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Aspen HYSYS process simulation and Aspen ICARUS cost estimation of CO_2 removal plant

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Summary:

For several years process simulation and cost estimation of CO_2 removal have been performed with Aspen HYSYS. This work is a continuation of the project work Fall 2009.

An Aspen HYSYS model of CO_2 removal was developed and modified with a split-stream configuration in order to reduce energy consumption in the reboiler. The model has been calculated with variation of parameters to optimize the process and find an optimum solution. For the selected base cases the heat exchanger minimum temperature difference was specified to 10K and the removal efficiency was 85%. The reboiler duty of 3.8 MJ/kg CO_2 removed for the standard process without split-stream was achieved with 18 absorber stages. 3.4 MJ/kg was achieved for the process with split-stream and 24 absorber stages. It was possible to further reduce reboiler energy consumption for the case with split-stream down to 3.0 MJ/kg with 26 stages in the absorber. In this case a heat exchanger minimum temperature difference was 5K.

Equipment cost estimations were calculated in Aspen ICARUS. The total installed equipment cost of the selected standard CO_2 removal process without split-stream was 760 MNOK. With a steam cost of 0.1 NOK/(kWh) the energy net present value for this process for a period of 10 years was 975 MNOK. The investment cost was increased with 212 MNOK due to added complexity of the process with split-stream and the operation cost for a period of 10 years was reduced with 139 MNOK. It means that the split-flow configuration is not economically attractive for 10 years period. The split-stream alternative becomes more attractive when the calculation period increases. With a period above 20 years the split-flow becomes most economical. The split-stream alternative also becomes more attractive when the energy cost increases.

The combination of Aspen HYSYS and Aspen ICARUS is a good tool for evaluating different process configurations. There are still challenges in improvement of the simulation robustness and the cost estimation accuracy.

Telemark University College accepts no responsibility for results and conclusions presented in this report.

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Preface

This is the main Master's thesis of Process Technology educational program at The University College of Telemark, spring 2010.

An amine based CO_2 removal process is designed, simulated and further developed with Aspen HYSYS program. Cost estimation of the process plant is done by use of Aspen ICARUS.
It is expected that the reader has some knowledge about CO_2 removal processes and preferably understanding of Aspen Tech programs, particularly HYSYS and ICARUS.

An author of this thesis would like to take the opportunity to thank her supervisor Lars Erik Øi for his guidance and patient replies to all questions, Nils Eldrup for his help with cost estimations and Ragnhild Skagestad at Tel-Tek for her kind assistance and help with Aspen ICARUS.

The report has a separate appendix part which includes both the Task Description, tables, the Aspen ICARUS cost estimation and a paper, written together with supervisor Lars Erik Øi.

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1 Introduction

1.1 General introduction

Nowadays there is a big discussion on global climate changes and a serious concern about the influencing factors. One of the main causes is the large amounts of carbon dioxide (CO_2) that are being emitted into the atmosphere through human activities, mainly through the burning of fossil fuels. This emission could be reduced significantly by capturing and storing carbon dioxide. The cost of CO_2 capturing using current technologies is very high, though the concentration level in the atmosphere should be stabilized or reduced to a level that the world community can agree upon [1].

Gas cleaning using amines is one of the oldest and most common process operations in the world. The main drawback is the expensiveness of the process, both of investment and operation costs. Minimization of equipment size and/or energy consumption are the two main ways to reduce the cost of the process. The attention grows intensively to alternative flow sheets which can reduce the heat load of the plant without increasing of a plant size [2].

1.2 Main objectives of the thesis

The research area of this Master's Thesis is based on process simulation and development of CO_2 removal by atmospheric exhaust gas absorption into an amine solution, focusing on process design and energy-saving solutions with following project management analysis involving cost reduction strategies.

The aim is to optimize and further develop an existing model in Aspen HYSYS, made by earlier project group [6], performing calculations of dependencies of different removal efficiencies, process choices, equipment dimensions and other assumptions.

The Aspen HYSYS model of general CO_2 removal process is further developed and modified by the split-flow configuration in order to reduce steam requirements.

These two models are energy optimized and compared by performing process equipment dimensioning, investment and operation cost estimations. Aspen ICARUS program is used as a tool for equipment cost estimation.

Task description is attached in the Appendix 1.

1.3 Literature overview

After a careful examination of existing literature about the selection of an efficient and reliable alternative flow sheet were found very few references. One of the reasons can be companies' secrets.

Three alternative flow schemes for gas sweetening plants have been presented by [2] as a way to optimize an existing and widely used basic model of gas sweetening by amines (see Figure 1).

First alternative is an absorber with a multiple feed. This choice allows to significantly decrease the amine flow rate to the top of absorber, that leads to greatly reduce an absorber diameter. In this way the investment cost will be reduced.

The second scheme that [2] suggests is to use multiple absorbers. It will lead to considerably lower circulation and steam rates as well as a cheaper compressor can be realized.

The last scheme that he mentions is a split-flow plant. Significant reduction of steam requirements can be realized by this configuration, which will reduce operation costs.

Adison Aroonwillas in [3] claims that there are basically two ways to reduce energy consumption in CO_2 absorption process. One is to use an absorption solvent that can be easily regenerated by heat or has a low reaction with CO_2.

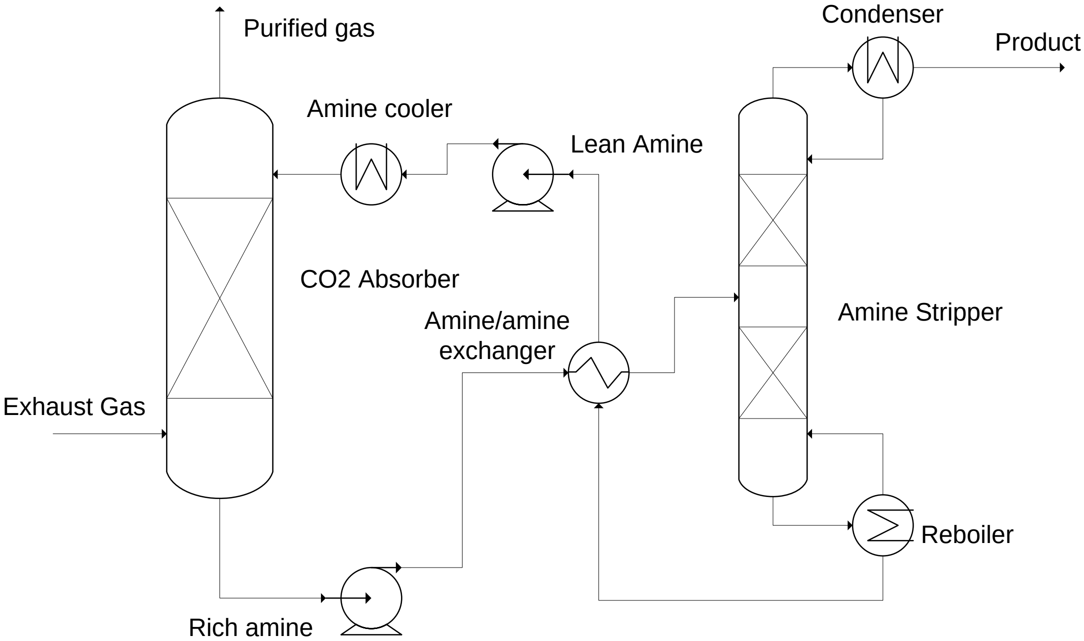

Figure 1Widely used basic model of CO_2 removal process

Another is to modify the conventional process configuration. In his other work he evaluates a split-flow scheme. The overall process is presented in terms of reboiler heat-duty for solvent regeneration, size of regeneration and size of absorber by energy consumption and cost of the CO_2 capture unit.

In this work it is claimed that with the capture efficiency of 95% a split-stream cycle leads to reduction of steam requirements to 2.9 kJ/kg CO_2 compared to minimum possible reboiler heat-duty of 4.1 kJ/kg CO_2 by the general conventional process [3].

2 Description of CO_2 removal process

2.1 General description of standard CO_2 capture process

The main source of CO_2 is the exhaust gas from the power plant. The exhaust gas is cooled before it reaches the capture process. It is done in order to optimize the process. The flue gas from the power plant will meet some physical resistance, which leads to the pressure drop in the exhaust gas.

A flow diagram of the CO_2 removal process is shown in Figure 2.

To minimize the losses of power in the power plant's gas turbine, a fan is installed before the cooling unit.

From the cooler the gases are brought to the bottom of absorption tower, which is filled with packing material of a large surface, that the absorption solvent follows down through the tower. CO_2 from the raw gas is absorbed by the counter-currently flowing solvent. The solvent is an amine or a mixture of amines dissolved in water, which absorb the CO_2 in the flue-gas. In this process monoethanolamine (MEA) is used.

The dissolved CO_2 gas is pumped to a stripping column first being heated by the heat exchanger.

Desorption of CO_2 takes place in the desorption tower (stripper), which operates as a distillation column. MEA is regenerated in the bottom of column. The amine containing the CO_2 flows down the packing material that fills the tower, while steam and CO_2 flows upwards. The steam transfers the necessary heat to the amine, and draws the released CO_2 out of the tower. The mixture of steam and CO_2 at the top of the stripper is cooled, and most of the steam is condensed and is returned to the stripper as reflux. The CO_2 will remain in a gaseous phase.

The amine goes to the reboiler, where the steam, used in desorption process, is generated. The heat for the reboiler is a steam from an external source. This reboiler is the largest consumer of heat in the CO_2 separation process. The CO_2 with some water is directed to dehydration and compression stages and on to transportation.

Water wash

A certain amount of amine will evaporate during the absorption process and be carried upwards through the tower along with the flue-gases. The gas is expected to be saturated with steam and amines. In order to minimize emissions of amines, a water-wash process is integrated at the top of the absorption tower. Cold water with a low concentration of amines washes the flue-gases, dissolving the amines.

Amines

Amines are subdivided into primary (e.g. monoethanolamine), secondary (e.g. diethanolamine) and tertiary (e.g. methyldiethanolamine) amines, according to the number of hydrogen atoms substituted by organic groups. Monoethanolamine (MEA) is used in this project. [7]

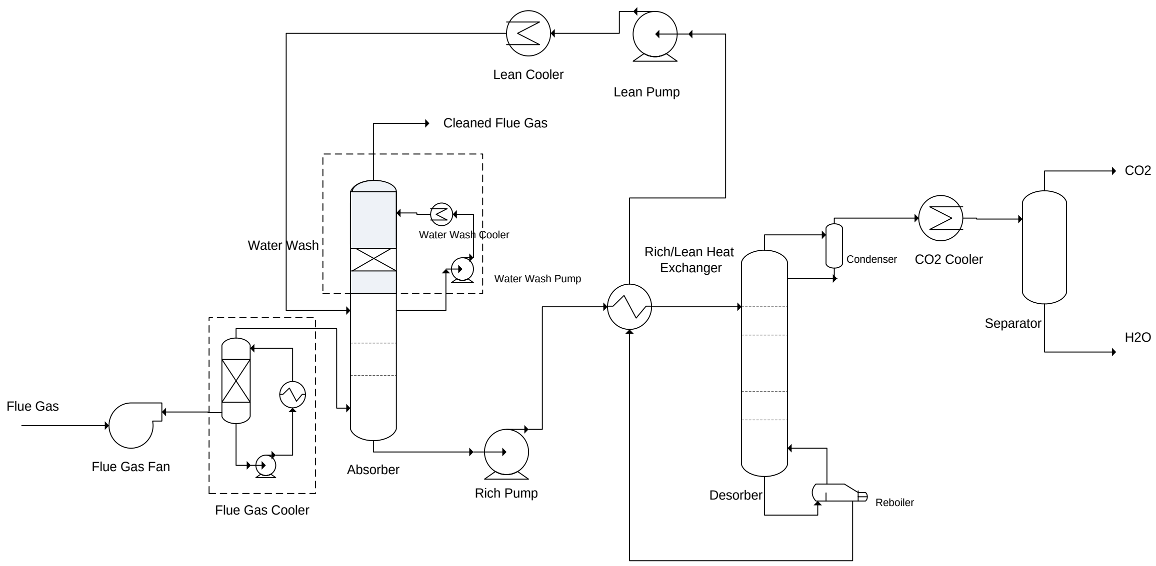

Figure 2 Model of CO_2 removal process [7]

2.2 Problem description

The traditional monoethanolamine process for CO_2 removal has the disadvantages of low carbon dioxide loading capacity (kg CO_2 absorbed per kg absorbent), equipment corrosion and a very high energy penalty during absorbent regeneration [1]. It means that in the simple absorption/stripping process the heat, and as a consequence the energy consumption required for CO_2 removal from flue gas, is very high. This results in large expenses on energy, which together with investment cost and other operation costs makes the CO_2 removal process very expensive.

Analysis of previous researches and works shows that the most expensive equipment units are the absorber and the main heat exchanger [7]. The reboiler is the largest heat consumer in the CO_2 separation process.

To reduce the heat load in the reboiler it is selected to use a split flow configuration of the plant. The main drawback is an increase of investment cost due to added complexity, which includes an increased equipment size, particularly the absorber column height and the main heat exchanger area. The analysis of trade off between reduced operation cost and increased investment cost can show if the split flow configuration is economically interesting.

There are very few references to the calculations using process simulation tools that make a big challenge to make such calculations in terms of process design, simulation and cost estimation.

2.3 Description of CO_2 capture process with split-flow

A standard split-stream scheme is selected as a flow modification for aqueous solutions to reduce energy consumption in reboiler.

The rich solution from the bottom is fed to the top of the stripping column, where only a portion flows downwards countercurrent to the stream of vapors rising from the reboiler to the bottom of the column. Lean amine is further recycled to the top of the absorber. The other portion of rich solution, the semilean amine stream, is taken from the middle of the stripper and fed to the middle of the absorption column. In this system the quantity of vapors rising through the stripping column is less than in a process without split-stream, which leads to savings in energy. Modifications of this process require increases in initial cost of the treating plant due to added complexity and increased heat transfer area of the heat exchanger. [4]

A flow diagram of the CO_2 removal process with split stream is shown in Figure 3.

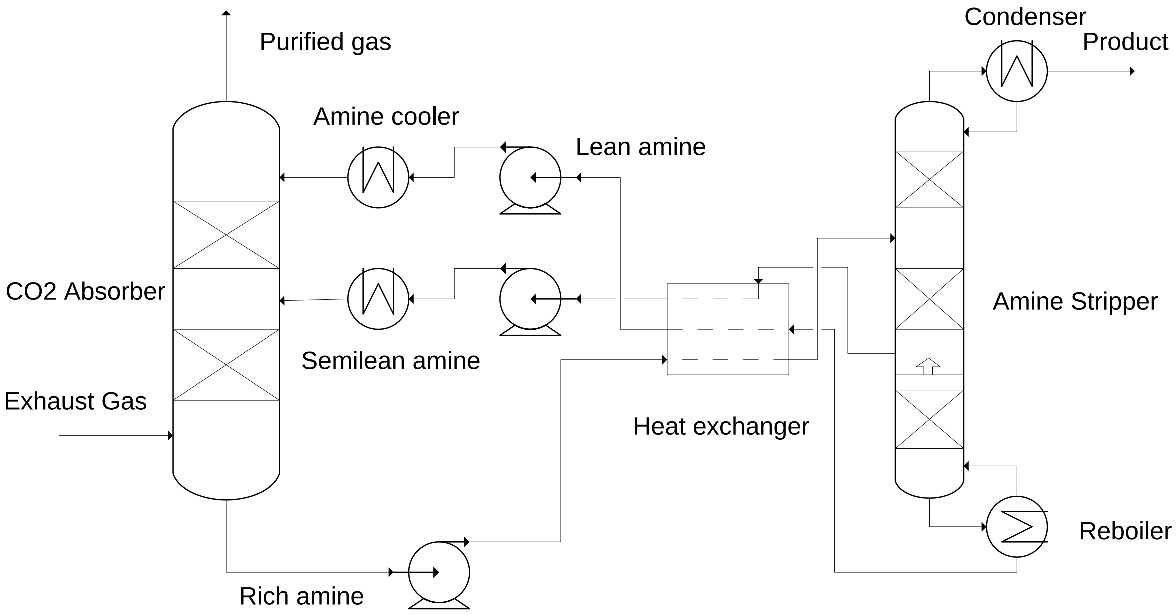

Figure 3 Standard CO_2 removal split stream flow diagram

This alternative was selected because this is a natural way to use only partly regenerated amine for the bulk part (bottom) of the absorber.

