	AR Bypass (t/h)
Simulation 0	228.2	-	58.9	-	297.5	0
Simulation 1	235.8	7.6	56.1	**-2.8**	302.3	0
Simulation 2	233.2	5.1	57.3	**-1.6**	290.0	41.1
Simulation 3	238.7	10.6	55.2	**-3.7**	289.9	21.1

Table 14: Simulation Results Summary

In this table, it can also be observed that the AR temperature required by the stabiliser reboiler is exceeded in Simulation 0 and 1. In these simulations, the bypass valve around C-1B-107 1/2 is closed and the total amount of AR flows through the heat exchanger. This means that the AR cannot be cooled down any further and that the crude oil cannot be further warmed up, at the given conditions with the available heat transfer area. The opposite behavior can be recognized in Simulation 2 and 3 where C-1A-107 1/2 is integrated. More heat can be recovered from the AR due to the larger area of the apparatus and an amount of atmospheric residue has to be bypassed around this heat exchanger to meet the energy requirement of the stabiliser reboiler. This reduces artificially the performance of C-1A-107 1/2 due to the sub-utilization of its heat transfer area.

The four sets of simulations cannot be directly compared due to the different AR temperatures at the inlet of the stabiliser reboiler and the different amounts of AR bypassed around C-1A-107 1/2. However the following conclusions can be made from the results obtained.

- Simulation 1 present a large diminution in the heater duty (2.8 MW). However with this configuration the AR is taken to the stabiliser at high temperature. This represents the sub-utilization of this temperature to heat up the crude oil in the preheat train. Additionally, the location of this heat exchanger diminishes the performance of the subsequent heat exchangers which is especially problematic for the middle and bottom pump arounds and can deteriorate the quality of the side and top products of the distillation column.

- Simulation 2 presented a reduction of 1.6 MW in the heater duty. However the potential of the larger heat transfer area of this exchanger is underestimated due to the amount of AR that has to be bypassed to meet the stabiliser energy requirement. Enlarging the C-1B-107 1/2 makes sense when there is another heat source available to supply the stabiliser reboiler. In that case, the heat transfer area of the exchanger can be used at full advantage for the preheating of the crude oil.

- Simulation 3 presented the best performance. With this configuration the heater inlet temperature increased by 10.6 °C reducing the heater duty by 3.7 MW compares to the actual state of the unit (Simulation 0). This result presents the less cost-intensive possibility to surpass the limitation in the CDU B, since this option only represents the changeover from processing heavy crude oils in the CDU B to processing them in the CDU A without requiring any additional capital investments. This result justifies the conduction of the test runs to evaluate the actual performance of the CDU A by processing heavy crude oils and to identify possible operational difficulties.

As mentioned in section 3.2.1 the amount of crude oil processed in the CDU B is limited by the fired heater capacity. The reduction in the heater duty allows to increase the crude oil input increasing the refinery yield and the process profitability. Table 15 shows the simulated crude oil amount that can be processed in the unit by the maximal combustion duty allowed (61.4 MW) for the analyzed versions of the simulation. Large amounts of heavy crude oil can be processed in CDU B with the evaluated configurations. However, the versions of the simulation were modeled regarding energy-oriented upgrade possibilities where the real amount of crude oil that can be processed might be limited by the unit hydraulic capacity or by the actual market demand.

Simulation CDU B	Heater Inlet Temp. (°C)	Crude Oil (t/h)
Simulation 1	235.7	409.2
Simulation 2	233.2	402.6
Simulation 3	238.7	417.2

Table 15: Crude Oil Input at maximal Heater Combustion Allowance

5. Test Runs Results Analysis

Test runs were conducted in CDU A to evaluate the unit's enhanced preheat train by processing heavy crude oils which are normally processed only in CDU B. Four heavy crude oil batches were processed in CDU A to evaluate the effect of its larger heat recovery capacity on the heater duty and on the steam generation in VDU. The first test batch was processed the 15th October 2014. A rough estimation of this first test was made to identify operational problems caused by the test and to determine if further test runs might be conducted (this evaluation is not shown in this thesis). The following three heavy crude oil batches were consecutively processed starting the 20th October 2014.

The aim of this chapter is to present the data gathered from the tests conducted in CDU A and analyze the target variables according to the obtained results. Information of the individual test runs is presented in this chapter. However, the average of the data sets are used for rating the results and to eliminate fluctuations and systematic deviations of the analyzed cases. At the end of this chapter an overall energy balance around the system CDU-VDU is presented. The configuration CDU B - VDU represents the reference state of the system and CDU A - VDU the final state. The variables considered for the overall balance are analyzed in the subsequent sections of this chapter.

The behavior of the target variables was evaluated considering the average values of four heavy crude oil batches processed in CDU B as a reference case "Reference". This Reference represents the current state by processing heavy crude oils in CDU B. This average is compared with the average of the data sets generated in the test runs. These batches were selected to provide an accurate comparison basis according to the crude's AR percentage, its density and the transfer temperature in the CDU and VDU (table 16).

	Unit	Crude Oil Type	AR Percent (%)	Density (kg/m3)	CDU Transfer Temperature °C	VDU Transfer Temperature °C
Reference	CDU B	Heavy	50	881	369	382
Test runs	CDU A	Heavy	50	880	374	382

Table 16: Relevant Data of the analyzed Heavy Crude Oil Batches

Figure 19 presents the crude oil input processed in the four test runs. It can be observed that different crude oil feed rates were processed during the first two test runs. This was made to estimate the processing capacity of CDU A at the maximal heater duty allowed. The maximal crude oil input 388.4 t/h was processed in the second test run. A very stable feed rate of approximately 359 t/h was processed in the third and fourth test runs.

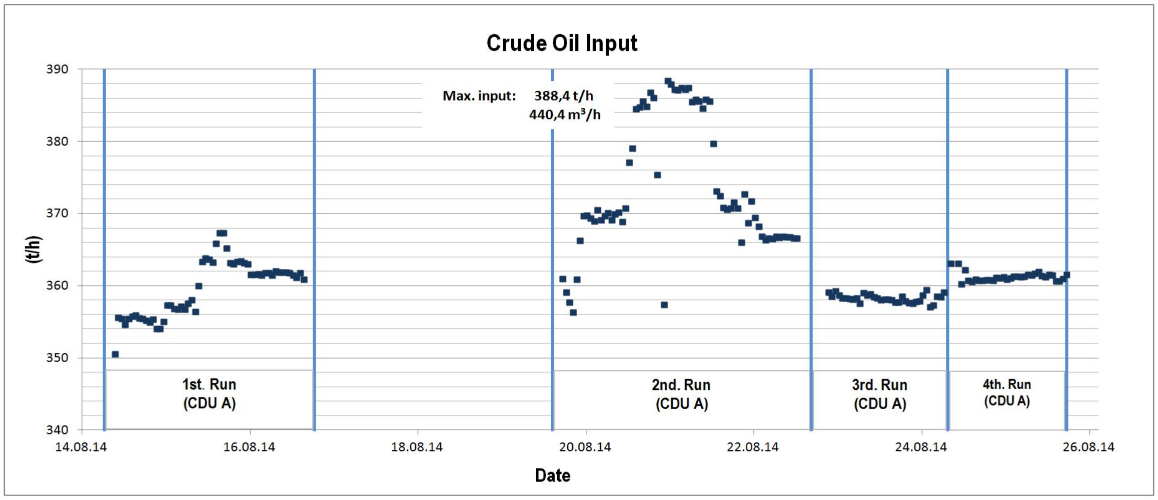


Figure 19: Crude Oil Input

5.1 CDU Heater Inlet Temperature and Heater Duty

A comparison between the heater inlet temperature and heater duty in both distillation units by processing heavy crude oils is evaluated in this section.

The measured heater inlet temperature and normalized heater duty of the Reference (in CDU B) and the average of the test runs conducted in the CDU A are presented in table 17. The normalization of the measured duty is conducted based on the crude oil input in the CDU B to eliminate the effect of the fluctuating crude feed rates and to allow an accurate comparison between the cases studied. The heater inlet temperature reached in the CDU A is 20.6 °C higher than the temperature reached in the reference case in the CDU B. This temperature change generates an effective reduction of 4.7 MW in the CDU heater duty.

Figure 20 shows the heater inlet temperature for the four test runs and the opening of the bypass valve around C-1A-107 1/2. It can be observed that this valve was irregularly opened during the test runs. This was caused by fluctuations in the energy requirement of the stabilizer reboiler due to operational conditions independent from the test runs which are not caused by the processing of heavy crude oils in the CDU A.

	Heater Inlet Temperature (°C)	Heater Duty (MW)
Reference	224.4	60.4
Test Runs	245.0	55.7*
Difference	**20.6**	**-4.7**

* Normalized based on the crude oil input in the reference case (CDU B)

Table 17: Heater Inlet Temperature and Duty

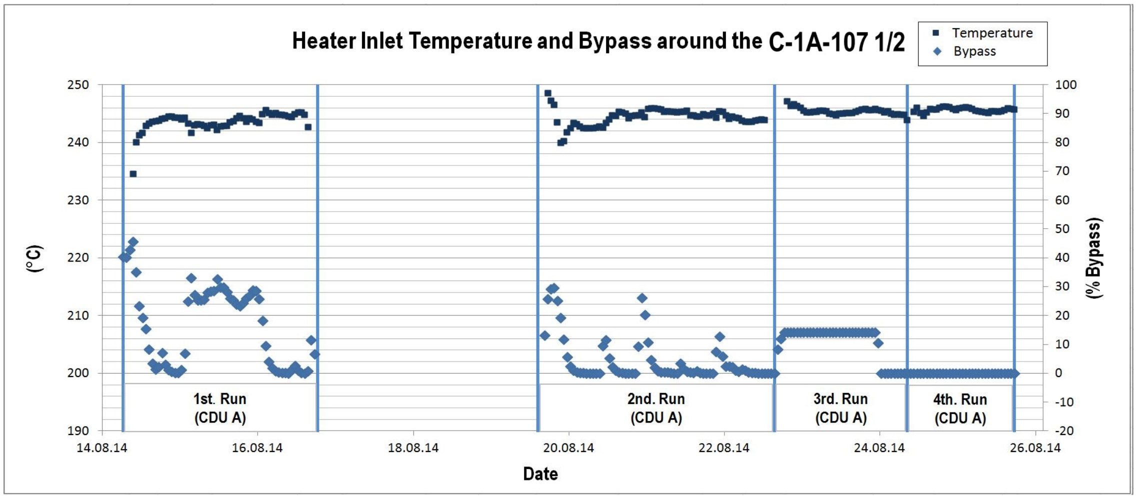


Figure 20: Heater Inlet Temperature and Bypass around C-1A-107 1/2

Figure 21 shows the measured and the normalized heater duty of the CDU A fired heater. The normalized CDU A heater duty is in average 55.7 MW, which is 4.7 MW lower than the required in CDU B by the same crude oil input basis (table 17) evidencing the significant effect of the enhanced preheat train in CDU A on the heater duty.

The crude oil feed rate can be increased in CDU A since lower energy is required in the heater to heat the crude oil up to its transfer temperature. During the second test run and for a period of 21 hours, CDU A was operated at high crude oil feed rates that made possible to determine the crude oil amount that can be processed in the unit at the maximal combustion duty allowed. The highest crude oil input processed in CDU A was 388.4 t/h at a measured heater duty of 61.1 MW. Table 18 compares this maximum with the average values in the reference case (CDU B). Due to the higher temperatures reached at the heater inlet in the CDU A, 27.2 t/h more of crude oil can be processed in this unit at a similar heater duty.

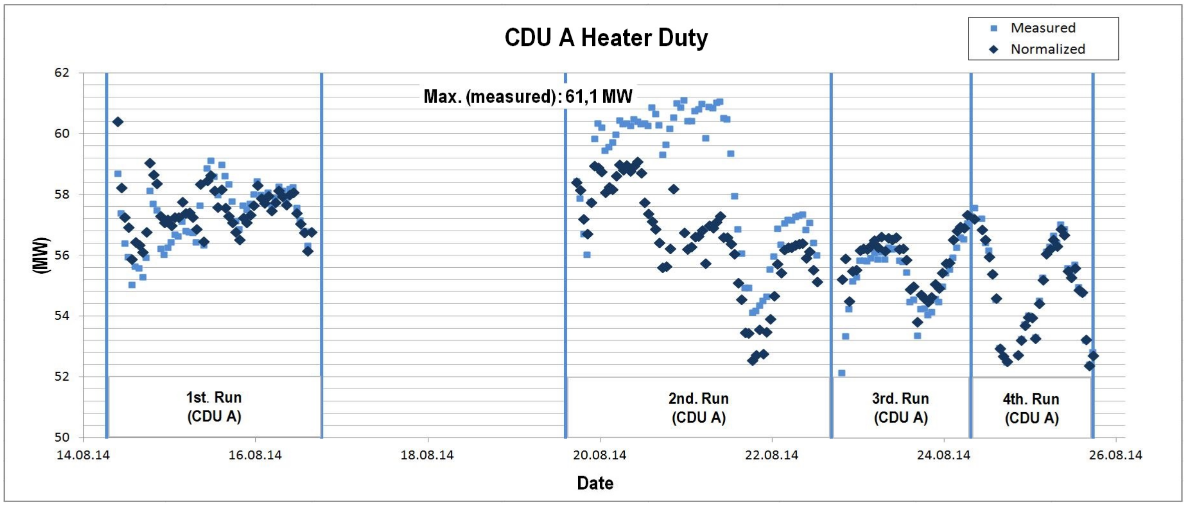


Figure 21: CDU A Heater Duty

	Heater Duty (MW)	Crude Oil Input (t/h)
Reference	60.4	360.8
2nd Test (Max.)	61.1	388
Difference	0.7	**27.2**

Table 18: Heater Duty and Crude Oil Input

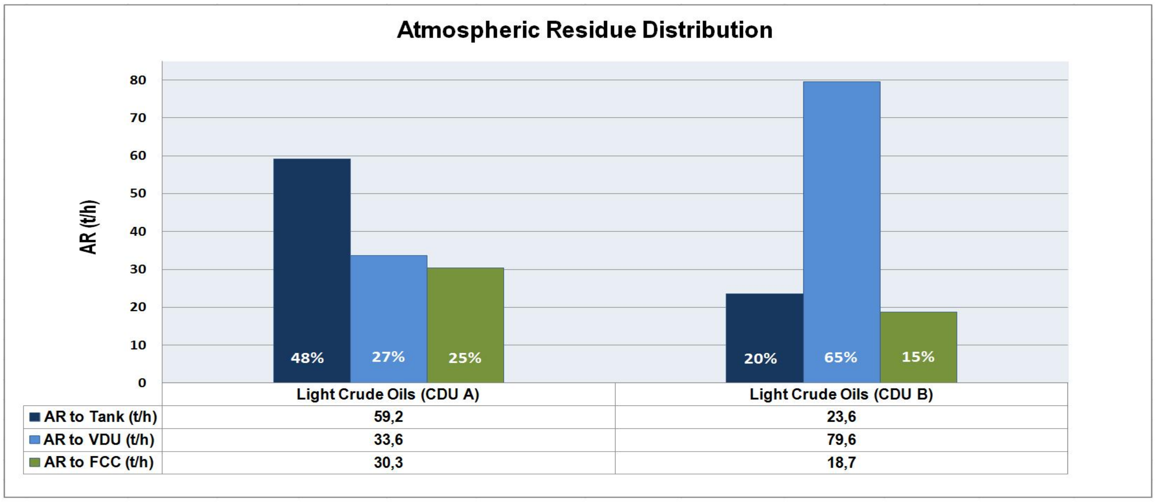
A restriction was recognized in CDU A in the period where the unit was operated at high crude oil input rates. In chapter 3, only the heat oriented modifications conducted in the units as a part of the ISAR project were described. However, these changes also caused hydraulic modifications in each of the units. Since large amounts of atmospheric residue are usually obtained from CDU B by the processing of heavy crude oils, a higher hydraulic capacity was implemented for the transport of the AR from this unit to the VDU. This additional hydraulic capacity was not required in CDU A due to the low AR amounts generated by the processing of light crude oils. During the second test run in CDU A it was necessary to operate with two pumps to overcome the system head and to drive the large load of AR into the vacuum distillation unit. Having to operate with the spare pump represents a risk in case of failure of one of the pumps and is an undesired measure in the process. Further studies are required to determine the hydraulic limit of the CDU A if a long term processing of heavy crude oils in this unit is desired.

5.2 AR outlet Temperature from CDU

As mentioned in section 3.4, there is a thermal dependency between the CDU where the heavy crude oils are processed and VDU. The main effect caused by this dependency is evidenced in the VDU heater duty and in the AR's temperature at the outlet of the CDU.

Due to the enhanced heat recovery in CDU A, the AR presented an outlet temperature of approx. 183 °C in the test runs, whereas the outlet temperature in the reference case from CDU B is 238 °C (Difference: 56 °C).

To meet the design specifications of the residue storage tanks, the AR has to be first cool down before it is stored. This final cooling down is achieved in both units by a heat exchanger that warms up tempered water. Since this water is not necessary in the process, this heat is considered lost. Figure 22 shows the distribution of the AR generated in both distillation units by processing light crude oils. Approximately 48 % of the atmospheric residue generated in CDU A is first stored in tanks for later processing. In CDU B on the other hand, the greatest portion is taken to the VDU and only 20 % of the AR is stored in tanks. Processing heavy crude oils in CDU A implies processing only light crude oils in CDU B and large amounts of AR taken from this unit to the storage tanks.



	Light Crude Oils (CDU A)	Light Crude Oils (CDU B)
■ AR to Tank (t/h)	59,2	23,6
■ AR to VDU (t/h)	33,6	79,6
■ AR to FCC (t/h)	30,3	18,7

Figure 22: Distribution of the Light Crude Oil Atmospheric Residue

Due to the higher temperature of the AR at the outlet of CDU B, more heat is lost in the final cool down when the residue proceeds from this unit. Table 19 compares three cases where large amounts of atmospheric residue (88 t/h, 97 t/h and 100 t/h) were taken to the storage tanks and the respective heat losses produced. This table compares the heat losses generated when the AR proceeds from each of the CDUs and shows that in the three cases, the heat losses are at least 48% higher in CDU B by a similar AR amount.

		CDU A	CDU B	CDU A	CDU B	CDU A	CDU B
AR to tank	(t/h)	88	88	97	97	100	100
Heat Flow Rate	(MW)	4.0	8.1	3.9	8.6	4.1	7.9
Difference	(MW)	4.1		4.6		3.8	
Difference	(%)	51		54		48	

Table 19: Heat Losses due to Final Cooling Down of AR (Comparison CDU A and CDU B)

Table 20 presents a rough estimation of the heat losses that would generate the processing of only light crude oils in CDU B. These losses are calculated using the average amount of AR that is currently taken to the tanks (from CDU A) and the AR outlet temperature from each CDU unit. The heat losses due to the final cool down of AR increase by 1.7 MW when only light crude oils are processed in CDU B and the AR is taken from this unit to the storage tanks.

	AR mass flow (t/h)	Temp. to Cooler(°C)	Heat Final Cooling (MW)
CDU A	59.2	183	3.3
CDU B	59.2	238	5.0
Difference	0	55	**1.7**

Table 20: Heat Losses due to Final Cooling Down of AR (at average AR amount to tank)

5.3 Fouling of the C-1B-107 1/2

The crude oil temperature at the heater inlet decreases with time due to the fouling of the heat exchangers in the preheat train. The temperature decrease rate was calculated for 100 days after each turnaround of the CDU B to study this effect. The results are presented in table 21 and in appendix 30. After the third turnaround in CDU B the heater inlet temperature decreases at 0.1 °C/day which is 40 % less than the decrease rate of the other analyzed periods.

	1st. Turnaround Mar. 2010	2nd. Turnaround Mar. 2012	3rd. Turnaround Mar. 2014
Temp. Decrease Rate (°C/day)	-0.17	-0.16	-0.10

Table 21: Temperature decrease rate 100 days after each turnaround in CDU B

The fouling in C-1B-107 1/2 has become significantly slower after the last turnaround of CDU B in march 2014. This can be observed in figure 14 (in section 3.3) at the end of the diagram starting from march 2014 where the heat flow rate of the exchanger does not decrease immediately after a cleaning like in the previous years.

An analysis of the operational mode in CDU B is conducted to determine the reason of this change. The mean composition of the crude oil processed, the number of heavy and light crude oils batches and the changing frequency of the crude oil type in the unit are considered. For the analysis, five months after the last two cleanings of C-1B-107 1/2 were considered. Period 2 evaluates the five months after the last cleaning of the heat exchanger, which took place during the last turnaround of the unit in March 2014. Period 1 evaluates the five months after the previous cleaning May 2013. Those cleanings can also be recognized in figure 14 when the heat flow rate of the exchanger exceeds 8 MW. The following results were obtained:

- After the third turnaround of the CDU B, the mean composition of the crude oil mixtures was upgraded. For instance, the percentage of Siberian light (one of the most expensive light crude oils processed by BO) was increased by 8 %, and the average content of Kuwait Export (heavy crude oil with a high sulfur content) was reduced by 21 % in the composition of the crude oil mixtures processed in CDU B.

- A significant alteration in the changing frequency of the crude oil type processed in CDU B was also identified after the third turnaround. Figure 23 illustrates the changing frequency of the crude oil type in CDU B for the two analyzed periods. In period 1, a light crude oil was processed after three or four batches of heavy crude oil. However in period 2 after the turnaround, the changing frequency increased significantly, processing a batch of light crude oil after one or two heavy crude oil batches.

These two factors show a considerable positive effect on the fouling in C-1B-107 1/2 as it can be seen in figure 14 from march 2014.

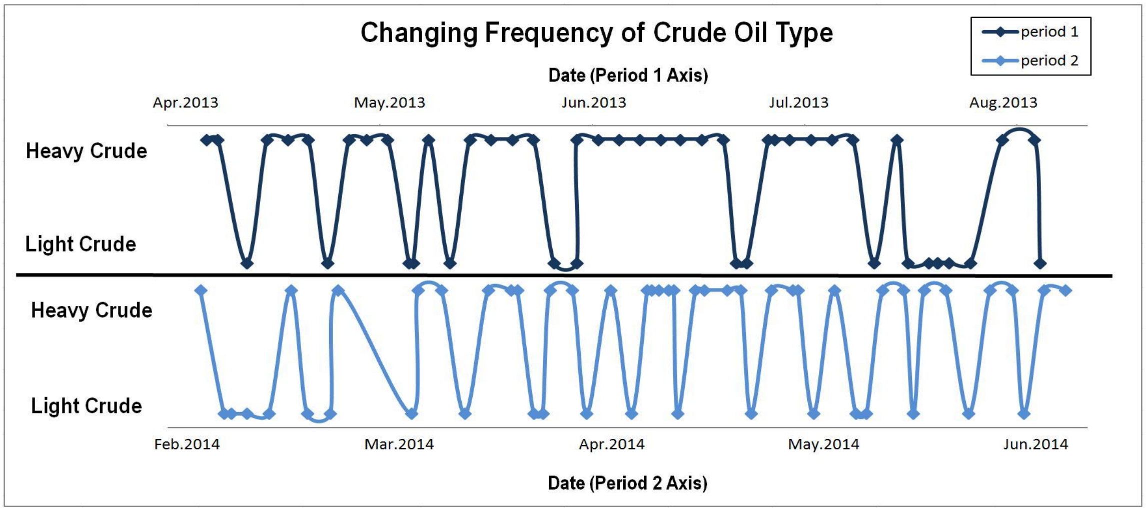


Figure 23: Changing Frequency of Crude Oil Type

The fouling of the heat exchangers C-1A-107 1/2 and C-1B-107 1/2 was estimated before the test runs. It was determined that both heat exchangers had a similar fouling factor by the time when the test runs were conducted (table 22) and that the energy comparisons wont be affected by this condition.