Other alternatives from [2] could also have been selected.

A more complex scheme will probably not be justified because a simple split-stream configuration is only almost economical.

3 Aspen HYSYS simulation

3.1 Aspen HYSYS description of a standard process without a split flow

In Aspen HYSYS an absorption and desorption process for a MEA based CO_2 removal has been simulated in an earlier group school project in Fall 2007 [6].

The model has been developed in this Master's thesis by changes in specifications and equipment order. Flue gas is used as feed in this model. The absorption column is specified with 18 stages each with a Murphree efficiency of 0.15. The stripper has 6 stages plus condenser and reboiler, efficiency is set to 1.0.

The thermodynamics for this mixture is described by an Amines Package available in Aspen HYSYS. The Kent Eisenberg [5] model is selected in the Amines Property Package. The Aspen HYSYS base case CO2 removal model is presented in Figure 4.

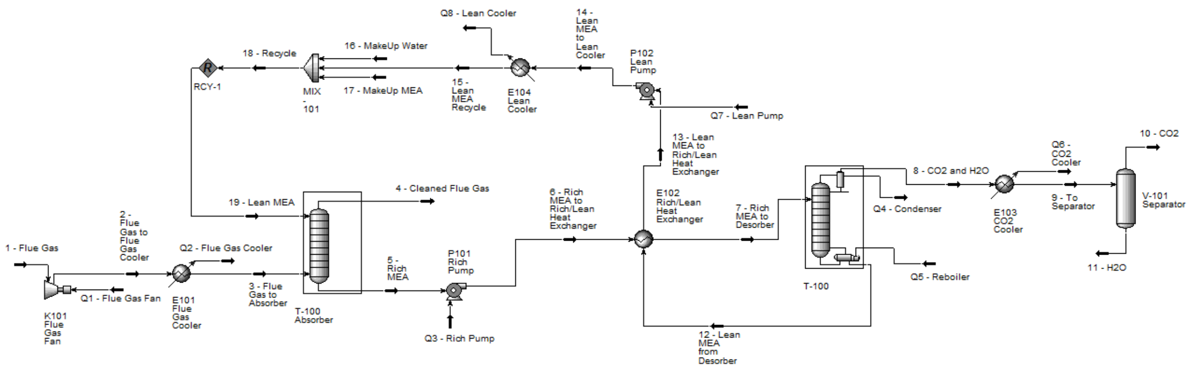

Figure 4 Standard CO_2 removal process simulated in Aspen HYSYS

3.2 Specifications for the Aspen HYSYS standard process without a split flow

Aspen HYSYS model made by Eirik Blaker in an earlier project is further developed with some specifications changes in this thesis. Specifications for the Aspen HYSYS process without a split flow with 85 % removal efficiency and heat exchanger minimum temperature difference 10 K are listed in the Table 3-1.

Table 3-1 Specifications for the process without a split flow

Inlet gas temperature	40 $^{\circ}C$
Inlet gas pressure	1,11 bar
Inlet gas flow	85000 kgmole/h
CO2 in inlet gas	3,73 mole-%
Water in inlet gas	6,71 mole-%
Lean amine temperature	40 $^{\circ}C$
Lean amine pressure	1,01 bar
Lean amine rate	148000 kgmole/h
MEA content in lean amine	29 mass-%
CO2 in lean amine	5,5 mass-%
Number of stages in absorber	18
Murphree efficiency in absorber	0,15
Rich amine pump pressure	2 bar
Heated rich amine temperature	104,2 $^{\circ}C$
Number of stages in stripper	6+Condenser+Reboiler
Murphree efficiency in stripper	1
Reflux ratio in stripper	0,1
Reboiler temperature	120 $^{\circ}C$
Lean amine pump pressure	2 bar

3.3 Aspen HYSYS split-stream process description

A split-stream model has been designed in Aspen HYSYS as a modification of a basic model of process without split-strem.

The absorption column is specified with 24 stages each with a Murphree efficiency of 0.15 and the semilean amine is fed to the 21st stage, stage numbering is from the top to the bottom. The stripper has 6 stages plus condenser and reboiler, with the stage efficiency 1.0.

The Kent Eisenberg model is selected in the Amines Property Package [5].

The Aspen HYSYS CO2 removal with split stream model is presented in Figure 5.

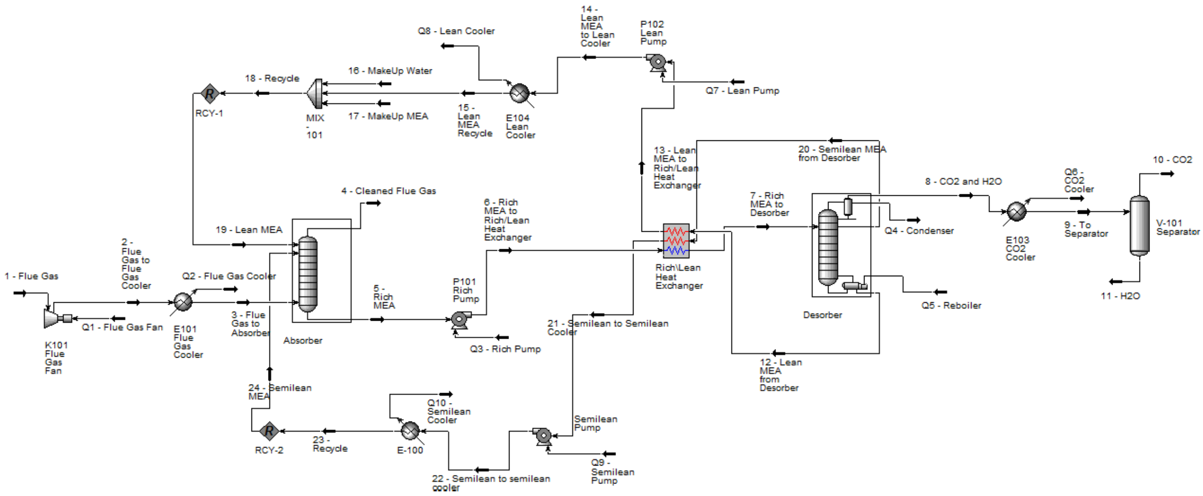

Figure 5 Aspen HYSYS flow diagram for split-stream CO_2 removal model

3.4 Specifications for the Aspen HYSYS process with a split flow

A split stream model is simulated in Aspen HYSYS. Specifications for the Aspen HYSYS process with a split flow with 85 % removal efficiency and heat exchanger minimum temperature difference 10 K are listed in the Table 3-2.

Table 3-2 Specifications for the process with a split flow

Inlet gas temperature	40 $^\circ C$
Inlet gas pressure	1,11 bar
Inlet gas flow	85000 kgmole/h
CO2 in inlet gas	3,73 mole-%
Water in inlet gas	6,71 mole-%
Lean amine temperature	40 $^\circ C$
Lean amine pressure	1,01 bar
Lean amine rate	103500 kgmole/h
MEA content in lean amine	29 mass-%
CO2 in lean amine	5,5 mass-%
Number of stages in absorber	24
Inlet stage number of the semilean MEA	21
Murphree efficiency in absorber	0,15
Rich amine pump pressure	2 bar
Heated rich amine temperature	96,6 $^\circ C$
Number of stages in stripper	6+Condenser+Reboiler
Murphree efficiency in stripper	1
Reflux ratio in stripper	0,1
Reboiler temperature	120 $^\circ C$
Lean amine pump pressure	2 bar
Semilean amine temperature	40 $^\circ C$
Semilean amine pressure	1,11 bar
Semilean amine rate	100000 kgmole/h
MEA content in semilean amine	28 mass-%
CO2 in semilean amine	9 mass-%

3.5 Aspen HYSYS parameters variation

Flowsheets with and without split-stream have been calculated in the process simulation program Aspen HYSYS. The removal efficiency is kept at 85 %.

Different parameters have been varied in order to obtain optimum as a minimum duty for cases with the heat exchanger minimum temperature differences of 5, 10 and 15 K, which is dependent on the rich amine stream temperature to the desorber. The energy consumption was reduced by increasing the number of stages in the absorption column.

A number of stages in absorber and a flow rate have been varied as the most influencing parameters. To keep constant efficiency the flow rates of streams were changed. The temperature of rich stream to desorber was adjusted to keep constant heat exchanger minimum temperature difference.

Parameters have been varied until the convergence problems occurred. It is considered that such problems occur because of inconsistency of the physical parameters for the process to run. The problems mostly occur in the absorption or stripping columns, in particular if there are too many stages specified in the columns. It is found that Modified Hysim Inside-Out algorithm with adaptive damping gives the best convergence [5].

Factors such as multiple flow splits or the number of the semilean take-off desorber stage have not been tried.

3.5.1 Parameters variation for the case without split-stream

In the process without split-stream it was possible to increase the number of stages up to 20. The reboiler duty was reduced slightly. More stages did not give any converged solution. The results for the cases with different heat exchanger minimum temperature differences are shown in tables below.

Table 3-3 Variation of absorber stages number with heat exchanger ΔTmin = 5 ˚C for the process without split-stream

Number of stages in absorber	Reboiler duty, MJ/kg
18	3,678
19	No convergence

Table 3-4 Variation of absorber stages number with heat exchanger ΔTmin = 10 ˚C for the process without split-stream

Number of stages in absorber	Reboiler duty, MJ/kg
18	3,835
19	3,794
20	3,790
21	No convergence

Table 3-5 Variation of absorber stages number with heat exchanger ΔTmin = 15 ˚C for the process without split-stream

Number of stages in absorber	Reboiler duty, MJ/kg
18	4,024
20	3,998
21	No convergence

3.5.2 Parameters variation for the case with split-stream

In the split-stream case with the different number of stages in absorber, the inlet stage of semilean stream into the absorber has been varied for the cases woth different heat exchanger minimum temperature differences.

Assuming a minimum heat exchanger temperature difference of 10 K, the reboiler duty is reduced from 3.8 MJ/kg to 3.4 MJ/kg CO_2removed. With 5 K, the energy consumption can be reduced further, down to 3.0 MJ/kg CO_2removed. With 15 K a split-flow configuration does not give any energy reduction.

The results for cases with different heat exchanger minimum temperature differences are shown in tables below.

Table 3-6 Variation of absorber stages number with heat exchanger ΔTmin = 5 ˚C for the process with split-stream

Number of stages in absorber	Inlet stage of semilean stream	Split flow rate	Reboiler duty, MJ/kg
18	14	0,72	3,498
20	16	0,82	3,263
22	19	0,80	3,206
24	20	0,85	3,162
25	21	0,88	3,037
26	21	0,88	3,035
27	No convergence		

Table 3-7 Variation of absorber stages number with heat exchanger ΔTmin = 10 ˚C for the process with split-stream

Number of stages in absorber	Inlet stage of semi-lean stream	Split flow rate	Reboiler duty, MJ/kg
18	14	0,86	3,871
20	16	1,07	3,677
22	19	0,88	3,540
24	21	0,97	3,387
25	No convergence		

Table 3-8 Variation of absorber stages number with heat exchanger ΔTmin = 15 ˚C for the process with split-stream

Number of stages in absorber	Inlet stage of semilean stream	Split flow rate	Reboiler duty, MJ/kg
18	14	0,86	4,336
20	15	0,99	4,388
21	No convergence		

3.6 Aspen HYSYS calculations and results

With the standard process, removal efficiency of 85 % and the heat exchanger minimum temperature difference 10 K, the minimum duty in the reboiler was reduced from 3.84 to 3.79 MJ/kg with increasing the number of stages in absorber from 18 to 20 stages.

With a split-stream configuration, an increase from 18 to 24 stages resulted in a reduction of energy consumption from 3.87 to 3.39 MJ/kg CO_2. the semilean stream is feed to stage 21 from the column top.

With 5 K, the energy consumption can be reduced down to 3.04 MJ/kg CO_2 removed with 26 absorber stages (and 21st from the bottom as semilean feed).

With 15 K in minimum temperature difference, a split-flow configuration does not give any energy reduction.

A process without a split flow with 18 stages in the desorber and a process with a split flow with 24 stages in the absorber at heat exchager minimum temperature difference of 10 K are chosen as a base cases for further calulations and comparison.

A heat flow in the reboiler and a mass flow of CO_2 were calculated for both models.
The reboiler duty for mass of CO_2 removed is calculated as:

$$Q', \mathrm{MJ/kg} = \frac{\text{Heat flow in the reboiler}}{1000 \cdot \text{Mass flow of CO2}} \tag{1}$$

The results from HYSYS calculations for the specified cases are shown in the Table 3-9.

Table 3-9 Aspen HYSYS calculation results

Specification	Standard model without split-stream	Split-stream model
Heat flow in the reboiler, kJ/h	$5{,}84 \cdot 10^8$	$5 \cdot 10^8$
Mass flow of CO_2, kg/h	152267,1	147781,4
Reboiler duty for mass of CO_2 removed, MJ/kg	3,84	3,39

3.7 Discussion of Aspen HYSYS simulation

Simulation of CO_2 capture process in Aspen HYSYS and comparison of both base case models with and without split-stream proves that it is possible to reduce a reboiler heat consumption by using a split flow configuration for the process with removal efficiency 85 % and a minimum heat exchanger temperature difference of 10 K.

In the standard CO_2 removal process it was possible to slightly reduce a reboiler duty by increasing the number of stages in absorber. The maximum possible number of stages in absorber, which is 20, gave a minimum of 3.79 MJ/kg CO_2 removed.

With a split stream configuration it was possible to increase a number of stages in absorber up to 24, that allowed to reduce energy consumption down to 3.39 MJ/kg.

Further variation of number of stages in absorber and a minimum heat exchanger temperature difference gave a minimum reboiler duty of 3.04 MJ/kg at 5 K and with 26 stages in absorber in the process with a split flow. In literature, a value of 2.9 MJ/kg using split-stream has been calculated [6].

Other split-stream possibilities might reduce the reboiler energy consumption slightly below 3.0 MJ/kg.

4 Process equipment dimensioning

For equipment dimensioning calculations the Aspen HYSYS specifications and calculation results are used.

The purpose of equipment dimensioning in this work is to determine the process investment cost by calculations performed in Aspen ICARUS. The types of equipment and material are assumed.