	Current Fouling factor $W/(m^2K)$
C-1A-107 1/2	0.004
C-1B-107 1/2	0.0035

Table 22: Current Fouling factor in C-1A-107 1/2 and C-1B-107 1/2

At the refinery a monthly corrosion inspection is conducted. For this inspection, the wall thickness is measured with sensors at critical points in the units. This allows to determine the actual corrosion state and rate in the units. The report generated for August (after the test runs in CDU A were conducted) detected a low corrosion in the potential critical points and no crude oil-attributable corrosion in CDU A. In CDU B, a low corrosion degree was detected as expected outside the heavy crude oils season. Since no changes in the corrosion rates were recognized by the test runs, this report suggest that corrosion in the units is caused by physical means.

Since corrosion fouling was not influenced by the test runs conducted in CDU A, it can be presumed that the fouling in the units is mainly caused by asphaltene deposition in the tubes of the heat exchangers due to the high temperatures. A detailed fouling study is out of the scope of this thesis. However, the test runs present a start point for further analysis about the fouling in C-1B-107 1/2 that can contribute to the upgrading of CDU B.

5.4 VDU Heater Duty

There are two main factors to be considered for the comparison of the VDU heater duty: the input rate and the inlet temperature of the AR. The other meaningful variables that influence the duty of a fired heater such as pressure and transfer temperature remain constant during the data sets considered for the analysis and are not relevant for this specific comparison. Table 23 presents the AR input rate, inlet temperature into the VDU, heater inlet temperature and normalized duty of the VDU heater for the analyzed cases.

	AR Input (t/h)	AR Temp. to VDU (°C)	VDU Heater Inlet Temp. (°C)	VDU Heater Duty (MW)
Reference	181.1	238.2	294.6	19.6
Test Runs	179.9	182.6	272.8	23.4*
Difference	-1.2	-55.6	-21.8	**3.8**

*Normalized based on the AR input rate in the reference case

Table 23: CDU and VDU Heater Duty

As it was mentioned in section 5.1, the normalization of the measured duty of the fired heater is conducted to provide an accurate evaluation of this variable eliminating the effect of the changing input rate. For this aim, the measured duty is normalized according to the input rate of the reference case. This presents a difficulty in the analysis of the VDU since the measurement techniques used for the heavy atmospheric residue have proven to be inaccurate. Thus to rate the deviation, the AR input was estimated with the following data:

- Energy balances around the heat exchangers on the AR line: The balances were conducted for C-1A-107 1/2 and for C-1A-137. The other heat exchangers on the AR line could not be considered, because of the lack of temperature measurements on the sink side. The results obtained from the energy balance of C-107 1/2 are not accurate for all test runs due to bypass valve and possible evaporation of the crude at the outlet of the exchanger. As C-1A-137 does not exist in the CDU B, this energy balance cannot provide the necessary data for the normalization of the heater duty. The calculations around the heat exchangers in the AR line were therefore discarded.

- Refinery balance: this mass balance is generated on a daily basis for accounting in the refinery. The measured input and output mass flows of the units are adjusted according to the data from end product and from crude oil tanks. This is one of the most accurate measurements of the refinery. However, these results present a deviation for the days where the switch between the operational modes takes place. This is caused because data of both operational modes are considered in the calculations when the switch does not happen at 00:00 (which is normally the case). On weekends the refinery balance presents another error source. The calculations are made on Mondays with the average data from Friday, Saturday and Sunday. The deviation between the measured AR input and the input calculated by this refinery balance was 12 % in the first test run. This was caused by a public holiday in Germany on Friday 15.08.2014. The refinery balance was generated at Monday of the following week with the average data of Thursday, Friday, Saturday and Sunday (14.08.2014 - 17.08.2014) where the results from two different operational modes were averaged and an unique value for those days was generated. On the other test runs, the deviation between the measurement and the calculated VDU input was 4.3 %.

- Crude oil tank data: this estimation was made in accordance with the regular measurements of the available volume in the crude oil tanks, the density of each heavy crude oil batch and its atmospheric residue percentage. This is a very reliable calculation and presented a constant deviation from the measured mass flow in all test runs; between 6 - 8 t/h above the measured value (average deviation 5 %).

Since the inaccuracy of the AR mass flow measurement was found to be relative low (deviation between 4.3% and 5%), this value was used without further corrections. The VDU input is presented in figure 24 for the three data sets considered and the four test runs.

Table 23 also presents the VDU heater inlet temperature. As mentioned in the last section, due to the enhanced preheat train of the CDU A, the AR reached lower temperatures at the outlet of this unit. The AR inlet temperature in the VDU is 55.6 °C lower when the AR proceeds from CDU A. The heat transfer potential of the exchangers on the VDU preheat train (C-403 1/3 and C-410 A/B) is increased due to a colder sink which reduces this difference to 21.8 °C. Nonetheless, the remaining difference represents an increase on the VDU heater duty of 3.6 MW when the AR proceeds from CDU A. This shows that when energy is saved in the CDU heater (by processing heavy crude oil in the CDU A), more energy is required in the VDU heater.

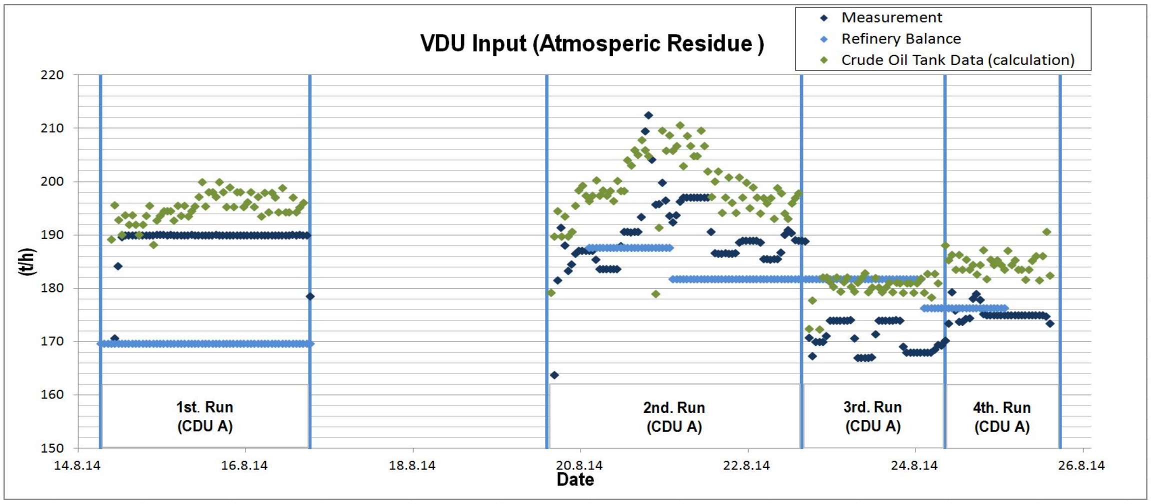


Figure 24: VDU Input

5.5 Steam Generation in the VDU

As mentioned in section 3.4, the AR inlet temperature in VDU plays an important role in the steam production. Since the AR inlet temperature in VDU is reduced during the test runs, the steam generation also presents a diminution. Table 24 reports the average ES and FS generation for the reference case (AR proceeding from CDU B) and for the test runs (AR proceeding from CDU A). It can be observed in this table, that ES was reduced in approx. 80 %, and FS in 20 %.

	FS Steam C-417 (t/h)	Total ES Steam C-418-1/2 (t/h)
Reference	7.1	4.4
Test Runs	5.7	1.0
Difference (t/h)	**-1.4**	**-3.5**
Difference (MW)	0.84	2.10
Reduction	20%	78%

Table 24: CDU and VDU Heater Duty

As mentioned in section 3.4, ES is generated in excess during summer and it is desirable to reduce this production in this period. Therefore, the results presented in table 24 represent a possitive effect of processing heavy crude oils in CDU A. Figure 25 shows ES and FS generation in VDU during the test runs. During the 2nd and 3rd test runs a complete reduction of ES can be observed indicating a significant impact on the steam balance of the refinery.

The FS generation was also reduced in the test runs, however in this case the reduction was less severe (20 %). As discussed in section 3.4, due to its thermodynamic properties, FS can be used for other applications such as a reboiler heat source. As a consequence, the low reduction on the FS steam production is considered as a positive effect.

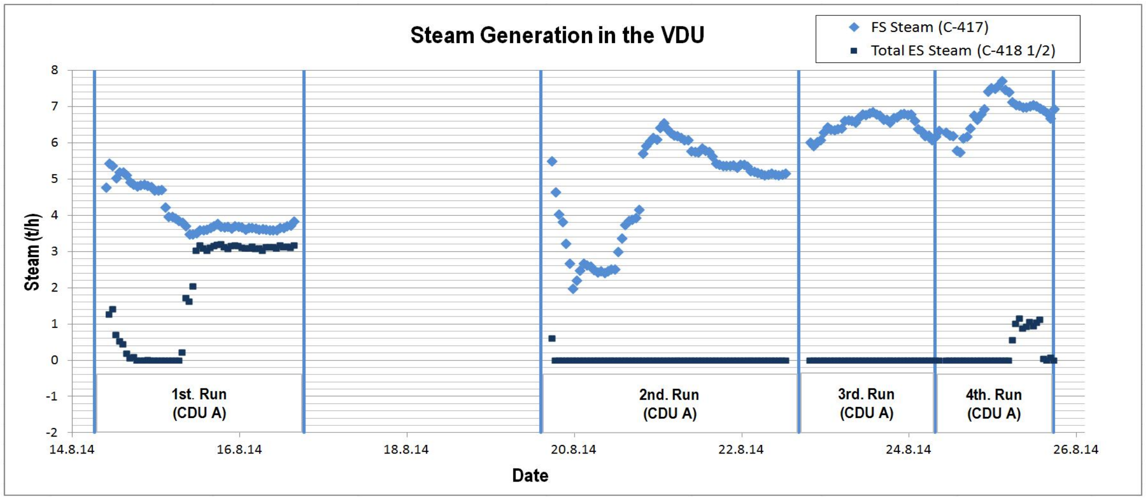


Figure 25: Steam Generation in the VDU

5.6 Additional Variables considered for the Overall Energy Balance

The additional variables that were affected by the changeover of the operational mode in the CDUs and whose changes were considered for the energy balance calculations of the system CDU-VDU are briefly described in this section. As mentioned at the beginning of this chapter, the configuration CDU B - VDU is considered the reference state of the balance system and the configuration CDU A - VDU as the final state.

5.6.1 C-1B-132 Heat Flow Rate

The heat exchanger C-1B-132 is only present in the crude oil preheat train of the CDU B thus it only has an effect on the reference state of the system. This heat exchanger rises the temperature of the crude oil in 8.6 °C by transferring 2.3 MW from a hot heavy wax distillate (SWD) stream.

Since this heat exchanger is only present in the reference state of the system, its heat flow rate is added to the final state to equalize the difference generated by the equipment.

5.6.2 Stabiliser Energy Consumption

The atmospheric residue generated in both distillation units is used as a heat source for the stabiliser reboiler and for the preheat of the stabiliser feed. During the test runs, less product was processed in the stabiliser than in the reference case due to operational conditions of the DHT, which are independent to the operation of the CDUs. This caused a lower energy consumption in the stabiliser reboiler and in the preheating of its feed. This reduction is shown in table 25 and was considered for the overall energy balance.

Heat Exchanger	Stabiliser Reboiler C-204 A/B (MW)	Stabiliser Feed Preheat C-205 1/3 (MW)
Reference	7.8	1.3
Test Runs	7.5	0.6
Difference	-0.3	-0.7

Table 25: Stabiliser Enery Consumption

5.6.3 Vacuum Residue Outlet Temperature

The temperature at which the vacuum residue (VR) leaves the VDU decreased during the test runs in 4.1 °C. This temperature difference represents 0.3 MW that are transported out of the CDU-VDU system by the VR in the reference state.

Therefore, this heat flow was normalized to the mass flow of VR and added to the final state of the system for the calculations of the energy balance.