Not listed equipment like filters, storage tanks and a reclaimer were neglected because the cost is low relative to the main equipment.

4.1 Flue gas fan

Fan type:	Radial centrifugal fan with adiabatic efficiency 75% (default number in HYSYS)
Material:	Stainless steal
Design factor:	Gas volume flow

The gas volume flow is calculated by Aspen ICARUS. It is similar for both cases with and without a split stream and is 3 197 189 m^3/h.

4.2 Fan motor

Motor:	Electrical motor
Material:	Stainless steal
Design factor:	Driver power

The driver motor power is calculated by Aspen ICARUS. It is similar for both cases with and without split-stream and is 11336 kW.

4.3 Direct contact cooler

Column type:	Cooling tower with heat exchanger
Material:	Exotic
Design factor:	Tower volume

A direct contact cooler, DCC, consists from three units: heat exchanger, cooling tower and pump. In Aspen ICARUS a direct contact cooler is calculated as one equipment unit.
The tower volume is similar for both cases with and without split-stream and is 1767 m^3.

4.4 Absorber

Type of column:	Packed tower
Skirt material:	Stainless steal
Packing material:	Structured packing
Design factors:	Total column height, $H_{absorber}$
	Total packing height, $h_{packing\ ,absorber}$
	Number of packed sections
	Absorber diameter, $D_{absorber}$

Parameters from Aspen HYSYS needed for absorber diameter and packing height calculations are listed in the table below, for both cases, with and without split-stream.

Table 4-1 Parameters used for absorber dimension calculations

Parameters	Base case without split-stream	Base case with split-stream
Flue gas volume flow, $\dot{V}_{absorber}$, m^3/h	$2{,}547 \cdot 10^6$	$2{,}547 \cdot 10^6$
Gas velocity in absorber, v, m/s	3	3
Number of stages, $N_{absorber}$	18	24

Absorber diameter calculation:

$$A_{absorber} = \frac{\dot{V}_{absorber}}{3600 \cdot v} \tag{2}$$

$$D_{absorber} = \sqrt{\frac{4 \cdot A_{absorber}}{\pi}} \tag{3}$$

$$D_{absorber} = \sqrt{\frac{\dot{V}_{absorber}}{900 \cdot v \cdot \pi}} \tag{4}$$

Absorber packing height calculation:

It is assumed that each stage is of 1 m height, which makes the total packing height as:

$$h_{packing\ ,absorber} = N_{absorber} \cdot 1m \tag{5}$$

Total absorber height and a number of packed sections are assumed.

The results for both cases are shown below.

Table 4-2 Absorber dimensions

Parameters	Base case without split-stream	Base case with split-stream
Total column height, m	30	35
Total packing height, m	18	24
Number of packed sections	2	3
Absorber diameter, m	17, 33	17, 33

4.5 Water wash

Type of column:	Packed tower
Skirt material:	Stainless steal
Packing material:	Structured packing
Design factors:	Total column height
	Total packing height
	Number of packed sections
	Water wash diameter

The water wash diameter is similar to absorber diameter. A total height and a number of packed sections are assumed. Results are equal for both base cases and are listed in the Table 4-3.

Table 4-3 Water wash dimensions

Total column height	10 m
Total packing height	5 m
Number of packed sections	1
Absorber diameter	17, 33 m

4.6 Rich pump

Type of pump: Centrifugal horizontal pump with adiabatic efficiency 75% (default number in HYSYS)

Type of material: Stainless steal

Design factors: Liquid flow rate

Fluid head

Liquid flow rate is calculated by Aspen HYSYS. A value of fluid head is assumed to be 60 m. Parameters are shown in a table below.

Table 4-4 Rich pump parameters calculated by Aspen HYSYS

Parameters	Base case without split-stream	Base case with split-stream
Liquid flow rate, L/s	946,8	1299

4.7 Rich/Lean heat exchanger

Type of heat exchanger: Float head, shell and tube heat exchanger

Type of material: Stainless steal

Design factors: Heat transfer area, $A_{heat\ exchanger}$

Number of shells, $N_{of\ shells}$

For heat transfer area calculation a basic equation is used:

$$A = \frac{Q}{3600 \cdot U \cdot \Delta T_{LM} \cdot F_c}, \qquad (6)$$

Where ΔT_{LM} - logarithmic mean temperature difference for the case without a split flow and calculated as:

$$\Delta T_{LM} = \frac{(T_{h,out} - T_{c,out}) - (T_{h,in} - T_{c,out})}{\ln(\frac{T_{h,out} - T_{c,out}}{T_{h,in} - T_{c,out}})} \quad (7)$$

The scheme of temperatures flows is shown in Figure 6.

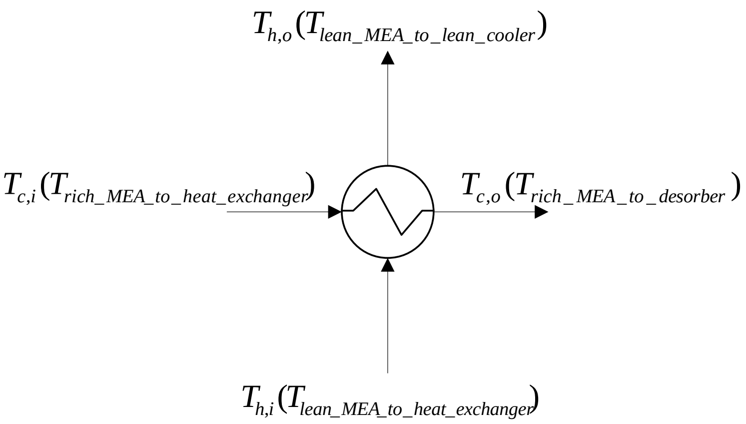

Figure 6 A simplified scheme of hot and cold streams over a heat exchanger for a standard process [7].

For the case with split-stream it is assumed a multi-stream heat exchanger. It is assumed that the area is calculated the same way as in case without split-stream.

Logarithmic mean temperature difference has been calculated by Aspen HYSYS. The result has been checked by standard Equation 7 for two pair of streams: rich amine with lean amine and rich amine with semi-lean amine. Arithmetic mean value has been calculated for these two values and compared with the result from Aspen HYSYS. It seems to be reasonable.

In practice a multiple heat exchangers can be used.

Parameters needed for heat transfer area calculations, calculated by Aspen HYSYS, are listed in the Table 4-5.

Table 4-5 Parameters calculated by Aspen HYSYS need for heat exchanger heat transfer area calculations

Parameters	Base case without split-stream	Base case with split-stream
Hot temperature in, $T_{h,in}$, ˚C	120	120
Hot temperature out, $T_{h,out}$, ˚C	52,65	50,55
Cold temperature in, $T_{c,in}$, ˚C	42,55	40,73
Cold temperature out, $T_{c,out}$, ˚C	104,2	96,6
Semi-lean temperature in, $T_{sl,in}$, ˚C	-	100,29
Semi-lean temperature out, $T_{sl,out}$, ˚C	-	50
LMTD, ΔT_{LM}, ˚C	12,74	10,44
Duty, $Q_{heat\ exchanger}$, kJ/h	$8,72 \cdot 10^8$	$1,274 \cdot 10^9$

An overall heat transfer number, U, is assumed to be $0,5\ kW/(m^2K)$ and correction factor F_c is 1.0.

The limitation for area per shell is assumed $1000\ m^2$, a number of shells in heat exchanger is calculated as:

$$N_{shells} = \frac{A_{heat\ exchanger}}{1000} \quad (8)$$

Results for cases with and without split-stream are shown in the table below.

Table 4-6 Main heat exchanger dimensions

Parameters	Base case without split-stream	Base case with split-stream
Heat transfer area, $A_{heat\ exchanger}$, m^2	38030	57205
Number of shells	38	57

4.8 Desorber

Type of column:	Packed tower
Type of material:	Stainless steal
Design factors:	Total column height, $H_{desorber}$
	Total packing height, $h_{packing\ ,desorber}$
	Number of packing sections
	Desorber diameter, $D_{desorber}$

The method of the desorber diameter calculation is referred to school group project in Fall 2007 [6] and is shown below. Necessary specifications are calculated by HYSYS and listed in the Table 4-7. Number of stages in desorber for both cases is assumed 6.

Table 4-7 Desorber specifications calculated by Aspen HYSYS

Parameters	Base case without split-stream	Base case with split-stream
Liquid mass density, ρ_{liq} , kg/m^3	989,2	989,4
Vapor mass density, ρ_{vap} , kg/m^3	1,942	2,300
Vapor mass flow, $\dot{m}_{vap}$, kg/h	225705	182640
Liquid mass flow, $\dot{m}_{liq}$, kg/h	3370049	2344785
Surface tension, σ, dyne/cm	53,22	54,28

Desorber diameter calculation:

X-axis position:

$$x - axis = \frac{\dot{m}_{liq}}{\dot{m}_{vap}} \cdot \sqrt{\frac{\rho_{vap}}{\rho_{liq}}} \tag{9}$$

Sounders and Brown factor:

$$C_{bs} = -0{,}0283 \cdot \ln(x - axis) + 0{,}0452 \tag{10}$$

Flooding velocity:

$$v_f = C_{bs} \cdot (\frac{\dot{m}_{liq}}{\dot{m}_{vap}})^{0,2} \cdot \sqrt{\frac{\rho_{liq} - \rho_{vap}}{\rho_{vap}}} \tag{11}$$

It is assumed 90 % flooding.

Gas velocity:

$$v_{gas} = v_f \cdot 0,9 \tag{12}$$

Desorber diameter:

$$D_{desorber} = \sqrt{\frac{4 \cdot \dot{m}_{vap}}{0,85 \cdot \pi \cdot \rho_{vap} \cdot 3600 \cdot v_{gas}}} \tag{13}$$

It is assumed that each stage is of 1 m height, which makes the total packing height as:

$$h_{packing,desorber} = N_{desorber} \cdot 1m \tag{14}$$

Results are shown in the Table 4-8.

Table 4-8 Desorber dimensions

Parameter	Base case without split-stream	Base case with split-stream
Desorber Diameter, m	5,869	4,969
Total column height, m	25	30
Total packing height, m	6	6
Number of packing sections	2	3

4.9 Reboiler

Type of heat reboiler: Kettle

Type of material: Stainless steal

Design factors: Heat transfer area, $A_{reboiler}$

Number of units, N_{units}

Reboiler heat transfer area calculation is similar to heat exchanger calculation. It is found with Equation 15.

$$A_{reboiler} = \frac{Q_{reboiler}}{3600 \cdot U_{reboiler} \cdot \Delta T}, \quad (15)$$

where $\Delta T = 32^{\circ}C$ is the difference between amine solution and steam temperatures. The overall heat transfer number, $U_{reboiler}$, is assumed to be 0.5 $kW/(m^2K)$.

Specifications calculated by Aspen HYSYS are listed in the table below.

Table 4-9 Reboiler specifications calculated by Aspen HYSYS

Parameter	Base case without split-stream	Base case with split-stream
Reboiler duty, $Q_{reboiler}$, kJ/h	$5{,}84 \cdot 10^8$	$5{,}00 \cdot 10^8$
Steam temperature, $^{\circ}C$	152	152
Amine solution temperature, $^{\circ}C$	120	120

The limitation for area per unit is $352\ m^2$, a number of reboiler units is calculated as:

$$N_{units} = \frac{A_{reboiler}}{352} \quad (16)$$

Calculation results are shown in the Table 4-10.

Table 4-10 Reboiler dimensions

Parameter	Base case without split-stream	Base case with split-stream
Reboiler heat transfer area, m^2	5069	4345,5
Number of units	14	12

4.10 Lean pump

Type of pump: Centrifugal horizontal pump with adiabatic efficiency 75% (default number in HYSYS)

Type of material: Stainless steal

Design factors: Liquid flow rate

Fluid head

Liquid flow rate is calculated by Aspen HYSYS. A value of fluid head is assumed to be 60 m.

Table 4-11 Lean pump specifications

Parameter	Base case without split-stream	Base case with split-stream
Liquid flow rate, L/s	946,3	658,3

4.11 Lean cooler

Type of cooler: Float head, shell and tube heat exchanger

Type of material: Exotic

Design factors: Heat transfer area, $A_{lean\ cooler}$

Number of shells, $N_{shells\ ,cooler}$

Reboiler heat transfer area calculation is similar to heat exchanger calculation. It is found with Equation 6. An overall heat transfer number, U, is assumed to be $0{,}5\,\mathrm{kW/(m^2K)}$ and correction factor F_c is 1.0. Other parameters needed for the calculations are listed in the Table 4-12. The results are shown in the Table 4-13.

Table 4-12 Lean cooler specifications calculated by Aspen HYSYS

Parameters	Base case without split-stream	Base case with split-stream
Hot temperature in, $T_{h,in}$, ˚C	52,65	50,55
Hot temperature out, $T_{h,out}$, ˚C	40	40
Cold temperature in, $T_{c,in}$, ˚C	6	6
Cold temperature out, $T_{c,out}$, ˚C	21	21
LMTD, ΔT_{LM}, ˚C	32,8	31,7
Duty, $Q_{lean\ cooler}$, kJ/h	$1{,}56 \cdot 10^8$	$9{,}03 \cdot 10^7$

Table 4-13 Lean cooler dimensions

Parameter	Base case without split-stream	Base case with split-stream
Heat transfer area, m^2	1651	988,8

4.12 Condenser

Type of condenser: Fixed tube and shell heat exchanger

Type of material: Exotic

Design factors: Heat transfer area

Condenser heat transfer area calculation is similar to heat exchanger area calculation. It is found with Equation 6. An overall heat transfer number, U, is assumed to be $1{,}0\,\mathrm{kW/(m^2K)}$ and correction factor F_c is 1.0. Logarithmic mean temperature difference is calculated with Equation 7. Other parameters needed for the calculations are listed in the Table 4-14. Calculation results are shown in the Table 4-15.

Table 4-14 Condenser specifications calculated by Aspen HYSYS

Parameters	Base case without split-stream	Base case with split-stream
Hot temperature in, $T_{h,in}$, ˚C	104,2	94,91
Hot temperature out, $T_{h,out}$, ˚C	101,6	90,75
Cold temperature in, $T_{c,in}$, ˚C	6	6
Cold temperature out, $T_{c,out}$, ˚C	21	21
Condenser duty, $Q_{condenser}$, kJ/h	$3,146 \cdot 10^7$	$2,268 \cdot 10^7$

Table 4-15 Condenser dimensions

Parameters	Base case without split-stream	Base case with split-stream
Condenser heat transfer area, m^2	97,9	79,55

4.13 CO_2 cooler

Type of condenser: Fixed tube and shell heat exchanger

Type of material: Exotic

Design factors: CO_2 cooler heat transfer area

CO_2 cooler heat transfer area calculation is similar to heat exchanger area calculation. It is found with Equation 6. An overall heat transfer number, U, is assumed to be 1,0 $kW/(m^2K)$ and correction factor F_c is 1.0. Logarithmic mean temperature difference is calculated with Equation 7. Other parameters needed for the calculations are listed in the Table 4-16. Calculation results are shown in the Table 4-17.