5.6.4 SWD Product Stream Outlet Temperature

The temperature at which the SWD product stream leaves the VDU decreased by 7 °C during the test runs. This temperature difference represents less energy transported out the system by the SWD (or from the opposite perspective, more energy that stays in the balanced system CDU-VDU compared to the referece case). This heat flow rate was normalized according to the SWD mass flow in the reference case and was added to the final state of the system.

5.6.5 Additional Product Streams Outlet Temperature

The test runs conducted in the CDUs caused no relevant change on the outlet temperature of the additional product streams leaving the CDU - VDU system.

5.7 Overall Energy Balance

Figures 26 and 27 show the process flow diagrams of the VDU-CDU system configuration for the reference state (CDU B - VDU) and for the final state (CDU A - VDU Test runs) of the balanced system. Only relevant information for the comparison between the two states of the unit is presented in these figures. Following the law of conservation of energy the calculation of the overall energy balance can be defined as follows:

$$\sum Q_{ref.\ state} = \sum Q_{final\ state}$$

$$\sum Q_{\substack{ref.\\ state}} = \left(Q_{\substack{CDU\\ Heater\ Duty}} + Q_{\substack{VDU\\ Heater\ Duty}} + Q_{\substack{In\ the\ form\\ of\ Steam}} + \Delta Q_{CB-132} - Q_{\substack{Transported\ out\\ of\ system}}\right)_{@\ Ref.\ state}$$

$$\sum Q_{\substack{final\\ state}} = \left(Q_{\substack{CDU\\ Heater\ Duty}} + Q_{\substack{VDU\\ Heater\ Duty}} + Q_{\substack{In\ the\ form\\ of\ Steam}} - Q_{\substack{Transported\ out\\ of\ system}}\right)_{@\ final\ state}$$

$$Q_{\substack{Transported\ out\\ of\ system}} = Q_{\substack{SWD\ stream\\ temperature}} + Q_{\substack{VR\ stream\\ temperature}} + Q_{\substack{Stabiliser\\ Reboiler}} + Q_{\substack{Preheat\ of\\ Stabiliser\ feed}}$$

Each of the variables considered for the overall energy balance were individually described in this chapter. The aim of this section is to provide an overview of the system behavior and to summarize the obtained results regarding energy consumption, from a global perspective of the analyzed system. Table 26 presents a summary of the overall energy balance results in the CDU - VDU system. In this table only the most important variables for the analysis are presented. A table with the other variables mentioned in this chapter can be find in appendix table 28.

As it can be observed in table 26, processing heavy crude oils in the unit with the greater heat recovery capacity achieves an effective decrease on the heater duty of the crude distillation unit. However, the thermal dependency between CDU and VDU causes a larger energy consumption in VDU heater and less heat in form of steam in

	CDU Heater Duty(MW)	VDU Heater Duty(MW)	C-1B-132 Heat Flow(MW)	System Energy Input (MW)
Reference	60.4	19.6	2.3	
Test Runs	55.7	23.4	0	**-3.3**
Difference	**-4.8**	**3.8**	**-2.3**	
	FS Steam (t/h)	ES Steam (t/h)		System Energy Output (MW)
Reference	7.1	4.4		
Test Runs	5.7	1.0		
Difference	-1.4	-3.5		**-3**
Associated Heat (MW)	**-0.9**	**-2.1**		

Table 26: Overall Energy Balance Results Summary

VDU. Thus processing heavy crude oils in CDU A provides a solution to the current process limitation in CDU B due to a shift of the energy requirements in the system and not due to an actual energy saving. Nevertheless, the reduction in ES production, is assessed as energy savings during summer where ES is considered as a useless product.

As mentioned in section 5.2, processing heavy crude oils in CDU A represents the permanent processing of light crude oils in CDU B generating 1.7 MW heat loses due to the final cooling of the AR before it is taken to the storage tanks. This presents an argument against the simple changeover of the CDUs operational modes and indicates that an option to cool down the AR and to use this high temperature levels has to be developed for this to be an economically viable alternative.

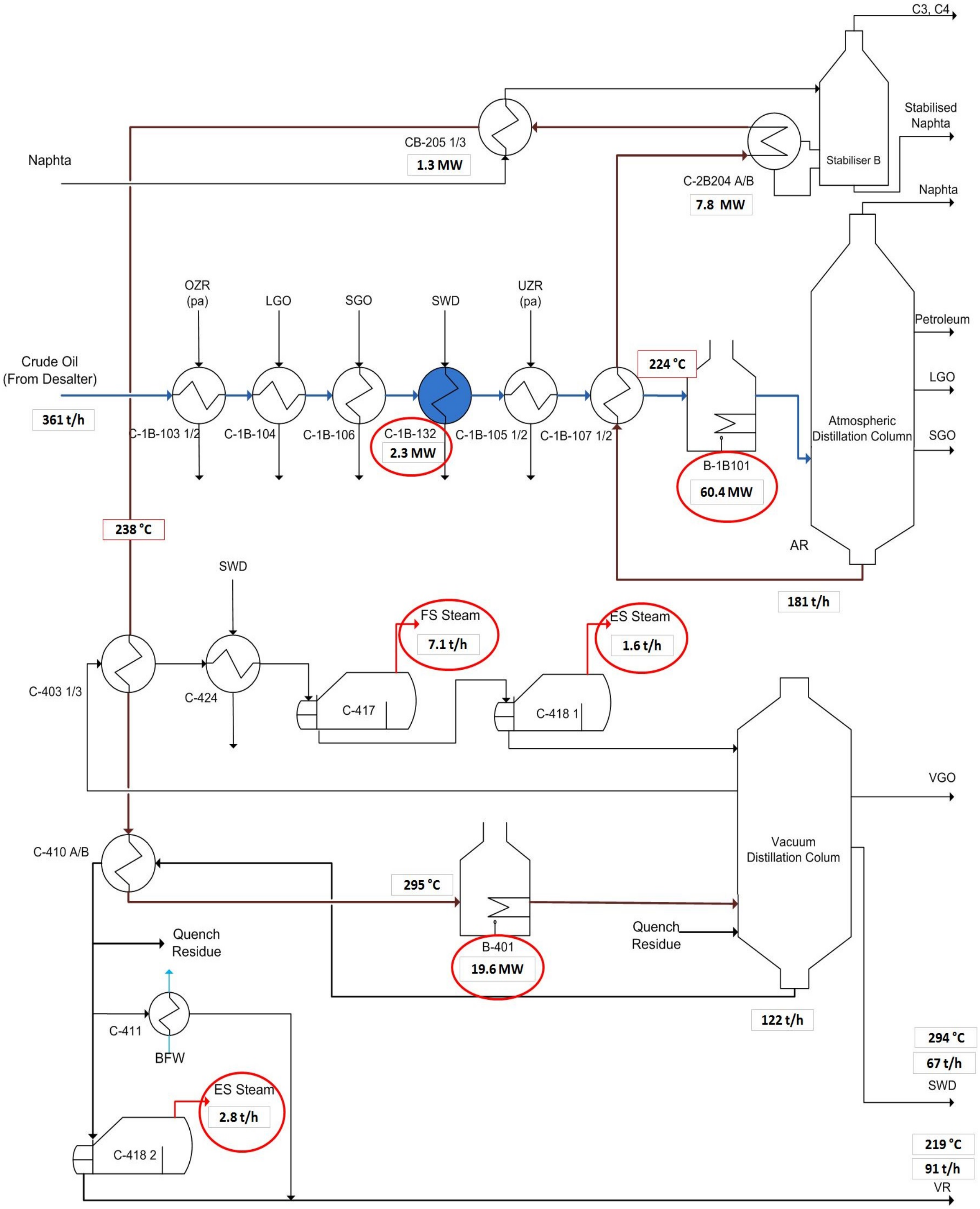


Figure 26: Reference state CDU B - VDU

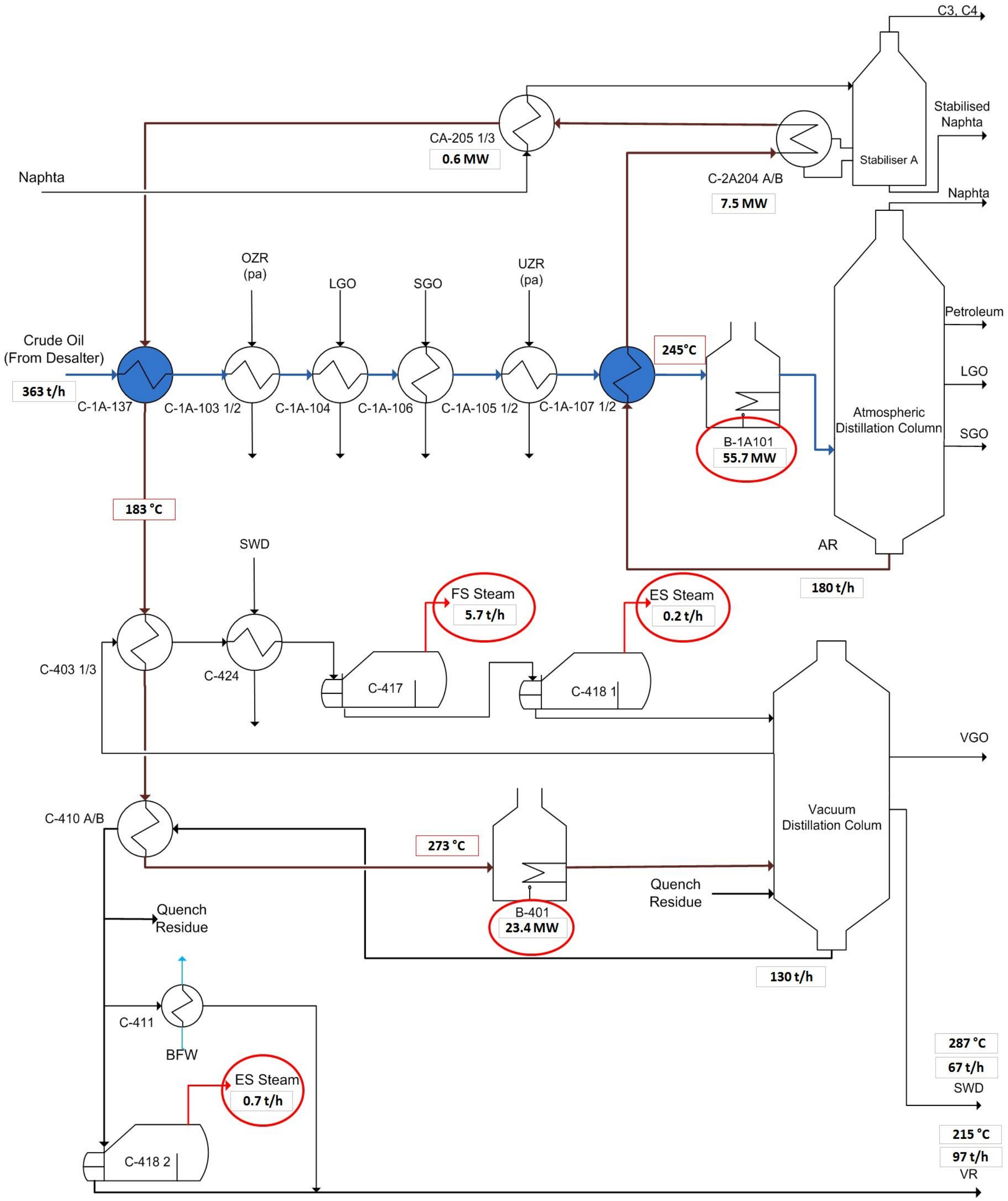


Figure 27: Final state CDU A - VDU (Test Runs)

6. Conclusions and Suggestions

The processing of heavy crude oils in the distillation unit with the larger preheat capacity (CDU A) evidenced a significant reduction of the heater combustion duty. However this is accomplished at the expense of heater duty in the vacuum distillation unit (VDU) and the steam generation.

A reduction of ES (Exhausted Steam) generation was achieved by the changeover of the distillation units operational modes. This reduction is assessed as a positive effect but only during half the year when an ES overproduction takes place and this steam is considered an useless product.

Permanent processing light crude oils in the unit with the lower heat recovery capacity (CDU B) leads to heat losses due to the final cool down of the atmospheric residue before it is taken to the storage tanks. This is an argument against the immediate implementation of processing heavy crude oils in CDU A.