Table 4-16 CO_2 cooler specifications calculated by Aspen HYSYS

Parameters	Base case without split-stream	Base case with split-stream
Hot temperature in, $T_{h,in}$, ˚C	101,63	90,75
Hot temperature out, $T_{h,out}$, ˚C	25	25
Cold temperature in, $T_{c,in}$, ˚C	6	6
Cold temperature out, $T_{c,out}$, ˚C	21	21
CO_2 cooler duty, $Q_{CO_2\ cooler}$, kJ/h	$1,98 \cdot 10^8$	$9,55 \cdot 10^7$

Table 4-17 CO_2 cooler dimensions

Parameters	Base case without split-stream	Base case with split-stream
CO_2 cooler heat transfer area, m^2	1287,78	679,66

4.14 Separator

Type of separator: Cylindrical separator

Type of material: Stainless steal

Design factors: Separator height

The separator height is calculated by Aspen ICARUS. It is similar for both cases with and without a split stream and is 13.87 m.

4.15 Semilean pump

Type of pump:	Centrifugal horizontal pump with adiabatic efficiency 75% (default number in HYSYS)
Type of material:	Stainless steal
Design factors:	Liquid flow rate

Liquid flow rate is calculated by Aspen HYSYS and equals 680.8 L/s

4.16 Semilean cooler

Type of cooler:	Float head, shell and tube heat exchanger
Type of material:	Exotic
Design factors:	Heat transfer area

Semi-lean cooler heat transfer area calculation is similar to heat exchanger area calculation. It is found with Equation 6. An overall heat transfer number, U, is assumed to be 0.8 kW/(m^2K) and correction factor F_c is 1.0. Logarithmic mean temperature difference is calculated with Equation 7. Other parameters needed for the calculations are listed in the Table 4-18.

Table 4-18 Semilean cooler specifications calculated by Aspen HYSYS

Parameters	Value
Hot temperature in, $T_{h,in}$, ˚C	50
Hot temperature out, $T_{h,out}$, ˚C	40
Cold temperature in, $T_{c,in}$, ˚C	6
Cold temperature out, $T_{c,out}$, ˚C	21
LMTD, ΔT_{LM}, ˚C	31,4
Duty, $Q_{semi-lean\ cooler}$, kJ/h	$8{,}586 \cdot 10^7$

Calculated value of heat transfer area is 948.44 m^2

5 Investment cost estimation

Equipment cost estimation is performed with the program Aspen ICARUS (version 16.0.0). It is a powerful tool for capital cost calculations, which allows companies to make more accurate estimations and use it in engineering process and business decision analysis.

There were few articles found about the cost estimation of CO_2 removal using amine absorption [13], [14], [15].

5.1 Aspen ICARUS results

Equipment cost estimation for CO_2 removal plant is made for two models separately. As inputs to the program's spreadsheet, process specifications from Aspen HYSYS and equipment dimensioning are used.

Calculated by Aspen ICARUS equipment costs are valid for the year 2007 with currency in Euro. Results for selected base cases are listed in the Table 5-1.

Table 5-1 Equipment cost calculated by Aspen ICARUS for the base cases with and without split-stream

List of equipment	**Equipment cost, EUR**	
	Base case without split-stream	Base case with split-stream
Flue gas blower	61500	61500
Fan motor	55500	55500
DCC	1630400	1630400
Absorber packing material	16457220	21942959
Absorber skirt	2344480	2683741
Water wash packing material	4571450	4571450
Water wash skirt	1452550	1452550
Rich pump	228000	332700
Rich/Lean heat exchanger	4247400	6296000
Desorber packing material	629168	451000
Desorber skirt	422232	388500
Reboiler	822600	705200
Lean pump	227900	153500
Lean cooler	230400	164300
CO2 cooler	164900	88000
Condenser	30400	30400
Separator	117000	117000
Semilean pump	-	153500
Semilean cooler	-	164300
Total equipment cost:	**34151400**	**41442500**

5.2 Cost estimation methods

5.2.1 Cost conversion

Equipment cost calculated in Aspen ICARUS is for year 2007 in Euro. Index method is used to calculate an updated price for current 2010 year:

$$\mathrm{Cost}_{\mathrm{kNOK},2010} = \mathrm{Cost}_{\mathrm{kNOK},2007} \cdot \frac{\mathrm{Cost\ Index}_{2010}}{\mathrm{Cost\ Index}_{2007}} \tag{17}$$

Cost indexes values are given in the Table 5-2.

Table 5-2 Cost indexes values for years 2007-2010 [10]

Year	Cost Index Value
2007	118,6
2010	129,3

Equipment cost in kNOK is calculated with Equation 18 using a currency exchange rate for year 2010. Values of exchange rates are given in the

Table *5-3*.

$$\mathrm{Cost}_{\mathrm{kNOK},2010} = \frac{\mathrm{Cost}_{\mathrm{EUR},2010} \cdot \mathrm{Exchange\ Rate}_{\mathrm{NOK/EUR},2010}}{1000} \tag{18}$$

Table 5-3 Currency exchange rates for years 2007-2010 [8], [9]

Exchange rate year	***Exchange rate value, NOK/EUR***
2007	8,0161
2010	7,9592

5.2.2 Limitations in Aspen ICARUS

Aspen ICARUS program imposes constraints on some of equipment specifications.

To go over these limitations and calculate a cost of equipment unit with real process specifications, calculated by Aspen HYSYS, a scaling method is used. It can be done with following equation:

$$\text{New cost} = \text{Old cost} \cdot \left(\frac{\text{Capasity}_{\text{real}}}{\text{Capasity}_{\text{limitaions}}}\right)^{0,65} \qquad (19)$$

5.2.3 Packing material cost estimation

In Aspen ICARUS two inches pall rings were specified as a packing material in absorber, water wash and desorber. It is assumed that for the selected structured packing with specific area 250 m^2/m^3 (like Mellapak 250Y) the cost is calculated as:

$$\text{New cost} = 1{,}4 \cdot \text{Cost}_{2''\text{SPR}} \qquad (20)$$

5.2.4 Installed cost calculations

To calculate an installed cost of the plant, material and cost factors are used for the equipment of different material than carbon steel.

Installed cost for each equipment unit was calculated as a product of equipment cost and a total installation factor. A material factor influences the cost of equipment and piping. The total installation factor includes factors such as material, piping, instrumentation, electrical, civil structures, administration and contingency. All cost factors are dependent on equipment cost, material and type of equipment and on the equipment cost.

All the cost factors can be found in Appendix 2 [16].

Material factors are listed in the table below. Exotic material is titanium or high quality stainless steel.

Table 5-4 Material factors [11].

Material	Material factor
Stainless Steel (SS316) Welded	1,75
Stainless Steel (SS304) Machined	1,3
Exotic	2,5

In Aspen ICARUS all the equipment is calculated for carbon steel material.

A total installed cost factor is calculated with the equation below**.**

$$f_I = f_{TC} - f_P - f_{Eq} + f_M \cdot (f_P + f_{Eq}), \qquad (21)$$

where:

f_I - installation cost factor;

f_{TC} - total cost factor;

f_P - piping cost factor;

f_{Eq} - equipment cost factor;

f_M - material factor.

Installed equipment cost is calculated with Equation 22.

$$\text{Installed cost} = \text{Equipment cost} \cdot f_I \qquad (22)$$

An exception in total cost factor calculation is for rich/lean heat exchanger.

If the number of shells in heat exchanger is *n*, then for first and for the last shells the total installation cost factor is calculated with Equation 22. For other *(n-2)* shells this factor is calculated as follows:

$$f_I' = f_I - f_E, \qquad (23)$$

where:

f_E - engineering cost factor;

Installed rich/lean heat exchanger cost is:

$$\text{Installed cost}_{hx} = \text{Equipment cost}_{1\ shell} \cdot (2 \cdot f_I + (n-2) \cdot f_I') \qquad (24)$$

5.3 Cost estimation of the base case process plant without split-stream

5.3.1 Equipment cost after indexing and currency converting

Equipment cost for current year and in currency NOK is calculated with Equation 17 and Equation 18. The results are listed in the table below.

Table 5-5 Equipment cost for the base case without split-stream (NOK, 2010)

List of equipment	Equipment cost, NOK
Flue gas blower	533652
Fan motor	481589
DCC	14147426
Absorber packing	142803788
Absorber skirt	20343693
Water wash packing	39667719
Water wash skirt	12604173
Rich pump	1978418
Rich/Lean heat exchanger	36855849
Desorber packing	5459462
Desorber skirt	3663822
Reboiler	7137925
Lean pump	1977550
Lean cooler	1999244
CO2 cooler	1430882
Condenser	263789
Separator	1015241
Total equipment cost	**292364222**

5.3.2 Equipment cost after scaling and sizing

Flue gas fan and fan motor costs that meet specifications calculated in Aspen HYSYS are calculated with Equation 19. Parameters for this calculations are listed in the Table 5-6.

Table 5-6 Flue gas fan and fan motor cost regulated for specifications calculated by Aspen HYSYS

Equipment	Aspen ICARUS equipment cost, NOK	Aspen ICARUS limitation	Aspen HYSYS specification	New cost, NOK
Flue gas fan	533652	254800 m^3/h	3197189 m^3/h	2762665
Fan motor	481589	300 kW	11336 kW	5104419

Cost of absorber, water wash and desorber structured packing material is calculated with Equation 20. The results are in the Table 5-7

Table 5-7 Structured packing cost for the base case without split-stream

Packing	Cost, NOK
Absorber	199925304
Water wash	55534807
Desorber	7643247
Total cost	**263103358**

5.3.3 Installed cost calculation results for the base case without split-stream

Installed cost of process equipment with material and cost factors are calculated and given in the Table 5-8.

Table 5-8 Installed cost of the process equipment with material and cost factors

List of equipment	Equipment cost, kNOK	Material type	Material factor	Total Cost factor	Piping cost factor	Equipment cost factor	Tatal installation factor	Installed cost, kNOK
Flue gas blower	2763	SS304	1,3	-	-	1	1,3	3591
Fan motor	5104	SS304	1,3	-	-	1	1,3	6636
DCC	14147	Exotic	2,5	3,5	0,29	1	5,44	76891
Absorber skirt	20344	SS316	1,75	2,8	0,21	1	3,71	75424
Water wash skirt	12604	SS316	1,75	3,5	0,29	1	4,47	56309
Rich pump	1978	SS304	1,3	-	-	1	1,3	2572
Rich/Lean heat exchanger	1024	SS316	1,75	4,64	0,46	1	5,74	191528
Desorber skirt	3664	SS316	1,75	3,85	0,34	1	4,86	17788
Reboiler	7138	SS316	1,75	3,5	0,29	1	4,47	31889
Lean pump	1978	SS304	1,3	-	-	1	1,3	2571
Lean cooler	1999	Exotic	2,5	4,64	0,46	1	6,83	13655
CO2 cooler	1431	Exotic	2,5	4,64	0,46	1	6,83	9773
Condenser	264	Exotic	2,5	6,81	0,79	1	9,5	2505
Separator	1015	SS316	1,75	4,64	0,46	1	5,74	5822
Absorber packing	199925	Structured	-	-	-	-	-	199925
Water wash packing	55535	Structured	-	-	-	-	-	55535
Desorber packing	7643	Structured	-	-	-	-	-	7643
Total installed cost of the plant:								**760057**

5.4 Cost estimation of the split stream case

5.4.1 Equipment cost after indexing and currency converting

Equipment cost for current year and in currency NOK is calculated with Equation 17 and Equation 18. The results are listed in the table below.

Table 5-9 Equipment cost for the base case with split-stream (NOK, 2010)

List of equipment	Equipment cost, NOK
Flue gas blower	533652
Fan motor	481589
DCC	14147426
Absorber packing	190405042
Absorber skirt	23287553
Water wash packing	39667719
Water wash skirt	12604173
Rich pump	2886929
Rich/Lean heat exchanger	54632110
Desorber packing	3913450
Desorber skirt	3371121
Reboiler	6119213
Lean pump	1331961
Lean cooler	1425676
CO2 cooler	763600
Condenser	263789
Separator	1015241
Semilean pump	1331961
Semilean cooler	1425676
Total equipment cost	**359607880**

5.4.2 Equipment cost after scaling and sizing

For both base cases with and without split-stream the cost of flue gas fan and fan motor are equal.

Cost of absorber, water wash and desorber structured packing material are calculated with Equation 20.

For the split-stream case results are in the Table 5-10.

Table 5-10 Structured packing cost for the base case with split stream

Packing	Cost, NOK
Absorber	266567059
Water wash	55534807
Desorber	5478830
Total cost	**327580696**

5.4.3 Installed cost calculation results for the base case with split stream

Installed cost of process equipment with material and cost factors are calculated and given in the Table 5-11.

Table 5-11 Installed cost of the process equipment with material and cost factors

List of equipment	Equipment cost, kNOK	Material type	Material factor	Total Cost factor	Piping cost factor	Equipment cost factor	Tatal installation factor	Installed cost, kNOK
Flue gas blower	2763	SS304	1,3	-	-	1	1,3	3591
Fan motor	5104	SS304	1,3	-	-	1	1,3	6636
DCC	14147	Exotic	2,5	3,5	0,29	1	5,44	76891
Absorber skirt	23288	SS316	1,75	2,8	0,21	1	3,71	86339
Water wash skirt	12604	SS316	1,75	3,5	0,29	1	4,47	56309
Rich pump	2887	SS304	1,3	-	-	1	1,3	3753
Rich/Lean heat	958	SS316	1,75	5,41	0,58	1	6,6	330251
Desorber skirt	3371	SS316	1,75	3,85	0,34	1	4,86	16367
Reboiler	6119	SS316	1,75	3,5	0,29	1	4,47	27338
Lean pump	1332	SS304	1,3	-	-	1	1,3	1732
Lean cooler	1426	Exotic	2,5	4,64	0,46	1	6,83	9737
CO2 cooler	764	Exotic	2,5	5,41	0,58	1	7,78	5941
Condenser	264	Exotic	2,5	6,81	0,79	1	9,5	2505
Separator	1015	SS316	1,75	4,64	0,46	1	5,74	5822
Absorber packing	266567	Structured	-	-	-	-	-	266567
Water wash packing	55535	Structured	-	-	-	-	-	55535
Desorber packing	5479	Structured	-	-	-	-	-	5479
Semi-lean pump	1332	SS304	1,3	-	-	1	1,3	1732
Semi-lean cooler	1426	Exotic	2,5	4,64	0,46	1	6,83	9737
Total installed cost of the plant:								**972261**

5.5 Discussion of investment cost estimation

The purpose of equipment dimensioning in this work is to determine the process investment cost by calculations performed in Aspen ICARUS. The types of equipment and material are assumed. This gives a high uncertainty in cost estimation.

The results obtained from the equipment cost calculations show that the absorber and the main heat exchanger are the most expensive. The uncertainty in cost estimation of specifically these two units lies in several aspects.

One is the cost assumption of selected absorber (also water wash and desorber) structured packing material. It has been assumed that its cost is 1.4 times higher than the specified two inches pall rings material in Aspen ICARUS. This guessed value brings the main inaccuracy in absorber cost determination.

Another aspect is a quite arbitrary choice of floating head main heat exchanger, especially for the case with a split stream, where a process requires a multiple stream heat exchanger or simply several heat exchangers. In the computation of heat transfer area the value of overall heat transfer number, $0.5\ \mathrm{kW/(m^2K)}$, is assumed. Cost of heat exchanger is proportional to this number.

6 Operation cost and net present value calculations

6.1 Calculation methods

Operation cost in terms of reboiler energy consumption is calculated for two chosen base cases with and without split-stream.