Processing heavy crude oils in the unit with the higher preheat capacity shows ultimately no energetic benefit except for the reduction of the ES generation in the VDU. This changeover represents a shift of the energy requirements in the overall CDU - VDU system and presents an alternative to overcome the process capacity limitation of the unit that currently processes heavy crude oils. This increases the processing capacity of the crude distillation unit and since the CDU is the first processing unit in a refinery, a larger processing capacity represents not only flexibility but also the possibility to increase the overall refinery yield by generating more feedstock for the downstream process units. This additional capacity is useful if there is a heavy crude oil derived products demand.

Suggestions

Suggestions for upgrading the actual situation in the crude distillation units are subsequently made based on the insights provided by this study. Two scenarios are be considered.

1st. Scenario: Processing heavy crude oils in CDU A

This scenario contemplates the case of a desirable yield increase. Since the benefit of processing heavy crude oils in CDU A is increasing the processing capacity, this alternative makes sense only if there is a market demand. For long-term heavy crude oil processing in CDU A, it is necessary to find an alternative to efficiently cool down the atmospheric residue generated in CDU B when processing light crude oils before it is taken to the storage tanks. The following alternative is suggested.

- **Use the AR high temperature to preheat the combustion air in the CDU B heater**
  Currently the combustion air for the heater is taken from the atmosphere with a natural draft (as briefly described in section 2.1.3) and undergoes no preheat. This air enters the heater at ambient temperature and leaves at a temperature of approx. 300 °C. Using the high temperature of the atmospheric residue to preheat the combustion air would increase the effective heat transferred to the crude oil by decreasing the heat taken by the combustion air and a lower heater duty would be required to take the crude oil to its transfer temperature. The capital investments in this case would include the construction of a new heat exchanger and its assembling.

2nd Scenario: Further processing heavy crude oils in CDU B

The further processing of heavy crude oils in CDU B might be considered in the case that no significant throughput increase is desired/required mainly due to a low market demand of heavy crude oils derived products. To upgrade the actual situation of the CDU - VDU system, two alternatives are discussed.

- **Use ES to preheat the combustion air in the CDU B heater** (Utilization of ES and reduction of the heater duty).
  Steam is produced in excess in summer, which is also the time where the heavy crude oil season takes place. Using the additionally generated steam for the preheat of the combustion air in CDU B heater presents an effective alternative to combine and solve two current problems in the CDU B - VDU system. With

this alternative, the heater duty is reduced by using an available useless product. Using the steam to preheat the combustion air also allows an efficient utilization of this resource due to a large heat transfer rate caused by steam condensation. For this alternative, the capital investment includes a new heat exchanger, its assembling and piping work for the removal of the ES steam from the steam network.

- **Enlargement of C-1B-107 1/2 and new heat Source for the Stabiliser Reboiler** (Reduction of ES and reduction of the heater duty)
  As shown in the test runs, the opening of the bypass valve around the enlarged C-1A-107 1/2 is necessary to maintain the atmospheric residue at a high enough temperature to meet the stabiliser reboiler required duty. This prevents the utilization of the available heat transfer area and a more effective preheating of the crude oil. As shown in Simulation 2, enlarging the C-1B-107 1/2 presents a possibility to decrease the CDU B heater duty but it requires another heat source for the stabiliser reboiler. This option would also allow a greater heat recovery from the atmospheric residue reducing its temperature and the steam generation in the VDU. The capital investment for this alternative is the enlargement of the heat exchanger.

BIBLIOGRAPHY

Awad, M. M. (2011). Fouling of heat exchangers surfaces, *Heat Transfer - Theoretical Analysis, Experimental Investigations and Industrial Systems* pp. 505–543.

Baukal, C. E. (2001). *The John Zink Combustion Handbook*, John Zink Company LLC.

BAYERNOIL (2001). *Begleitunterlagen zur Anlagenausbildung in der Rohoel-Destillationsanlage*, BAYERNOIL Raffineriegesellschaft mbH.

BAYERNOIL (2006). *Begleitunterlagen zur Anlagenausbildung, Dampferzeugung*, BAYERNOIL Raffineriegesellschaft mbH.

BAYERNOIL (2014a). *BAYERNOIL Intranet*, BAYERNOIL Raffineriegesellschaft mbH.

BAYERNOIL (2014b). *BAYERNOIL Raffinerie Information System, BORIS im BAYERNOIL Intranet*, BAYERNOIL Raffineriegesellschaft mbH.

Boege, A. (2007). *Vieweg Handbuch Maschinenbau: Grundlagen und Anwendungen der Maschinenbau-Technik.*

Chen, J. C. (1996). *Convective Flow Boiling.*

David S. J. Jones, P. R. P. (2006). *Handbook of Petroleum Processing*, Springer Science & Business Media.

E.J. Dittus, L. B. (1930). Publications of engineering, university of california, **120(1)**: 193–213.

ENGGcyclopedia (2011). Engineering design encyclopedia enggcyclopedia, atmospheric distillation unit. Available online:
$http://www.enggcyclopedia.com/2011/05/atmospheric-distillation-unit/$
(Accessed 2.Juni2014).

Favennec, J. (2001). *Band 5 von Petroleum Refining: Refinery Operation and Management*, Editions TECHNIP.

Incropera, F. P. (2011). *Introduction to Heat Transfer*, Univ. of Notre Dame.

James G. Speight, B. O. (2001). *Petroleum Refining Processes*, CRC Press.

Jukic, A. (2013). *Presentation. Petroleum Refining: Distillation*, Faculty of chemical engineering and technology, University of Zagreb.

Ke-fa Cen, Yong Chi, J. Y. (2009). Characteristics of fluid flow and heat transfer in shellside of heat exchangers with longitudinal flow of shellside fluid with different supporting structures, *Challenges of Power Engineering and Environment: Proceedings of the International Conference on Power Engineering 2007* **1**: 474 – 479.

Maria, M. H. J. (2013). *Disenho y calculo de intercambiadores de calor monofasicos.*

Mueller-Steinhagen, H. (2000). *Heat Exchanger Fouling: Mitigation and Cleaning Techniques.*

Nam-Trung Nguyen, S. T. W. (2009). *Fundamentals and Applications of Microfluids.*

NPTEL (No date given). National programme on technology enchanced learning (nptel), module: Heat exchangers, lecture 35. Available online:
$http : //nptel.ac.in/courses/103103032/$
(Accessed 15. July2014).

of Delaware, U. (No date given). Thermal laboratory. Available online:
$http : //research.me.udel.edu/\ prasad/meeg346/labs/heat_exchanger/heatex.pdf$
(Accessed 08.July 2014).

OSHA (1999). Occupational safety & health administration osha, petroleum refining processes. Available online:
$https : //www.osha.gov/dts/osta/otm/otm_iv/otm_iv_2.html$
(Accessed 2.Juni 2014).

Ramesh K. Shah, D. P. S. (2003). *Fundamentals of Heat Exchanger Design*, John Wiley & Sons.

Ramsden, E. (2000). *A-Level Chemistry*, Nelson Thornes.

Sölken, W. (2011). Explore the world of piping. Available online:
$http : //www.wermac.org/equipment/heatexchanger_part5.html$
(Accessed 03.July 2014).

VDI (1997). *VDI - WAERMEATLAS*, Verein Deutscher Ingenieure VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen.

Vette, C. (2014). *Thermodynamische Auslegung und transiente Simulation eines ueberkritischen Organic Rankine Cycles fuer einen leistungsoptimierten Betrieb.*

Wauquier, J. (1994). *Petroleum Refining: Crude Oil Petroleum Products Process Flowsheets*, Editions TECHNIP.

Wiehe, I. A. (2008). *Process Chemistry of Petroleum Macromolecules.*

Appendix

Unit	Heater	Heater Duty (MW)	Maximal Duty Allowed (MW)
CDU A	B-1A101	52.19	61.40
CDU B	B-1B101	61.29	61.40
VDU	B-401	16.26	48.00

Table 27: Combustion Performance Capacity of Fired Heaters (BAYERNOIL 2014b)

	CDU Heater Duty(MW)	VDU Heater Duty(MW)	Stabi. Reboiler Duty(MW)	Stabi. Feed Preheat(MW)	CB-132 Heat Flow(MW)
Reference	60.4	19.6	7.8	1.3	2.3
Test Runs	55.7	23.4	7.5	0.6	0
Difference	**-4.8**	**3.8**	**-0.3**	**-0.7**	**-2.3**
	FS Steam (t/h)	ES Steam (t/h)	VR Outlet Temp.(°C)	SWD Outlet Temp.(°C)	
Reference	7.1	4.4	219.2	294.0	
Test Runs	5.7	1.0	215.0	287.0	
Difference	-1.4	-3.5	-4.1	-7.0	
Associated Heat (MW)	**-0.9**	**-2.1**	**-0.3**	**-0.4**	