6.1.1 Energy consumption and cost calculations

Energy consumption in the reboiler for a one year period is calculated with following equation:

$$\mathrm{Cost}_{\mathrm{energy},1\mathrm{y}} = \frac{\mathrm{Energy\ price} \cdot \mathrm{T}_{\mathrm{op},1\mathrm{y}} \cdot \mathrm{Q}}{3600}, \tag{25}$$

where:

Energy price is 0.1 NOK/(kWh);

$\mathrm{T}_{\mathrm{op},1\mathrm{y}}$ is 8000 h/year, annual plant operation time;

Q - heat flow in the reboiler, kJ/h. The values for both base cases are in the Table 3-9.

6.1.2 Energy net present value calculations

Accumulated energy Net Present Value is calculated with following equation:

$$\mathrm{NPV}_{(\mathrm{n})} = \sum_{0}^{\mathrm{n}} \left(\frac{1}{\left(1 + \frac{\mathrm{p}}{100}\right)^{\mathrm{n}}} \cdot \mathrm{Cost}_{\mathrm{energy},1\mathrm{y}} \right), \tag{26}$$

Where p is 7%, rate *[Nils H. Eldrup]* and n is a year number. First is considered to be a 0 year. For a period of 10 years n=0..9, For a period of 20 years, n=0..19.

6.2 Calculation results

6.2.1 Energy cost of the process without split-stream for 1 year period

Operation cost for the selected base case process without a split stream for a period of 1 year is calculated with Equation 25 and is 130 MNOK.

6.2.2 Energy cost of the process without split-stream for 10 years period

Energy Net Present Value for the selected base case process without a split stream for the period of 10 years is calculated with Equation 26 and is 975 MNOK.

Results for each year are show in the Table 6-1.

Table 6-1 Energy net present value for the base case without split-stream

Year number, n	OPEX for current year, kNOK
0	129765
1	121276
2	113342
3	105927
4	98997
5	92521
6	86468
7	80811
8	75525
9	70584
Accumulated NPV, 10 years	**975217**

6.2.3 Energy cost of the process with split-stream for 1 year period

Operation cost for the selected base case process with split-stream configuration is calculated with Equation 25 and is 111 MNOK.

6.2.4 Energy cost of the process with split-stream for 10 years period

Energy Net Present Value for the selected base case process with split-stream configuration for the period of 10 years is calculated with Equation 26 and is 836 MNOK.

Results for each year are show in the Table 6-2.

Table 6-2 Energy net present value for the base case with split-stream

Year number, n	OPEX for current year, kNOK
0	111230
1	103953
2	97153
3	90797
4	84857
5	79306
6	74117
7	69269
8	64737
9	64737
Accumulated NPV, 10 years	**835920**

6.2.5 Energy cost of both processes with and without split-stream for 20 years period

Energy Net Present Value for the period of 20 years is calculated with Equation 26.

For the base case without split-stream NPV is 1485 MNOK and with split-stream configuration is 1273 MNOK.

6.3 Total net present value of both process plants with and without split-stream

Total net present values for the process plant for base cases with and without split-stream for calculation periods of 10 and 20 years are listed in the table below.

Table 6-3 Total NPV (Investment and operation costs)

Period	Total NPV for the base case without split-stream	Total NPV for the base case with split-stream
10 years	1735	1808
20 years	2245	2245

6.4 Discussion of operation cost estimation

The investment and operation (energy) costs of two selected base cases, with and without split-stream, are compared.

In modified process with split-stream a total investment cost of the CO_2 removal plant increases due to a more complex process. Main features are the higher absorption column and the larger heat exchanger. The total equipment installed cost of the plant is increased by 212 MNOK compared to the standard configuration without split-stream.

This scheme allowed to reduce the reboiler energy demand, which leaded to the reduction in operation costs. For calculation period of 10 years it can be saved about 139 MNOK. So with specified period of 10 years pay-back time, the standard process without split-stream is the most economical.

The split-stream alternative becomes more attractive when the calculation period increases. For a calculation period of 20 years savings increase up to 212 MNOK. It means that with more than 20 years calculation period, the split-stream configuration becomes the most economical.

These results therefore need to be interpreted with caution because of some uncertainties. The issues emerging from energy cost calculations relate specifically to a high sensitivity to energy price and a calculation period.

The split-stream alternative becomes more attractive when the energy cost and calculation period increase.

7 Paper on optimum CO_2 absorption with split stream configuration

A paper is accepted at the international conference on “Processes and Technologies for a Sustainable Energy” in Ischia, Italy.

The purpose of this paper is to present the principle of split-stream scheme in CO_2 absorption in an aqueous amine solution (see Figure 3). The objectives of this research are to determine whether it is possible to reduce energy with this modified process configuration and if it is interesting from economical point of view.

Process design and simulation are performed by Aspen HYSYS. Specifications from the Table 3-1 and Table 3-2 are used.

Parameters like the absorber number of stages and flow rates were varied in order to obtain an optimum. Cases with different minimum heat exchanger temperature difference were investigated.

Selected cases were cost estimated in Aspen ICARUS. The equipment dimensions calculated in Chapter 4 and parameters calculated in Aspen HYSYS were used as input parameters.

Different cases were compared in terms of energy consumption and in terms of investment and operation expenditures.

The conclusions (as stated in the paper) are:

It has been shown that it is possible to reduce the energy consumption considerably in a CO_2 removal plant using a split-stream configuration. An energy consumption of 3.0 GJ/ton CO_2 has been calculated using a simple split-stream configuration and 5 K temperature difference in the main heat exchanger. With 15 K temperature difference, a split-stream configuration will not reduce the energy consumption.

Capital cost and operating cost for the cases have been calculated. The capital cost increases with a split-stream configuration due to a more complex process. At base case conditions with 10 K temperature difference and 10 years calculation period, the standard process without split-stream was most economical.

With more than 20 years calculation period, the split-stream configuration was most economical. The split-stream alternative becomes more attractive when the energy cost increases.

The paper itself is included in the Appendix 3.

8 Conclusion

For several years process simulation and cost estimation of CO_2 removal have been performed with Aspen HYSYS. This work is a continuation of the project work Fall 2009.

An Aspen HYSYS model of CO_2 removal was developed and modified with a split-stream configuration in order to reduce energy consumption in the reboiler. The model has been calculated with variation of parameters to optimize the process and find an optimum solution. The removal efficiency in each case was 85 %.

Among the varied parameters that influenced the reboiler duty were: number of stages in absorber, the inlet stage of semilean stream to absorber, lean and semilean stream flow rates and heat exchanger minimum temperature difference, which was kept constant by adjusting the temperature of rich stream into the stripper.

For the case without split-stream at heat exchanger minimum temperature difference of 10K it was possible to slightly reduce the reboiler energy consumption from 3.84 MJ/kg to 3.79 MJ/kg CO_2 removed by increasing the number stages in absorber from 18 to 20. It was not possible to calculate the lower heat consumption by further increase the number of stages in the absorber because of the convergence problems.

For the case with split-stream at heat exchanger minimum temperature difference of 10K it was possible to reduce the reboiler energy consumption from 3.87 MJ/kg to 3.39 MJ/kg CO_2 removed by increasing the number of stages in absorber from 18 to 24.

It was possible to further reduce reboiler energy consumption for the case with split-stream down to 3.0 MJ/kg with 26 stages in the absorber. In this case a heat exchanger minimum temperature difference was 5K. With 15 K in minimum temperature difference, a split-flow configuration does not give any energy reduction.

Two cases with the heat exchanger minimum temperature difference of 10K were chosen as base: the process without split-stream with 18 absorber stages and 3.84 MJ/kg CO_2 removed, and the process with split-stream with 24 absorber stages and 3.39 MJ/kg.

These two cases were cost estimated and compared in terms of investments and operation expenditures.

Equipment cost estimations were calculated in Aspen ICARUS. The total installed equipment cost of the selected standard CO_2 removal process without split-stream was 760 MNOK. With a steam cost of 0.1 NOK/(kWh) the energy net present value for this process for a period of 10 years was 975 MNOK.

The investment cost was increased with 212 MNOK due to added complexity of the process with split-stream and the operation cost for a period of 10 years was reduced with 139 MNOK. It means that the split-flow configuration is not economically attractive for 10 years period. The split-stream alternative becomes more attractive when the calculation period increases.

With a period above 20 years the split-flow becomes most economical. The split-stream alternative also becomes more attractive when the energy cost increases.

The combination of Aspen HYSYS and Aspen ICARUS is a good tool for evaluating different process configurations. There are still challenges in improvement of the simulation robustness and the cost estimation accuracy.

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10 Appendices

Appendix 1 Task description

Telemark University College

Faculty of Technology

FMH606 Master's Thesis

Aspen HYSYS process simulation and Aspen Icarus cost estimation of CO_2 removal plant

TUC supervisor: Lars Erik Øi

Task description:

Aims:

Improve a model in HYSYS (Aspen HYSYS) for calculation of CO_2 removal from atmospheric exhaust gas.

Improve models for calculation, equipment dimensioning and cost estimation of CO_2 removal from atmospheric exhaust gas.

Tasks:

1. Evaluation of earlier projects on process simulation and cost estimation of CO_2 removal plants.

2. HYSYS calculations of CO_2 removal with absorption and desorption in an amine solution. Calculations of dependencies of different removal efficiencies, process choices, equipment dimensions and other assumptions.

3. Extend the model to include water wash section and possibly split stream configurations.

4. Perform comparison calculations, especially for split stream configurations.

5. Evaluation of uncertainties in the calculations.

Adress: Kjølnes ring 56, NO-3918 Porsgrunn, Norway. **Phone:** 35 57 50 00. **Fax:** 35 55 75 47.

Task background:

The most actual method for removal of CO_2 from atmospheric exhaust is by the help of amine solutions.

HYSYS has been much used in student projects at Telemark University College for process simulation of CO_2 removal. There are several possibilities to improve the existing models.

Reference:

Øi, L.E.(speaker), "Aspen HYSYS Simulation of CO_2 Removal by Amine Absorption from a Gas Based Power Plant", SIMS2007 Conference, Gøteborg 30.-31.10.2007. Internett: http://www.ep.liu.se/ecp/027/008/ecp072708.pdf

Student category:

PT or EET

Practical arrangements:

The working place will be HiT.

Signatures:

Student (date and signature): 25.05.10

Supervisor (date and signature): 25/5-2010

Document: leo1/23.11.2009

Appendix 2 Cost factors table

Table 10-1 Cost factors table [16]

2005/2006	Fluid								Solid						
Cost of equipment in Carbon Steel (CS)	0-20	20-100	100-500	500-1000	1000-2000	2000-5000	5000-15000	>15000	0-20	20-100	100-500	500-1000	1000-2000	2000-5000	>5000
Equipment	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Erection	0,63	0,33	0,18	0,13	0,1	0,08	0,07	0,05	1,39	0,74	0,43	0,31	0,25	0,18	0,15
Piping	2,52	1,36	0,79	0,58	0,46	0,34	0,29	0,21	0,51	0,28	0,15	0,12	0,09	0,07	0,06
Electric	0,73	0,5	0,34	0,29	0,24	0,2	0,18	0,13	1,23	0,77	0,51	0,4	0,33	0,28	0,23
Instrument	2,52	1,36	0,79	0,58	0,46	0,34	0,29	0,21	1	0,55	0,32	0,23	0,19	0,13	0,11
Civil work	0,39	0,25	0,18	0,14	0,12	0,1	0,09	0,06	0,89	0,53	0,34	0,26	0,21	0,17	0,14
Steel & concrete	1,27	0,83	0,56	0,45	0,39	0,31	0,28	0,2	1,77	1,1	0,72	0,56	0,47	0,37	0,33
Insulation	0,48	0,24	0,13	0,1	0,08	0,06	0,04	0,03	0,48	0,24	0,13	0,1	0,08	0,06	0,04
Direct Cost	**9,53**	**5,87**	**3,98**	**3,28**	**2,85**	**2,42**	**2,22**	**1,88**	**8,27**	**5,21**	**3,6**	**2,99**	**2,61**	**2,25**	**2,06**
Engineering Process	0,87	0,31	0,17	0,13	0,11	0,09	0,08	0,06	0,87	0,31	0,17	0,13	0,11	0,09	0,08
Engineering Mechanical	0,69	0,17	0,07	0,04	0,03	0,02	0,01	0,01	0,87	0,26	0,12	0,08	0,06	0,04	0,03
Engineering Piping	0,76	0,41	0,24	0,18	0,13	0,1	0,09	0,06	0,15	0,08	0,04	0,03	0,02	0,02	0,02
Engineering Electric	0,74	0,22	0,11	0,08	0,07	0,06	0,04	0,03	0,86	0,29	0,14	0,11	0,09	0,07	0,06
Engineering Instrument	1,31	0,51	0,25	0,18	0,14	0,1	0,09	0,06	0,85	0,25	0,11	0,08	0,06	0,04	0,03
Engineering Civil	0,28	0,08	0,03	0,02	0,02	0,01	0,01	0,01	0,35	0,12	0,06	0,04	0,03	0,02	0,02
Engineering Steel &	0,41	0,17	0,09	0,07	0,06	0,04	0,04	0,03	0,48	0,2	0,11	0,09	0,08	0,06	0,06
Engineering Insulation	0,19	0,06	0,02	0,01	0,01	0,01	0,01	0,01	0,19	0,06	0,02	0,01	0,01	0,01	0,01
Engineering Cost	**5,24**	**1,9**	**0,98**	**0,7**	**0,57**	**0,43**	**0,37**	**0,27**	**4,62**	**1,56**	**0,77**	**0,57**	**0,45**	**0,35**	**0,31**
Procurement	1,1	0,37	0,14	0,09	0,06	0,03	0,02	0,02	1,1	0,37	0,14	0,09	0,06	0,03	0,02
Project Control	0,26	0,1	0,04	0,03	0,03	0,02	0,02	0,02	0,23	0,08	0,04	0,03	0,02	0,02	0,01
Site Management	0,47	0,3	0,2	0,17	0,14	0,12	0,11	0,08	0,4	0,25	0,18	0,14	0,13	0,11	0,11
Project management	0,63	0,32	0,21	0,17	0,14	0,12	0,11	0,08	0,54	0,28	0,18	0,14	0,12	0,11	0,1
Administration Cost	**2,46**	**1,09**	**0,59**	**0,45**	**0,37**	**0,3**	**0,26**	**0,19**	**2,27**	**0,98**	**0,54**	**0,41**	**0,33**	**0,28**	**0,24**
Commissioning	0,51	0,23	0,12	0,07	0,07	0,04	0,04	0,03	0,44	0,21	0,11	0,08	0,06	0,04	0,03
Total Known Cost	**17,7**	**9,1**	**5,67**	**4,5**	**3,86**	**3,19**	**2,9**	**2,37**	**15,6**	**7,96**	**5,02**	**4,04**	**3,45**	**2,92**	**2,64**
Contingency	3,52	1,82	1,14	0,91	0,78	0,66	0,59	0,43	3,05	1,56	1	0,8	0,69	0,59	0,54
Total Cost	**21,2**	**10,9**	**6,81**	**5,41**	**4,64**	**3,85**	**3,5**	**2,8**	**18,6**	**9,52**	**6,02**	**4,84**	**4,14**	**3,51**	**3,18**

Appendix 3 Paper on optimizing CO_2 absorption using split-stream configuration

L.E. Øi, I.O. Vozniuk

Telemark University College, Porsgrunn, NORWAY

1. Introduction

CO_2 absorption in an aqueous amine solution is the most mature technology for large scale CO_2 removal from atmospheric exhaust gases. The principle of a standard CO_2 absorption and desorption process is shown in Fig. 1. CO_2 is absorbed into the amine solution in the absorber. The amine loaded with CO_2 (rich amine) is pumped to the stripper, and regenerated (lean) amine is recirculated back to the absorber. This process has a large energy demand, and the most important is the steam consumption in the reboiler.

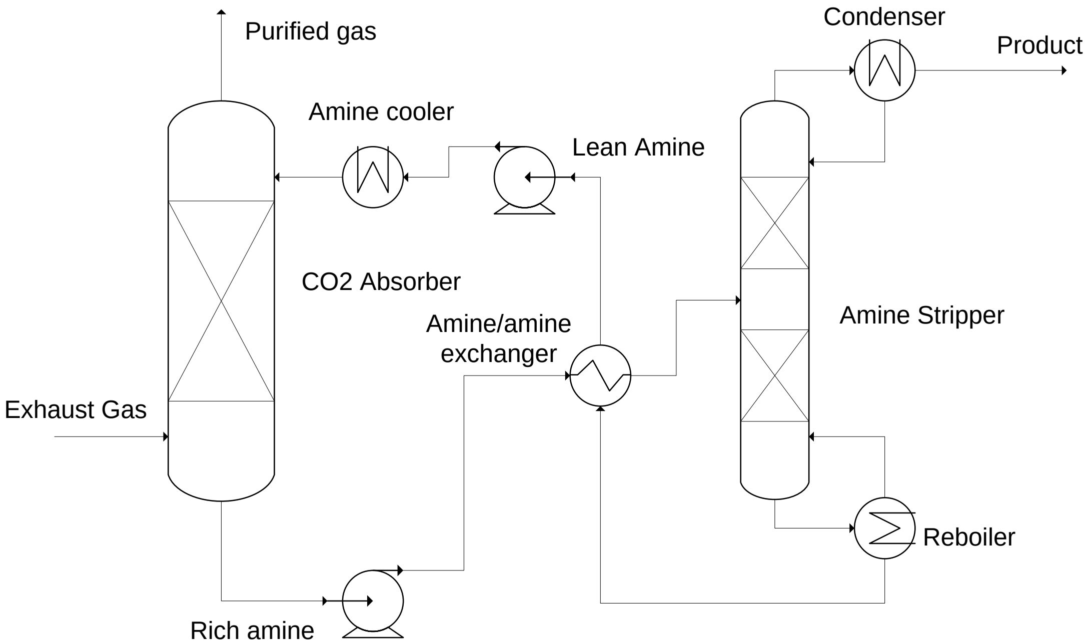

Fig. 1 Principle for a standard CO_2 absorption and desorption process

There are different ways to reduce the energy consumption in this process using alternative flow schemes [1], [2], [3]. A traditional alternative is a split-stream configuration as in Fig. 2. A partly regenerated (semilean) amine solution is pumped from the middle of the stripper to the middle of the absorption column, and a completely regenerated (lean) amine to the top.

A split-stream configuration is expected to increase the investment of the process due to added complexity. The purpose of this paper is to calculate and compare the energy consumption and the total cost for a standard CO_2 absorption process based on monoethanol amine (MEA) and for a split-stream configuration.

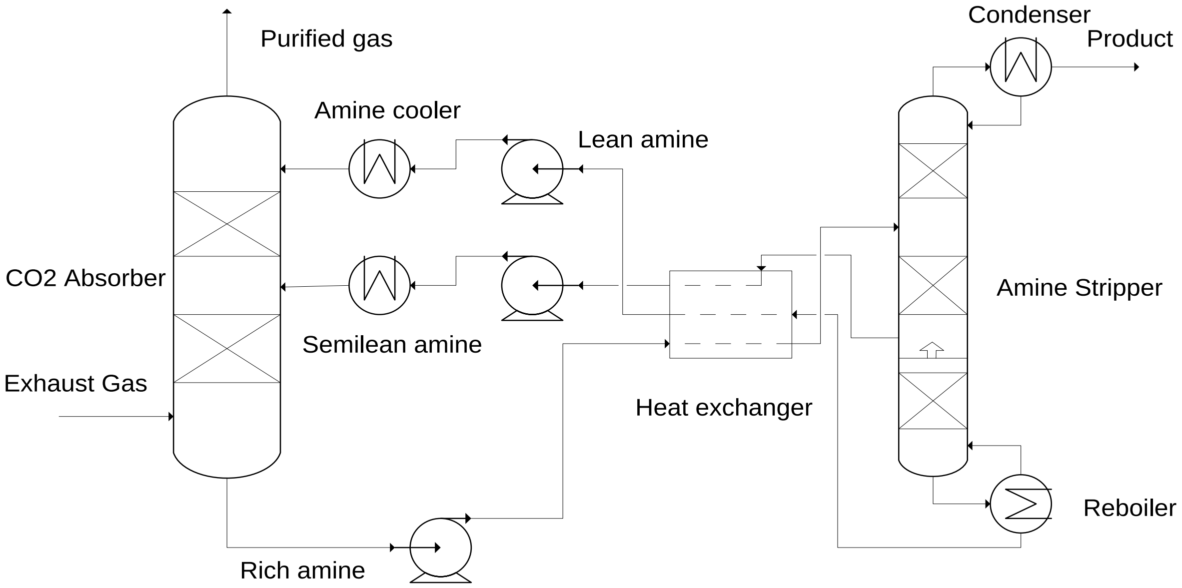

Fig. 2 Principle for CO_2 absorption and desorption using split-stream configuration

2. Process simulation

2.1. Base case specifications

The flowsheet in Fig. 3 with and without split-stream has been calculated with Aspen HYSYS version 7.0, and the amine package with the Kent Eisenberg model was used. Input specifications for both the standard process and the split-stream process are given in Table 1. The calculation method is based on earlier simulations of CO_2 removal using Aspen HYSYS [4].

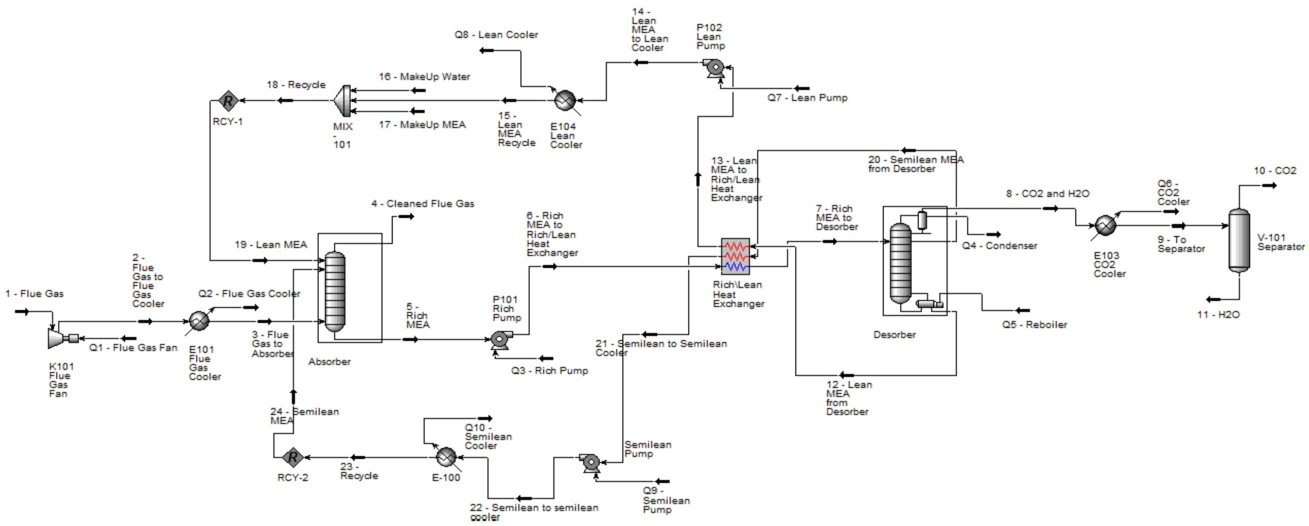

Fig.3 Aspen HYSYS flowsheet for a CO_2 removal using split-stream configuration

Specifications	Base case without split-stream	Base case with split-stream
Inlet gas temperature, ˚C	40	40
Inlet gas pressure, bar	1,11	1,11
Inlet gas flow, kgmole/h	85000	85000
CO_2 in inlet gas, mole-%	3,73	3,73
Water in inlet gas, mole-%	6,71	6,71
Lean amine temperature, ˚C	40	40
Lean amine pressure, bar	1,01	1,01
Lean amine rate, kgmole/h	148000	103500
MEA content in lean amine, mass-%	29	29
CO_2 in lean amine, mass-%	5,5	5,5
Number of stages in absorber	18	24 (semilean to 21)
Murphree efficiency in absorber	0,15	0,15
Rich amine pump pressure, bar	2	2
Heated rich amine temperature, ˚C	104,2	96,6
Number of stages in stripper	6+Condenser+Reboiler	6+Condenser+Reboiler
Murphree efficiency in stripper	1	1
Reflux ratio in stripper	0,1	0,1
Reboiler temperature, ˚C	120	120
Lean amine pump pressure, bar	2	2
Semilean amine temperature, ˚C	-	40
Semilean amine pressure, bar	-	1,11
Semilean amine rate, kgmole/h	-	100000
MEA content in semilean amine, mass-%	-	28
CO_2 in semilean amine, mass-%	-	9,1

Table 1 Input specifications for Aspen HYSYS calculations with 85% removal efficiency and minimum heat exchanger temperature difference of 10 K

2.2. Calculation sequence

The calculation sequence in Aspen HYSYS was based on guessed (or specified) flow rates and compositions to the absorption column. The exhaust gas fan and the following cooler was calculated first. Then the absorption column was calculated with the modified HYSIM in and out solver method with adaptive damping. Then the rich amine pump and the rich side of a multistream heat exchanger were calculated before the stripper was calculated. Then the lean and semilean side of the multistream heat exchanger, the return pumps and the coolers were calculated. Then the concentrations of the lean and semilean streams were checked manually against the specified concentrations in the feed streams to the absorber.

In the base cases with minimum heat exchanger temperature difference 10 K, the energy consumption was calculated to 3.8 GJ/ton CO_2 removed in the standard process and 3.4 GJ/ton with the split-stream configuration.

2.3. Parameter variations

The energy consumption can be reduced by increasing the number of stages in the absorption column. With the standard process and 10 K in minimum temperature difference, minimum energy consumption was 3.8 GJ/ton CO_2 with 20 stages. With a split-stream configuration, an increase from 18 to 24 stages resulted in a reduction of energy consumption from 3.8 to 3.4 GJ/ton CO_2. In literature, a value of 2.9 GJ/ton using split-stream has been calculated [2].

With 5 K temperature difference, the energy consumption has been reduced down to 3.0 GJ/ton CO_2 with 26 stages in the absorber and the semilean stream feed at stage 21 from the column top. With 15 K in minimum temperature difference, a split-flow configuration does not give any energy reduction. To vary the minimum temperature difference, the temperature specification on heated rich amine to the stripper column was adjusted.

The semilean feed stage to the absorber column was varied in each calculation to find the optimum. The removal stage for semilean amine from the stripper was stage 4 from top in all the calculations. The lean and semilean amine flow rates were varied to maintain 85 % CO_2 removal. The ratio between lean and semilean flow rate and the removal stage for semilean amine from the stripper column are parameters that can be further optimized.

3. Dimensioning and cost estimation

3.1. Dimensioning of process equipment

The fan was specified as a radial centrifugal fan with adiabatic efficiency 75 % (default value in HYSYS) and electrical motor. The fan was cost estimated with the gas volume flow as dimensioning factor. The direct contact cooler after the fan was calculated based on the tower dimensions, 15 meter diameter and 10 meter height.

The absorber column diameter is calculated based on a gas velocity of 3 m/s. The packing height is calculated based on 1 meter of structured packing for each stage with efficiency 0.15. The packing height of a water wash section above the main section was 5 meter. The total column height was estimated to the packing height + 12 meter without and + 14 meter with split-stream.

The pumps were specified with 75 % adiabatic efficiency and with electrical motors.

The heat exchangers (except the kettle type reboiler) were specified as shell and tube heat exchangers with floating head and with ideal countercurrent flows. The multi-stream exchanger might actually be a system of traditional heat exchangers. The total heat transfer numbers were 500 $W/(m^2 \cdot K)$ for the amine/amine exchanger, 800 $W/(m^2 \cdot K)$ for the amine coolers and the reboiler and 1000 $W/(m^2 \cdot K)$ for the condenser and the CO_2 cooler. The cost was estimated with heat exchange area as the dimensioning factor. The areas were calculated from heat duties and logarithmic mean temperatures from Aspen HYSYS combined with the heat transfer numbers.

The stripper column diameter was calculated based on a gas velocity of 1 m/s. The total column height was estimated to 25 meter without and 30 meter with split-stream. The separator after the condenser was specified as a cylindrical separator with 14 meter height.

Not listed equipment like filters, storage tanks and a reclaimer were neglected because the cost is low relative to the main equipment. Materials, material factors and total installation factors are specified in Table 2. Exotic material is titanium or high quality stainless steel.
The details in the calculations are given in the Master Thesis report [5].

3.2. Capital cost estimation

The base case processes have been cost estimated with basis in 2007 with Aspen ICARUS (version 16.0.0) and regulated to 2010. Installed cost for each equipment unit was calculated as a product of equipment cost and a total installation factor. A material factor influences the cost of equipment and piping. The total installation factor includes factors for e.g. material, piping, instrumentation, electrical, civil structures, administration and contingency. All cost factors are dependent on equipment cost, material and type of equipment. A structured packing with specific area 250 m^2/m^3 is specified in the columns. It is assumed that the packing cost is 1.4 times higher than the cost for 2" pall rings calculated by Aspen ICARUS.