Table 28: Overall Energy Balance Results Summary

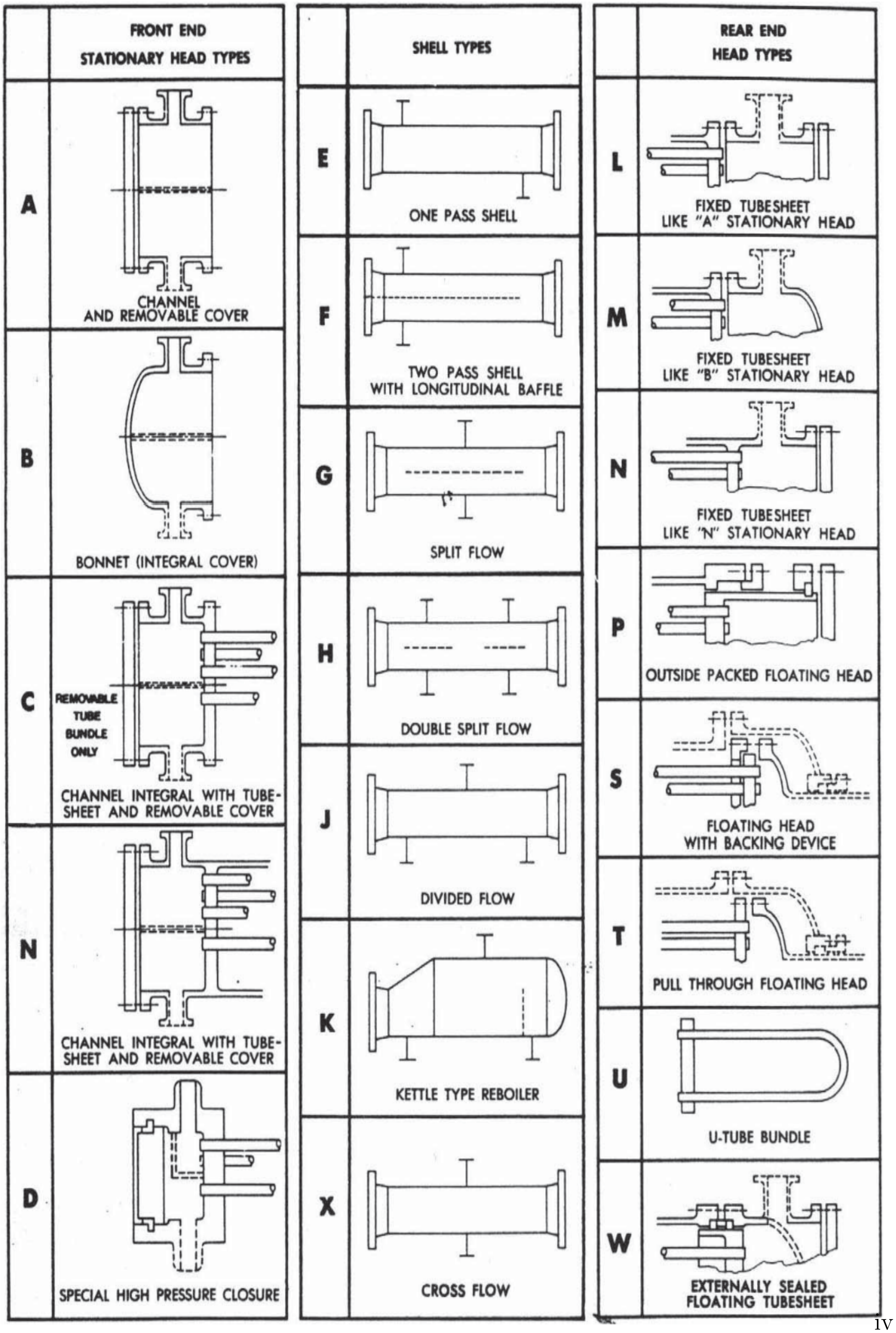


Figure 28: TEMA Standards

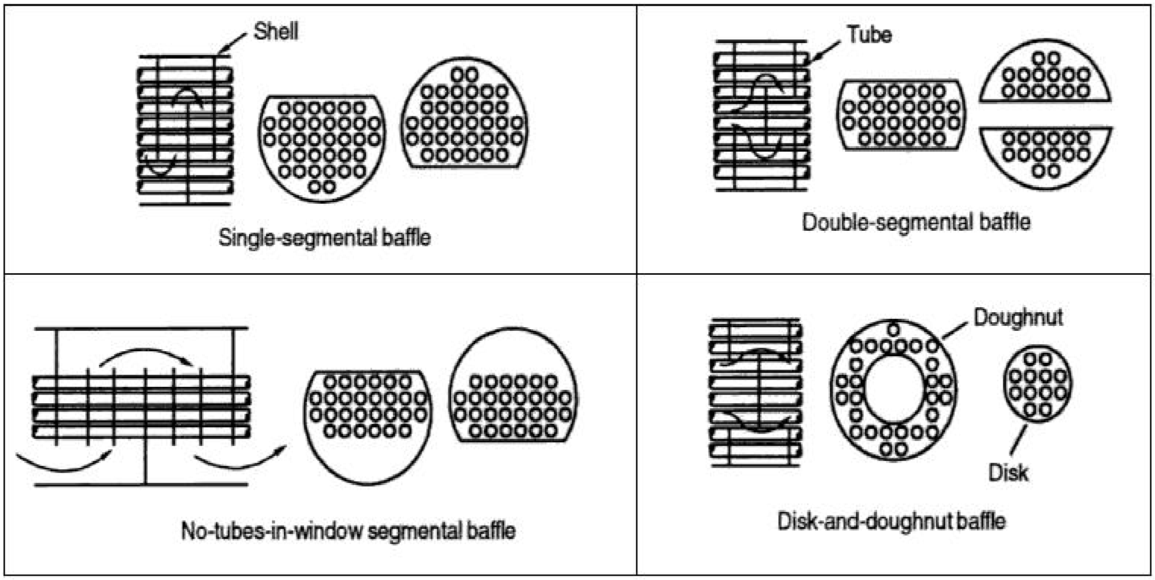


Figure 29: Common Types of Baffles (Modified from (Ramesh K. Shah 2003))