Equipment list	Equipment cost, base case, kEUR	Equipment cost, split stream, kEUR,	Material type	Material factor	Total installation factor, base case	Total installation factor, split stream	Installed cost, base case, kEUR	Installed cost, split stream, kEUR
Flue gas blower	347	347	SS304	1,3	1,3	1,3	451	451
Fan motor	641	641	SS304	1,3	1,3	1,3	834	834
DCC	1777	1777	Exotic	2,5	5,43	5,435	9661	9661
Absorber skirt	2556	2926	SS316	1,75	3,71	3,71	9476	10848
Water wash skirt	1584	1584	SS316	1,75	4,47	4,47	7075	7075
Rich pump	249	363	SS304	1,3	1,3	1,3	323	472
Rich/Lean heat exch.	129	120	SS316	1,75	5,74	6,6	24064	41493
Desorber skirt	460	424	SS316	1,75	4,86	4,86	2235	2056
Reboiler	897	769	SS316	1,75	4,47	4,47	4007	3435
Lean pump	248	167	SS304	1,3	1,3	1,3	323	218
Lean cooler	251	179	Exotic	2,5	6,83	6,83	1716	1223
CO_2 cooler	180	96	Exotic	2,5	6,83	7,78	1228	746
Condenser	33	33	Exotic	2,5	9,5	9,5	315	315
Separator	128	128	SS316	1,75	5,74	5,74	732	732
Absorber packing	25119	33492	SS316	-	-	-	25119	33492
Water wash packing	6977	6977	SS316	-	-	-	6977	6977
Desorber packing	960	688	SS316	-	-	-	960	688
Semi-lean pump	-	167	Exotic	1,3	-	1,3	-	218
Semi-lean cooler	-	179	Exotic	2,5	-	6,83	-	1223
Total	42536	51057					95494	122156

Table 2 Equipment and installed cost for CO_2 removal plant

3.3 Operating cost and total cost

The operating cost is estimated from the energy cost. The electricity cost was specified to 0.05 EUR/kWh and the steam cost (130 ºC steam) was 0.013 EUR/kWh. Operating time was 8000 hours/year and interest rate was 7 %.
For a period of 10 years, the net present (negative) value of the energy consumption of the split-stream process was 109 mill. EUR compared to 127 mill. EUR for the standard process.
The increase of the installed cost (from Table 2) is 27 mill. EUR, so with 10 years pay-back time, the standard process without split-stream is most economical. The absolute value of the installed cost (capital cost) is not expected to be very accurate, but it is expected to include most of the cost factors that vary with size and capacity.
The split-stream alternative becomes more attractive when the calculation period increases. If the period of calculation is set to 20 years, the reduction in operating cost increases to 27 mill. EUR, and with a calculation period above 20 years, the split flow is most economical. The advantage of the split-stream alternative is sensitive to the energy cost. If the energy cost increases, the split-stream alternative becomes more economical.

4. Conclusion

It has been shown that it is possible to reduce the energy consumption considerably in a CO_2 removal plant using a split-stream configuration. An energy consumption of 3.0 GJ/ton CO_2 has been calculated using a simple split-stream configuration and 5 K temperature difference in the main heat exchanger. With 15 K temperature difference, a split-stream configuration will not reduce the energy consumption.
Capital cost and operating cost for the cases have been calculated. The capital cost increases with a split-stream configuration due to a more complex process. At base case conditions with 10 K temperature difference and 10 years calculation period, the standard process without split-stream was most economical. With more than 20 years calculation period, the split-stream configuration was most economical. The split-stream alternative becomes more attractive when the energy cost increases.

5. Acknowledgements

Many thanks to Nils Eldrup and Ragnhild Skagestad for help with the cost estimation.

6. References

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Appendix 4 Equipment cost estimation for the base case without split-stream performed by Aspen ICARUS

Flue Gas Fan

Project : HIT
Scenario : BASECASE

Flue Gas Fan

Item Code: EFN CENTRIF
Internal Name : EFN CENTRIF Flue Gas Fan

Design Data

Parameter	Value	Units
Item type	CENTRIF	
Material	CS	
Actual gas flow rate	254800.00	M3/H
Speed	1500.000	RPM
Driver power	200.000	KW
Total weight	2600	KG

Summary Costs

Item	Material(EUR)	Manpower(EUR)	Manhours
Equipment&Setting	61500.	5258.	106
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**61500**	**5258**	**106**

Total material and manpower cost=EUR 66800.

Fan Motor

Processing Date : Fri Nov 06 11:29:29 AM 2009
Version : IPM 16.0.0(Build 2032)
List of Items :

Project : co2 removal student
Scenario : BaseCase
Fan motor

Project : CO2 REMOVAL STUDENT
Scenario : BASECASE

Fan motor

Item Code: EMOTVARY
SPEED
Internal Name : EMOTVARY SPEEDFan motor

Design Data

Parameter	**Value**	**Units**
Item type	VARY SPEED	
Low speed	250.000	RPM
High speed	1800.000	RPM
Driver power	300.000	KW
Total weight	2500	KG

Summary Costs

Item	**Material(EUR)**	**Manpower(EUR)**	**Manhours**
Equipment&Setting	55500.	6668.	134
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**55500**	**6668**	**134**

Total material and manpower cost=EUR 62200.

DCC Cooling Tower

Project : HIT

Scenario : BASECASE

Cooling tower (DCC)

Item Code: DTW DC HE TW

Internal Name : DTW DC HE TW Cooling tower (DCC)

Design Data

Parameter	Value	Units
Item type	DC HE TW	
Number of identical items	1,00	
EQUIPMENT DESIGN DATA		
Liquid volume	1767.025	M3
Design gauge pressure	100.002	KPAG
Design temperature	340.000	DEG C
Operating temperature	121.111	DEG C
COLUMN DATA		
Shell material	A 515	
Diameter option	OD	
Vessel diameter	15.000	M
Vessel tangent to tangent height	10.000	M
Head type	HEMI	
MECHANICAL DESIGN DATA		
Wind or seismic design	W+S	
Weld efficiency	85.000	PERCENT
Base material thickness	12.000	MM
Corrosion allowance	3.1750	MM
THICKNESSES REQUIRED		
Thickness for internal pressure	2521818,00	MM
Wind or seismic design thickness	1745708,00	MM
PACKING DATA		
Number of distributor plates	4,00	
Number of packed sections	2,00	
Section height	1132313,00	M
Cross sectional area	176.714	M2
SECTION 1		
Packing type Section 1	68PVC	
Packing height Section 1	7.0000	M
Packing volume	1237,00	M3

Packing volume per unit height	176.716	M3/M
VESSEL SKIRT DATA		
Skirt material	CS	
Skirt height	1132497,00	M
Skirt thickness	25.000	MM
NOZZLE AND MANHOLE DATA		
Nozzle ASA rating	150,00	CLASS
Nozzle material	A 515	
Nozzle A Quantity	4,00	
Nozzle A Diameter	1200.000	MM DIAM
Nozzle A Location	S	
Nozzle B Quantity	6,00	
Nozzle B Diameter	50.000	MM DIAM
Nozzle B Location	S	
Number of manholes	2,00	
Manhole diameter	900.000	MM
PROCESS DESIGN DATA		
WEIGHT DATA		
Shell	44400,00	KG
Trays and supports	36400,00	KG
Heads	50000,00	KG
Nozzles	28,00	KG
Manholes and Large nozzles	3400,00	KG
Skirt	88200,00	KG
Base ring and lugs	11100,00	KG
Ladder clips	80,00	KG
Platform clips	260,00	KG
Fittings and miscellaneous	70,00	KG
Total weight less packing	233900,00	KG
VENDOR COST DATA		
Packing cost	364972,00	EURO
Material cost	558676,00	EURO
Field fabrication cost	145217,00	EURO
Fabrication labor	12998,00	HOURS
Shop labor cost	116136,00	EURO
Shop overhead cost	120400,00	EURO
Office overhead cost	159873,00	EURO
Profit	165127,00	EURO
Total cost	1630400,00	EURO
Cost per unit weight	2850871,00	EUR/KG

Cost per unit height or length	232914.28	EUR/M
Cost per unit volume	1318.018	EUR/M3
Cost per unit area	9226.182	EUR/M2

Summary Costs

Item	Material(EUR)	Manpower(EUR)	Manhours
Equipment&Setting	1630400.	64077.	1300,00
Piping	0.	0.	0,00
Civil	0.	0.	0,00
Structural Steel	0.	0.	0,00
Instrumentation	0.	0.	0,00
Electrical	0.	0.	0,00
Insulation	0.	0.	0,00
Paint	0.	0.	0,00
Subtotal	**1630400,00**	**64077,00**	**1300,00**

Total material and manpower cost=EUR 1694500.

Absorber

Project : CO2 REMOVAL STUDENT
Scenario : BASECASE

Absorber

Item Code: DTW PACKED
Internal Name : DTW PACKED Absorber

Design Data

Parameter	Value	Units
Item type	PACKED	
Number of identical items	1	
EQUIPMENT DESIGN DATA		
Application	ABSORB	
Liquid volume	7075.669	M3
Design gauge pressure	100.002	KPAG
Design temperature	340.000	DEG C
Operating temperature	305.000	DEG C
COLUMN DATA		
Shell material	A 515	
Diameter option	OD	
Vessel diameter	17.330	M
Vessel tangent to tangent height	30.000	M
Head type	HEMI	
MECHANICAL DESIGN DATA		
Wind or seismic design	W+S	
Weld efficiency	85.000	PERCENT
Thickness Average	13.154	MM
Corrosion allowance	3.1750	MM
THICKNESSES REQUIRED		
Thickness for internal pressure	12.686	MM
Wind or seismic design thickness	14.233	MM
PACKING DATA		
Number of distributor plates	4	
Number of packed sections	2	

Section height	9.0000	M
Cross sectional area	235.878	M2
SECTION 1		
Packing type	2.0SPR	
Total packing height	18.000	M
Packing volume	4246	M3
Packing volume per unit height	235.879	M3/M
VESSEL SKIRT DATA		
Skirt material	CS	
Skirt height	9.5000	M
Skirt thickness	40.000	MM
NOZZLE AND MANHOLE DATA		
Nozzle ASA rating	150	CLASS
Nozzle material	A 515	
Nozzle A Quantity	4	
Nozzle A Diameter	1200.000	MM DIAM
Nozzle A Location	S	
Nozzle B Quantity	9	
Nozzle B Diameter	50.000	MM DIAM
Nozzle B Location	S	
Number of manholes	7	
Manhole diameter	900.000	MM
PROCESS DESIGN DATA		
WEIGHT DATA		
Shell	168700	KG
Trays and supports	46900	KG
Heads	96400	KG
Nozzles	40	KG
Manholes and Large nozzles	6100	KG
Skirt	163400	KG
Base ring and lugs	22700	KG
Ladder clips	160	KG
Platform clips	470	KG
Fittings and miscellaneous	70	KG
Total weight less packing	504900	KG
VENDOR COST DATA		

Packing cost	16457220	EURO
Material cost	971396	EURO
Field fabrication cost	328776	EURO
Fabrication labor	36743	HOURS
Shop labor cost	217278	EURO
Shop overhead cost	224990	EURO
Office overhead cost	296214	EURO
Profit	305828	EURO
Total cost	18801701	EURO
Cost per unit weight	37.238	EUR/KG
Cost per unit height or length	1044539.	EUR/M
Cost per unit volume	4428.282	EUR/M3
Cost per unit area	79709.55	EUR/M2

Summary Costs

Item	Material(EUR)	Manpower(EUR)	Manhours
Equipment&Setting	18801700.	161589.	3279
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**18801700**	**161589**	**3279**

Total material and manpower cost=EUR 18963300.

Water wash

Project : CO2 REMOVAL STUDENT
Scenario : BASECASE

Water wash

Item Code: DTW PACKED
Internal Name : DTW PACKED Absorber

Design Data

Parameter	Value	Units
Item type	PACKED	
Number of identical items	1	
EQUIPMENT DESIGN DATA		
Application	ABSORB	
Liquid volume	2358.683	M3
Design gauge pressure	100.002	KPAG
Design temperature	340.000	DEG C
Operating temperature	305.000	DEG C
COLUMN DATA		
Shell material	A 515	
Diameter option	OD	
Vessel diameter	17.330	M
Vessel tangent to tangent height	10.000	M
Head type	HEMI	
MECHANICAL DESIGN DATA		
Wind or seismic design	W+S	
Weld efficiency	85.000	PERCENT
Base material thickness	15.000	MM
Corrosion allowance	3.1750	MM
THICKNESSES REQUIRED		
Thickness for internal pressure	9.1044	MM
Wind or seismic design thickness	9.5660	MM
PACKING DATA		
Number of distributor plates	2	
Cross sectional area	235.878	M2

SECTION 1		
Packing type	2.0SPR	
Total packing height	5.0000	M
Packing volume	1179	M3
Packing volume per unit height	235.879	M3/M
VESSEL SKIRT DATA		
Skirt material	CS	
Skirt height	9.5000	M
Skirt thickness	28.000	MM
NOZZLE AND MANHOLE DATA		
Nozzle ASA rating	150	CLASS
Nozzle material	A 515	
Nozzle A Quantity	4	
Nozzle A Diameter	1200.000	MM DIAM
Nozzle A Location	S	
Nozzle B Quantity	6	
Nozzle B Diameter	50.000	MM DIAM
Nozzle B Location	S	
Number of manholes	4	
Manhole diameter	900.000	MM
PROCESS DESIGN DATA		
WEIGHT DATA		
Shell	64100	KG
Trays and supports	23500	KG
Heads	74100	KG
Nozzles	28	KG
Manholes and Large nozzles	4500	KG
Skirt	114100	KG
Base ring and lugs	14300	KG
Ladder clips	80	KG
Platform clips	260	KG
Fittings and miscellaneous	70	KG
Total weight less packing	295000	KG
VENDOR COST DATA		
Packing cost	4571450	EURO
Material cost	592339	EURO

Field fabrication cost	177506	EURO
Fabrication labor	13540	HOURS
Shop labor cost	152147	EURO
Shop overhead cost	157610	EURO
Office overhead cost	183532	EURO
Profit	189417	EURO
Total cost	6024000	EURO
Cost per unit weight	20.420	EUR/KG
Cost per unit height or length	1204800.	EUR/M
Cost per unit volume	5107.703	EUR/M3
Cost per unit area	25538.66	EUR/M2

Summary Costs

Item	Material(EUR)	Manpower(EUR)	Manhours
Equipment&Setting	6024000.	81343.	1651
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**6024000**	**81343**	**1651**

Total material and manpower cost=EUR 6105300.

Rich Pump

Project : CO2 REMOVAL STUDENT
Scenario : BASECASE

Rich Pump

Item Code: DCP CENTRIF
Internal Name : DCP CENTRIF Rich Pump

Design Data

Parameter	Value	Units
Item type	CENTRIF	
Number of identical items	1	
EQUIPMENT DESIGN DATA		
Casing material	CS	
Design temperature	120.000	DEG C
Design gauge pressure	350.000	KPAG
Fluid head	60.000	M
ASA rating	150	CLASS
Driver power	710.000	KW
Speed	1500.000	RPM
Driver type	MOTOR	
Motor type	TEFC	
Pump efficiency	82.000	PERCENT
Seal type	SNGL	
PROCESS DESIGN DATA		
Liquid flow rate	946.800	L/S
Fluid density	1000.004	KG/M3
Fluid viscosity	1.0000	MPA-S
Power per liquid flow rate	0.7499	KW/L/S
Liquid flow rate times head	56807	L/S -M
WEIGHT DATA		
Pump	3200	KG

Motor	2000	KG
Base plate	670	KG
Fittings and miscellaneous	570	KG
Total weight	6400	KG
VENDOR COST DATA		
Motor cost	71026	EURO
Material cost	7268	EURO
Shop labor cost	44390	EURO
Shop overhead cost	45278	EURO
Office overhead cost	28553	EURO
Profit	31486	EURO
Total cost	228000	EURO
Cost per unit weight	35.625	EUR/KG
Cost per unit liquid flow rate	240.811	EUR/L/S
Cost per unit power	321.127	EUR/KW

Summary Costs

Item	**Material(EUR)**	**Manpower(EUR)**	**Manhours**
Equipment&Setting	228000.	14892.	301
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**228000**	**14892**	**301**

Total material and manpower cost=EUR 242900.