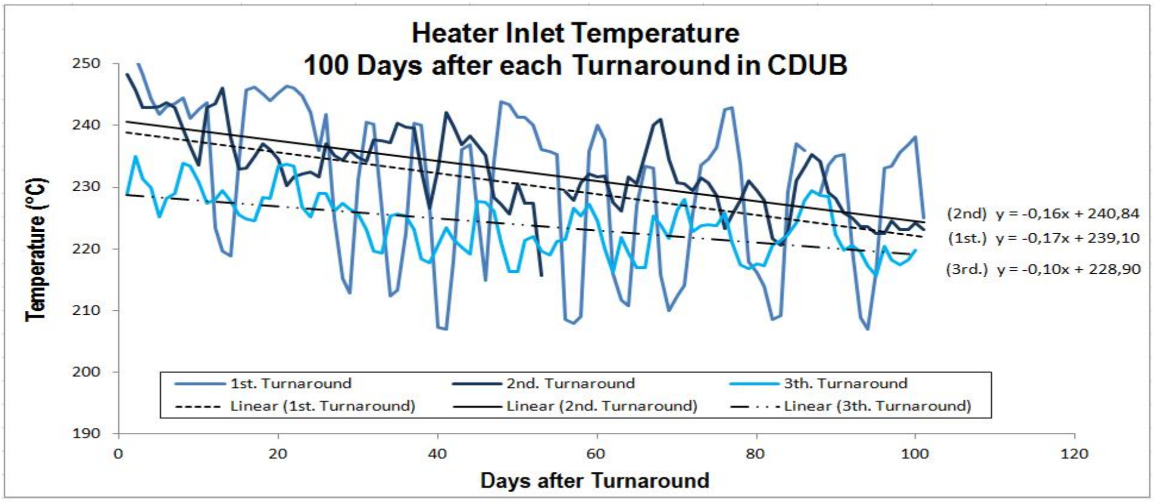


Figure 30: Temperature Decrease Rate in CDU B 100 days after each turnaround

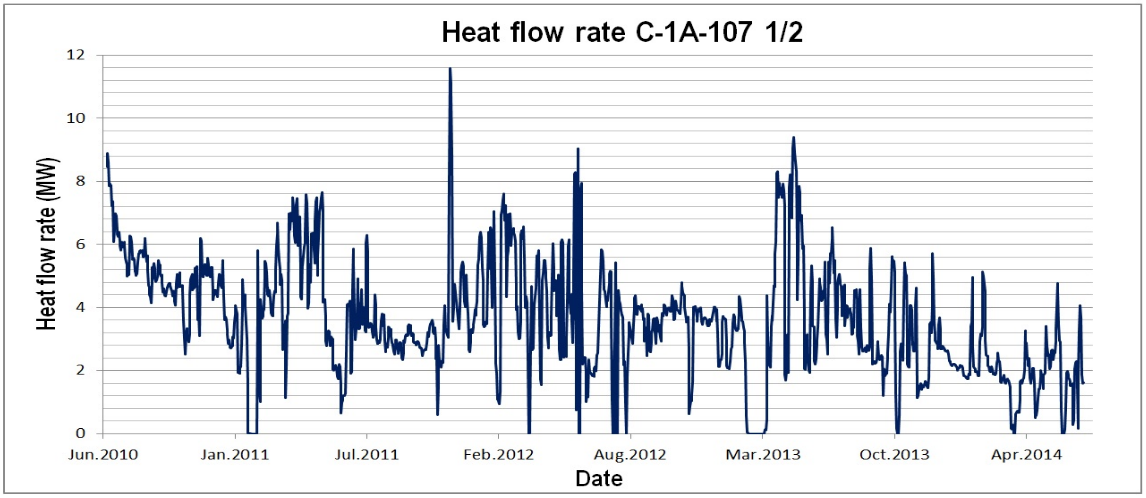


Figure 31: Heat Flow Transfer Rate in CA-107 1/2 Heat Exchanger

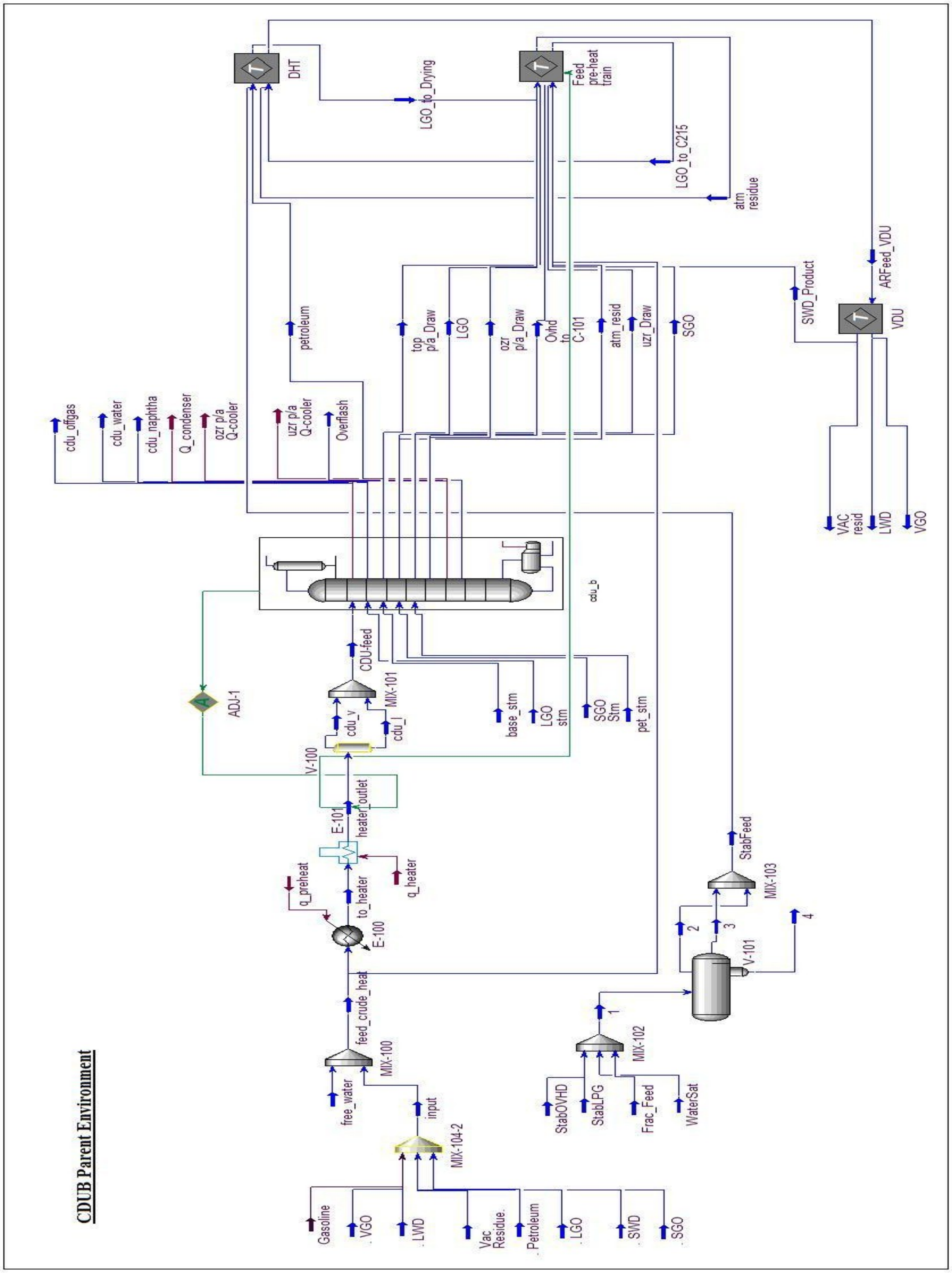


Figure 32: Parent Environment CDU B Simulation

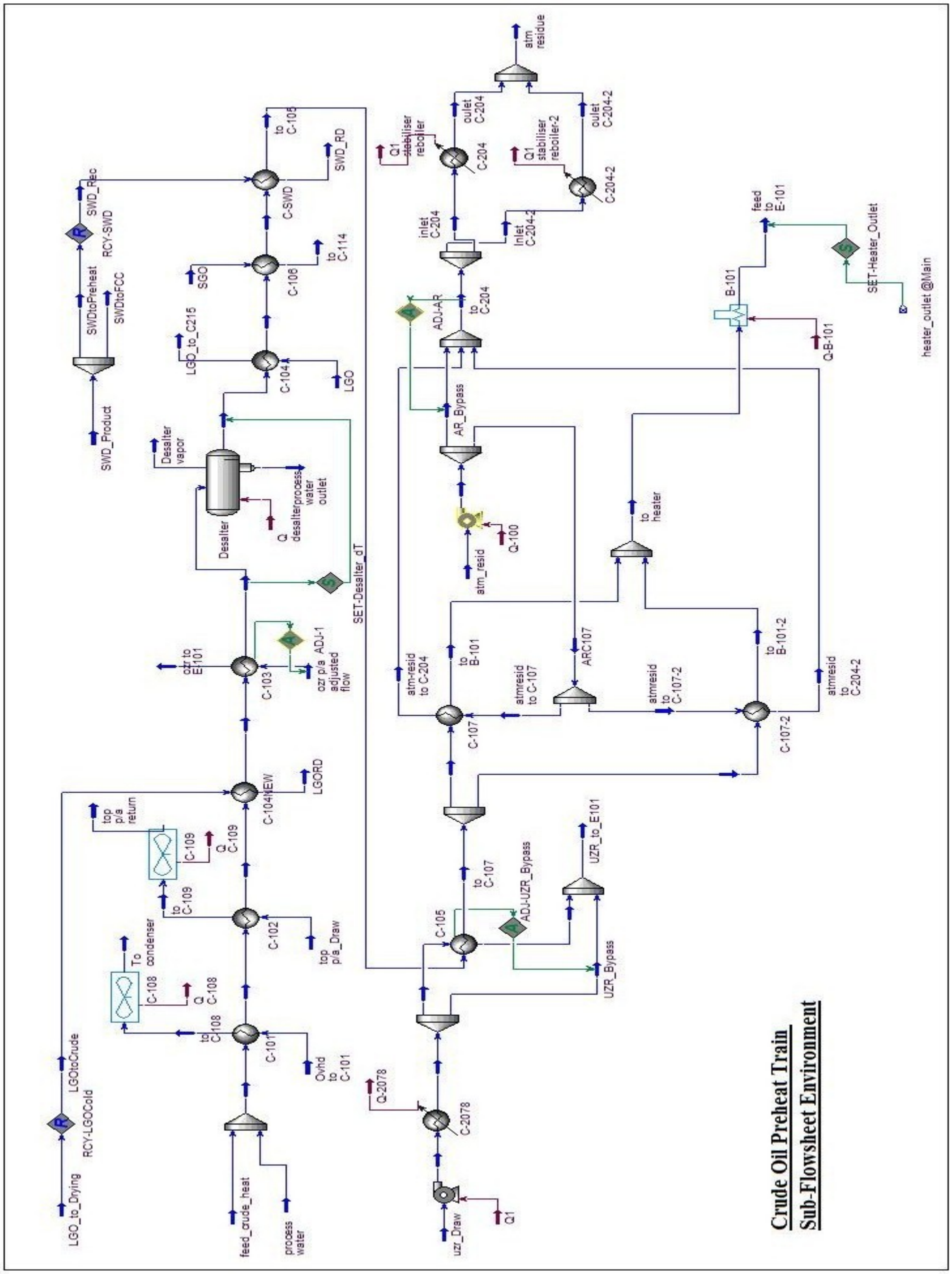


Figure 33: Crude Oil Preheat Train, Simulation Sub-Flowsheet Environment

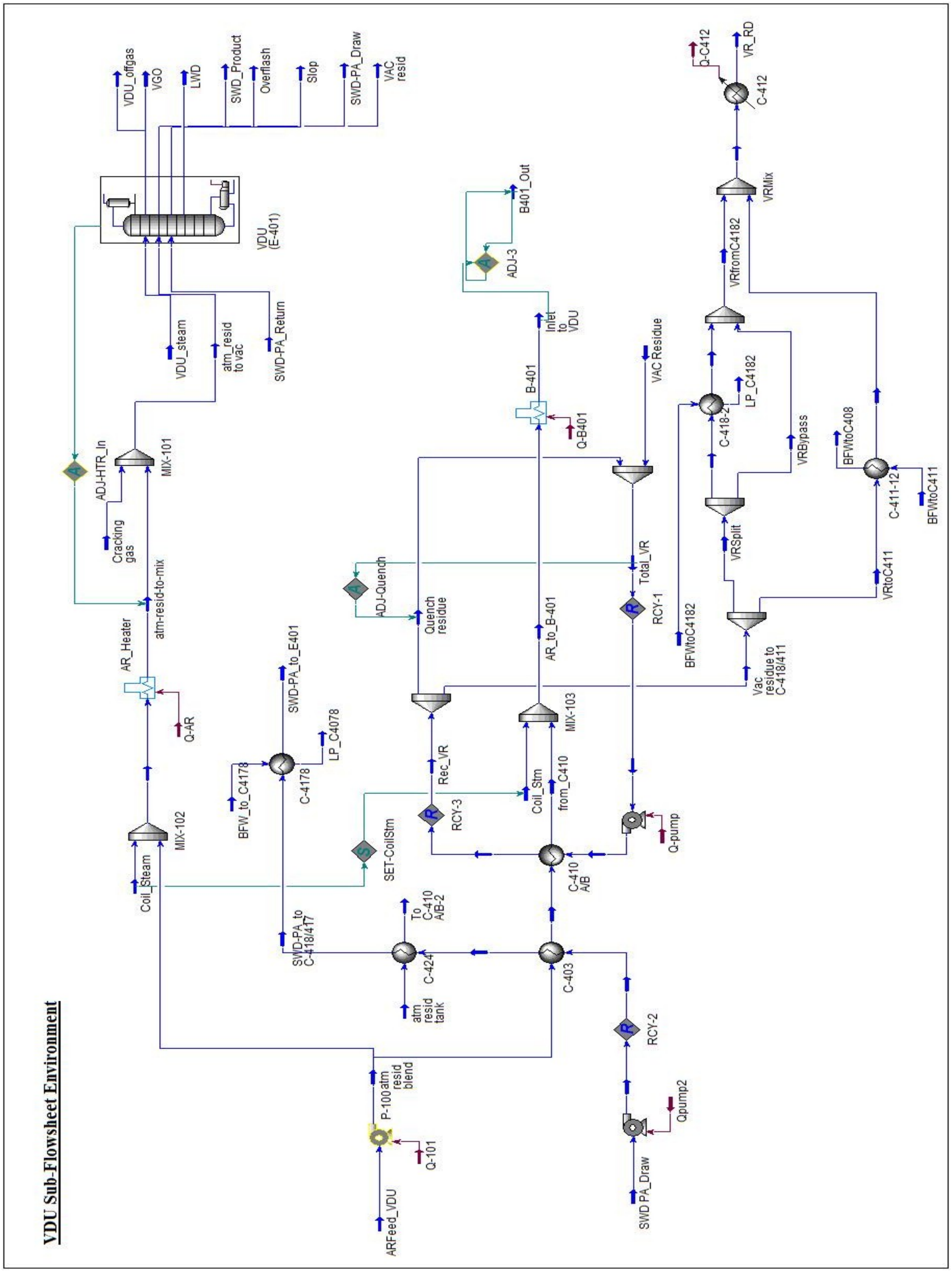
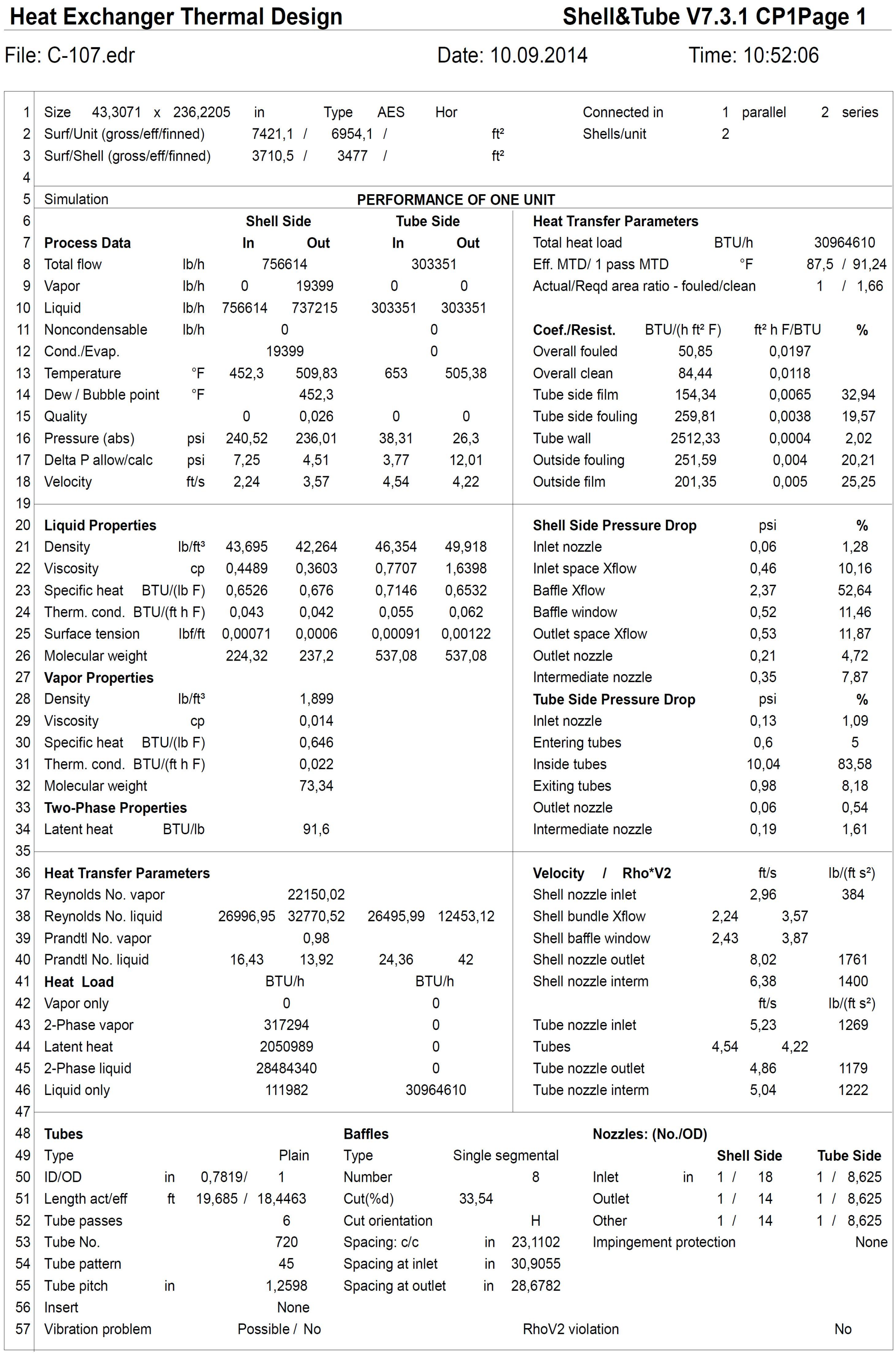


Figure 34: VDU, Simulation Sub-Flowsheet Environment



Heat Exchanger Thermal Design **Shell&Tube V7.3.1 CP1Page 1**

File: C-107.edr Date: 10.09.2014 Time: 10:52:06

Size	43,3071 x 236,2205	in	Type	AES	Hor	Connected in	1 parallel	2 series
Surf/Unit (gross/eff/finned)	7421,1 / 6954,1 /	ft²				Shells/unit	2	
Surf/Shell (gross/eff/finned)	3710,5 / 3477 /	ft²						

Simulation **PERFORMANCE OF ONE UNIT**

		Shell Side		**Tube Side**	
Process Data		**In**	**Out**	**In**	**Out**
Total flow	lb/h	756614		303351	
Vapor	lb/h	0	19399	0	0
Liquid	lb/h	756614	737215	303351	303351
Noncondensable	lb/h	0		0	
Cond./Evap.		19399		0	
Temperature	°F	452,3	509,83	653	505,38
Dew / Bubble point	°F		452,3		
Quality		0	0,026	0	0
Pressure (abs)	psi	240,52	236,01	38,31	26,3
Delta P allow/calc	psi	7,25	4,51	3,77	12,01
Velocity	ft/s	2,24	3,57	4,54	4,22
Liquid Properties					
Density	lb/ft³	43,695	42,264	46,354	49,918
Viscosity	cp	0,4489	0,3603	0,7707	1,6398
Specific heat	BTU/(lb F)	0,6526	0,676	0,7146	0,6532
Therm. cond.	BTU/(ft h F)	0,043	0,042	0,055	0,062
Surface tension	lbf/ft	0,00071	0,0006	0,00091	0,00122
Molecular weight		224,32	237,2	537,08	537,08
Vapor Properties					
Density	lb/ft³		1,899		
Viscosity	cp		0,014		
Specific heat	BTU/(lb F)		0,646		
Therm. cond.	BTU/(ft h F)		0,022		
Molecular weight			73,34		
Two-Phase Properties					
Latent heat	BTU/lb		91,6		
Heat Transfer Parameters					
Reynolds No. vapor			22150,02		
Reynolds No. liquid		26996,95	32770,52	26495,99	12453,12
Prandtl No. vapor			0,98		
Prandtl No. liquid		16,43	13,92	24,36	42
Heat Load		BTU/h		BTU/h	
Vapor only		0		0	
2-Phase vapor		317294		0	
Latent heat		2050989		0	
2-Phase liquid		28484340		0	
Liquid only		111982		30964610	

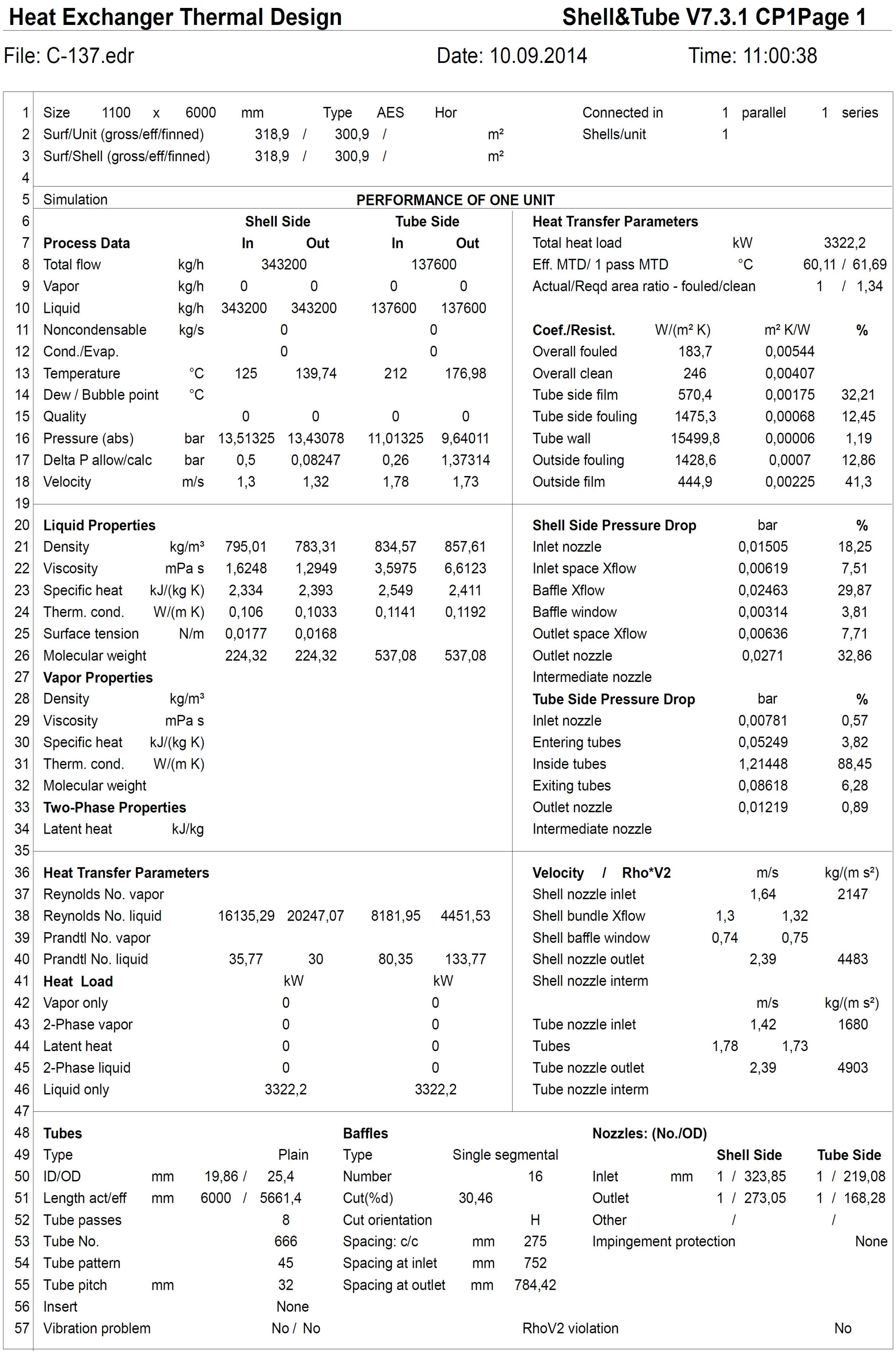
Heat Transfer Parameters			
Total heat load	BTU/h		30964610
Eff. MTD/ 1 pass MTD	°F		87,5 / 91,24
Actual/Reqd area ratio - fouled/clean			1 / 1,66
Coef./Resist.	BTU/(h ft² F)	ft² h F/BTU	**%**
Overall fouled	50,85	0,0197	
Overall clean	84,44	0,0118	
Tube side film	154,34	0,0065	32,94
Tube side fouling	259,81	0,0038	19,57
Tube wall	2512,33	0,0004	2,02
Outside fouling	251,59	0,004	20,21
Outside film	201,35	0,005	25,25

Shell Side Pressure Drop	psi	**%**
Inlet nozzle	0,06	1,28
Inlet space Xflow	0,46	10,16
Baffle Xflow	2,37	52,64
Baffle window	0,52	11,46
Outlet space Xflow	0,53	11,87
Outlet nozzle	0,21	4,72
Intermediate nozzle	0,35	7,87
Tube Side Pressure Drop	psi	**%**
Inlet nozzle	0,13	1,09
Entering tubes	0,6	5
Inside tubes	10,04	83,58
Exiting tubes	0,98	8,18
Outlet nozzle	0,06	0,54
Intermediate nozzle	0,19	1,61

Velocity / Rho*V2		ft/s	lb/(ft s²)
Shell nozzle inlet		2,96	384
Shell bundle Xflow	2,24	3,57	
Shell baffle window	2,43	3,87	
Shell nozzle outlet		8,02	1761
Shell nozzle interm		6,38	1400
		ft/s	lb/(ft s²)
Tube nozzle inlet		5,23	1269
Tubes	4,54	4,22	
Tube nozzle outlet		4,86	1179
Tube nozzle interm		5,04	1222

Tubes			**Baffles**			**Nozzles: (No./OD)**			
Type		Plain	Type		Single segmental			**Shell Side**	**Tube Side**
ID/OD	in	0,7819/ 1	Number		8	Inlet	in	1 / 18	1 / 8,625
Length act/eff	ft	19,685 / 18,4463	Cut(%d)		33,54	Outlet		1 / 14	1 / 8,625
Tube passes		6	Cut orientation		H	Other		1 / 14	1 / 8,625
Tube No.		720	Spacing: c/c	in	23,1102	Impingement protection			None
Tube pattern		45	Spacing at inlet	in	30,9055				
Tube pitch	in	1,2598	Spacing at outlet	in	28,6782				
Insert		None							
Vibration problem		Possible / No				RhoV2 violation			No

Figure 35: CA-107 1/2 EDR Overall Result Summary



```
Heat Exchanger Thermal Design                              Shell&Tube V7.3.1 CP1Page 1
File: C-137.edr                              Date: 10.09.2014          Time: 11:00:38

 1  Size      1100    x    6000     mm         Type    AES    Hor          Connected in        1  parallel      1  series
 2  Surf/Unit (gross/eff/finned)         318,9   /    300,9   /            m²     Shells/unit         1
 3  Surf/Shell (gross/eff/finned)        318,9   /    300,9   /            m²
 4
 5  Simulation                                       PERFORMANCE OF ONE UNIT
 6                                  Shell Side            Tube Side       Heat Transfer Parameters
 7  Process Data                    In      Out          In      Out      Total heat load              kW          3322,2
 8  Total flow          kg/h          343200               137600         Eff. MTD/ 1 pass MTD         °C     60,11 / 61,69
 9  Vapor               kg/h       0          0         0          0      Actual/Reqd area ratio - fouled/clean   1   /  1,34
10  Liquid              kg/h   343200    343200    137600    137600
11  Noncondensable      kg/s             0                    0           Coef./Resist.     W/(m² K)     m² K/W       %
12  Cond./Evap.                          0                    0           Overall fouled      183,7      0,00544
13  Temperature         °C       125     139,74       212     176,98      Overall clean        246       0,00407
14  Dew / Bubble point  °C                                                Tube side film      570,4      0,00175     32,21
15  Quality                        0          0         0          0      Tube side fouling  1475,3      0,00068     12,45
16  Pressure (abs)      bar  13,51325  13,43078  11,01325   9,64011      Tube wall         15499,8      0,00006      1,19
17  Delta P allow/calc  bar      0,5    0,08247      0,26    1,37314     Outside fouling    1428,6       0,0007     12,86
18  Velocity            m/s      1,3       1,32      1,78      1,73      Outside film        444,9      0,00225      41,3
19
20  Liquid Properties                                                     Shell Side Pressure Drop          bar          %
21  Density            kg/m³   795,01    783,31    834,57    857,61      Inlet nozzle                   0,01505      18,25
22  Viscosity          mPa s   1,6248    1,2949    3,5975    6,6123      Inlet space Xflow              0,00619       7,51
23  Specific heat    kJ/(kg K)  2,334     2,393     2,549     2,411      Baffle Xflow                   0,02463      29,87
24  Therm. cond.       W/(m K)  0,106    0,1033    0,1141    0,1192      Baffle window                  0,00314       3,81
25  Surface tension      N/m   0,0177    0,0168                          Outlet space Xflow             0,00636       7,71
26  Molecular weight           224,32    224,32    537,08    537,08      Outlet nozzle                   0,0271      32,86
27  Vapor Properties                                                      Intermediate nozzle
28  Density            kg/m³                                              Tube Side Pressure Drop           bar          %
29  Viscosity          mPa s                                              Inlet nozzle                   0,00781       0,57
30  Specific heat    kJ/(kg K)                                            Entering tubes                 0,05249       3,82
31  Therm. cond.       W/(m K)                                            Inside tubes                   1,21448      88,45
32  Molecular weight                                                      Exiting tubes                  0,08618       6,28
33  Two-Phase Properties                                                  Outlet nozzle                  0,01219       0,89
34  Latent heat        kJ/kg                                              Intermediate nozzle
35
36  Heat Transfer Parameters                                              Velocity   /  Rho*V2            m/s     kg/(m s²)
37  Reynolds No. vapor                                                    Shell nozzle inlet               1,64       2147
38  Reynolds No. liquid     16135,29  20247,07   8181,95   4451,53        Shell bundle Xflow         1,3      1,32
39  Prandtl No. vapor                                                     Shell baffle window       0,74      0,75
40  Prandtl No. liquid         35,77        30     80,35    133,77        Shell nozzle outlet              2,39       4483
41  Heat  Load                       kW                   kW              Shell nozzle interm
42  Vapor only                        0                    0                                               m/s     kg/(m s²)
43  2-Phase vapor                     0                    0              Tube nozzle inlet                1,42       1680
44  Latent heat                       0                    0              Tubes                     1,78      1,73
45  2-Phase liquid                    0                    0              Tube nozzle outlet               2,39       4903
46  Liquid only                  3322,2               3322,2              Tube nozzle interm
47
48  Tubes                                  Baffles                           Nozzles: (No./OD)
49  Type                          Plain    Type           Single segmental                      Shell Side     Tube Side
50  ID/OD          mm    19,86 /   25,4    Number                      16    Inlet        mm    1  /  323,85   1  /  219,08
51  Length act/eff mm     6000  /  5661,4  Cut(%d)          30,46            Outlet             1  /  273,05   1  /  168,28
52  Tube passes                      8     Cut orientation             H     Other                 /              /
53  Tube No.                       666     Spacing: c/c        mm    275     Impingement protection                None
54  Tube pattern                    45     Spacing at inlet    mm    752
55  Tube pitch     mm               32     Spacing at outlet   mm  784,42
56  Insert                        None
57  Vibration problem          No /  No                           RhoV2 violation                                 No
```

Figure 36: CA-137 EDR Overall Result Summary