Rich/Lean heat exchanger

Project : CO2 REMOVAL STUDENT
Scenario : BASECASE

Rich/Lean HX

Item Code: DHE FLOAT HEAD
Internal Name : DHE FLOAT HEADHeae Exchanger - BaseCase

Design Data

Parameter	Value	Units
Item type	FLOAT HEAD	
Number of identical items	1	
GENERAL DESIGN DATA		
TEMA type	BES	
Heat exchanger design option	STAND	
Heat transfer area	38030.00	M2
Area per shell	1000.789	M2
Number of shells	38	
Number of tube passes	2	
Number of shell passes	1	
Vendor grade	HIGH	
SHELL DATA		
Shell material	A285C	
Shell diameter	1300.000	MM
Shell length	10.100	M
Shell design gauge pressure	1000.001	KPAG
Shell design temperature	340.000	DEG C
Shell operating temperature	340.000	DEG C
Shell corrosion allowance	3.0002	MM
Shell wall thickness	12.000	MM
ASA rating Shell side	300	CLASS
Number of baffles	19	
Shell fabrication type	PLATE	
Expansion joint	NO	
TUBE DATA		

Tube material	A 214	
Number of tubes per shell	1394	
Tube outside diameter	25.000	MM
Tube length extended	9.0000	M
Tube design gauge pressure	690.000	KPAG
Tube design temperature	120.000	DEG C
Tube operating temperature	120.000	DEG C
Tube corrosion allowance	0.0600	MM
Tube wall thickness	1.7000	MM
Tube gauge	16	BWG
Tube pitch symbol	TRIANGULAR	
Tube pitch	32.000	MM
Tube seal type	SEALW	
TUBE SHEET DATA		
Tube sheet material	A 515	
Tube sheet thickness	60.000	MM
Tube sheet corrosion allowance	3.0001	MM
Channel material	A 515	
FLOATING HEAD DATA		
Head material Tube side	A 515	
Floating head thickness	7.0002	MM
SHELL SIDE HEAD DATA		
Head material Shell side	A285C	
ASA rating Shell side	300	CLASS
Head thickness Shell side	12.000	MM
HEAD DATA		
Head material Tube side	A 515	
ASA rating Tube side	150	CLASS
Head thickness Tube side	7.0002	MM
WEIGHT DATA		
Shell	4000	KG
Tubes	12100	KG
Heads	810	KG
Internals and baffles	1500	KG
Nozzles	350	KG
Flanges	1800	KG

Base ring and lugs	35	KG
Tube sheet	760	KG
Saddles	210	KG
Fittings and miscellaneous	1500	KG
Total weight per item	23100	KG
Total weight	877800	KG
VENDOR COST DATA		
Material cost	56433	EURO
Shop labor cost	19548	EURO
Shop overhead cost	18911	EURO
Office overhead cost	8197	EURO
Profit	8686	EURO
Total cost	4247400	EURO
Cost per unit weight	4.8387	EUR/KG
Cost per unit area	111.686	EUR/M2
Cost per shell	111773	EUR/SHEL

Summary Costs

Item	**Material(EUR)**	**Manpower(EUR)**	**Manhours**
Equipment&Setting	4247400.	51657.	1048
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**4247400**	**51657**	**1048**

Total material and manpower cost=EUR 4299100.

Desorber

Project : CO2 REMOVAL STUDENT
Scenario : BASECASE

Desorber

Item Code: DTW PACKED
Internal Name : DTW PACKED Absorber

Design Data

Parameter	Value	Units
Item type	PACKED	
Number of identical items	1	
EQUIPMENT DESIGN DATA		
Application	ABSORB	
Liquid volume	676.451	M3
Design gauge pressure	200.000	KPAG
Design temperature	200.000	DEG C
Operating temperature	165.000	DEG C
COLUMN DATA		
Shell material	A 515	
Diameter option	OD	
Vessel diameter	5.8690	M
Vessel tangent to tangent height	25.000	M
Head type	HEMI	
MECHANICAL DESIGN DATA		
Wind or seismic design	W+S	
Fluid volume	20.000	PERCENT
Weld efficiency	85.000	PERCENT
Thickness Average	9.3842	MM
Corrosion allowance	3.1750	MM
THICKNESSES REQUIRED		
Thickness for internal pressure	5.1010	MM
Wind or seismic design thickness	8.1300	MM
PACKING DATA		
Number of distributor plates	4	

Number of packed sections	2	
Section height	3.0000	M
Cross sectional area	27.053	M2
SECTION 1		
Packing type	2.0SPR	
Total packing height	6.0000	M
Packing volume	162	M3
Packing volume per unit height	27.053	M3/M
VESSEL SKIRT DATA		
Skirt material	CS	
Skirt height	8.8000	M
Skirt thickness	18.000	MM
NOZZLE AND MANHOLE DATA		
Nozzle ASA rating	150	CLASS
Nozzle material	A 515	
Nozzle A Quantity	2	
Nozzle A Diameter	600.000	MM DIAM
Nozzle A Location	S	
Nozzle B Quantity	1	
Nozzle B Diameter	500.000	MM DIAM
Nozzle B Location	S	
Nozzle C Quantity	1	
Nozzle C Diameter	750.000	MM DIAM
Nozzle C Location	S	
Nozzle D Quantity	8	
Nozzle D Diameter	50.000	MM DIAM
Nozzle D Location	S	
Number of manholes	6	
Manhole diameter	900.000	MM
PROCESS DESIGN DATA		
WEIGHT DATA		
Shell	33900	KG
Trays and supports	7100	KG
Heads	6800	KG
Nozzles	36	KG
Manholes and Large nozzles	4000	KG

Skirt	23100	KG
Base ring and lugs	2800	KG
Ladder clips	130	KG
Platform clips	400	KG
Fittings and miscellaneous	70	KG
Total weight less packing	78300	KG
VENDOR COST DATA		
Packing cost	629168	EURO
Material cost	155360	EURO
Field fabrication cost	81372	EURO
Fabrication labor	3702	HOURS
Shop labor cost	37831	EURO
Shop overhead cost	39204	EURO
Office overhead cost	53341	EURO
Profit	55123	EURO
Total cost	1051400	EURO
Cost per unit weight	13.428	EUR/KG
Cost per unit height or length	175233.33	EUR/M
Cost per unit volume	6477.334	EUR/M3
Cost per unit area	38864.23	EUR/M2

Summary Costs

Item	**Material(EUR)**	**Manpower(EUR)**	**Manhours**
Equipment&Setting	1051400.	34971.	710
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**1051400**	**34971**	**710**

Total material and manpower cost=EUR 1086400.

Reboiler

Project : CO2 REMOVAL STUDENT
Scenario : BASECASE

Reboiler

Item Code: DRB KETTLE
Internal Name : DRB KETTLE Reboiler

Design Data

Parameter	Value	Units
Item type	KETTLE	
Number of identical items	1	
GENERAL DESIGN DATA		
TEMA type	BKT	
Heat exchanger design option	STAND	
Heat transfer area	5069.054	M2
Area per shell	362.075	M2
Number of shells	14	
Number of tube passes	2	
Number of shell passes	1	
Vendor grade	HIGH	
SHELL DATA		
Shell material	A285C	
Shell diameter	1150.000	MM
Shell length	11.300	M
Shell design gauge pressure	1000.001	KPAG
Shell design temperature	340.000	DEG C
Shell operating temperature	340.000	DEG C
Shell corrosion allowance	3.0002	MM
Shell wall thickness	12.000	MM
ASA rating Shell side	300	CLASS
Number of baffles	23	
Shell fabrication type	PLATE	
Expansion joint	NO	
TUBE DATA		

Tube material	A 214	
Number of tubes per shell	505	
Tube outside diameter	25.000	MM
Tube port diameter	787.000	MM
Tube length extended	9.0000	M
Tube design gauge pressure	200.000	KPAG
Tube design temperature	200.000	DEG C
Tube operating temperature	200.000	DEG C
Tube corrosion allowance	0.0600	MM
Tube wall thickness	1.7000	MM
Tube gauge	16	BWG
Tube pitch symbol	TRIANGULAR	
Tube pitch	32.000	MM
Tube seal type	SEALW	
TUBE SHEET DATA		
Tube sheet material	A 515	
Tube sheet thickness	38.000	MM
Tube sheet corrosion allowance	3.0001	MM
Channel material	A 515	
PROCESS DESIGN DATA		
Duty	63.963	MEGAW
Heat of vaporization	350.000	KJ/KG
Vaporization	90.000	PERCENT
Specific gravity tower bottoms	0.5000	
Molecular weight Bottoms	100.000	
HEAD DATA		
Head material Tube side	A 515	
ASA rating Tube side	150	CLASS
Head thickness Tube side	7.0002	MM
WEIGHT DATA		
Shell	3900	KG
Tubes	4400	KG
Heads	290	KG
Internals and baffles	640	KG
Nozzles	300	KG
Flanges	400	KG

Base ring and lugs	31	KG
Tube sheet	190	KG
Saddles	170	KG
Fittings and miscellaneous	930	KG
Total weight per item	11300	KG
Total weight	158200	KG
VENDOR COST DATA		
Material cost	24816	EURO
Shop labor cost	12547	EURO
Shop overhead cost	11564	EURO
Office overhead cost	4727	EURO
Profit	5104	EURO
Total cost	822600	EURO
Cost per unit weight	5.1997	EUR/KG
Cost per unit area	162.279	EUR/M2
Cost per shell	58757	EUR/SHEL

Summary Costs

Item	Material(EUR)	Manpower(EUR)	Manhours
Equipment&Setting	822600.	6199.	126
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**822600**	**6199**	**126**

Total material and manpower cost=EUR 828800.

Lean Pump

Project : CO2 REMOVAL STUDENT
Scenario : BASECASE

Lean Pump

Item Code: DCP CENTRIF
Internal Name : DCP CENTRIF Lean Pump

Design Data

Parameter	Value	Units
Item type	CENTRIF	
Number of identical items	1	
EQUIPMENT DESIGN DATA		
Casing material	CS	
Design temperature	120.000	DEG C
Design gauge pressure	150.000	KPAG
Fluid head	60.000	M
ASA rating	150	CLASS
Driver power	710.000	KW
Speed	1500.000	RPM
Driver type	MOTOR	
Motor type	TEFC	
Pump efficiency	82.000	PERCENT
Seal type	SNGL	
PROCESS DESIGN DATA		
Liquid flow rate	946.300	L/S
Fluid density	1000.004	KG/M3
Fluid viscosity	1.0000	MPA-S
Power per liquid flow rate	0.7503	KW/L/S
Liquid flow rate times head	56777	L/S -M
WEIGHT DATA		
Pump	3200	KG
Motor	2000	KG

Base plate	670	KG
Fittings and miscellaneous	570	KG
Total weight	6400	KG
VENDOR COST DATA		
Motor cost	71026	EURO
Material cost	7262	EURO
Shop labor cost	44356	EURO
Shop overhead cost	45242	EURO
Office overhead cost	28541	EURO
Profit	31473	EURO
Total cost	227900	EURO
Cost per unit weight	35.609	EUR/KG
Cost per unit liquid flow rate	240.833	EUR/L/S
Cost per unit power	320.986	EUR/KW

Summary Costs

Item	Material(EUR)	Manpower(EUR)	Manhours
Equipment&Setting	227900.	14892.	301
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**227900**	**14892**	**301**

Total material and manpower cost=EUR 242800.

Lean Cooler

Project : CO2 REMOVAL STUDENT
Scenario : BASECASE

Lean Cooler

Item Code: DHE FLOAT HEAD
Internal Name : DHE FLOAT HEADLean Cooler

Design Data

Parameter	Value	Units
Item type	FLOAT HEAD	
Number of identical items	1	
GENERAL DESIGN DATA		
TEMA type	BES	
Heat exchanger design option	STAND	
Heat transfer area	1651.000	M2
Area per shell	550.333	M2
Number of shells	3	
Number of tube passes	2	
Number of shell passes	1	
Vendor grade	HIGH	
SHELL DATA		
Shell material	A285C	
Shell diameter	975.000	MM
Shell length	10.100	M
Shell design gauge pressure	1000.001	KPAG
Shell design temperature	340.000	DEG C
Shell operating temperature	340.000	DEG C
Shell corrosion allowance	3.0002	MM
Shell wall thickness	12.000	MM
ASA rating Shell side	300	CLASS
Number of baffles	25	
Shell fabrication type	PLATE	
Expansion joint	NO	
TUBE DATA		
Tube material	A 214	

Number of tubes per shell	767	
Tube outside diameter	25.000	MM
Tube length extended	9.0000	M
Tube design gauge pressure	690.000	KPAG
Tube design temperature	340.000	DEG C
Tube operating temperature	340.000	DEG C
Tube corrosion allowance	0.0600	MM
Tube wall thickness	1.7000	MM
Tube gauge	16	BWG
Tube pitch symbol	TRIANGULAR	
Tube pitch	32.000	MM
Tube seal type	SEALW	
TUBE SHEET DATA		
Tube sheet material	A 515	
Tube sheet thickness	50.000	MM
Tube sheet corrosion allowance	3.0001	MM
Channel material	A 515	
FLOATING HEAD DATA		
Head material Tube side	A 515	
Floating head thickness	7.0002	MM
SHELL SIDE HEAD DATA		
Head material Shell side	A285C	
ASA rating Shell side	300	CLASS
Head thickness Shell side	12.000	MM
HEAD DATA		
Head material Tube side	A 515	
ASA rating Tube side	150	CLASS
Head thickness Tube side	7.0002	MM
WEIGHT DATA		
Shell	3000	KG
Tubes	6700	KG
Heads	440	KG
Internals and baffles	1100	KG
Nozzles	190	KG
Flanges	1100	KG
Base ring and lugs	19	KG

Tube sheet	380	KG
Saddles	130	KG
Fittings and miscellaneous	1100	KG
Total weight per item	14200	KG
Total weight	42600	KG
VENDOR COST DATA		
Material cost	35326	EURO
Shop labor cost	15067	EURO
Shop overhead cost	14224	EURO
Office overhead cost	5877	EURO
Profit	6307	EURO
Total cost	230400	EURO
Cost per unit weight	5.4085	EUR/KG
Cost per unit area	139.552	EUR/M2
Cost per shell	76800	EUR/SHEL

Summary Costs

Item	Material(EUR)	Manpower(EUR)	Manhours
Equipment&Setting	230400.	5822.	118
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**230400**	**5822**	**118**

Total material and manpower cost=EUR 236200.

Condenser

Project : CO2 REMOVAL STUDENT
Scenario : BASECASE

Condenser

Item Code: DHE FIXED T S
Internal Name : DHE FIXED T S Condenser

Design Data

Parameter	Value	Units
Item type	FIXED T S	
Number of identical items	1,00	
GENERAL DESIGN DATA		
TEMA type	BEM	
Heat exchanger design option	STAND	
Heat transfer area	97.900	M2
Number of shells	1,00	
Number of tube passes	1,00	
Number of shell passes	1,00	
Vendor grade	HIGH	
SHELL DATA		
Shell material	A285C	
Shell diameter	525.000	MM
Shell length	6.0000	M
Shell design gauge pressure	1000.001	KPAG
Shell design temperature	340.000	DEG C
Shell operating temperature	340.000	DEG C
Shell corrosion allowance	3.0002	MM
Shell wall thickness	12.700	MM
ASA rating Shell side	300,00	CLASS
Number of baffles	16,00	
Shell fabrication type	PIPE	
Expansion joint	NO	
TUBE DATA		
Tube material	A 214	
Number of tubes per shell	218,00	
Tube outside diameter	25.000	MM
Tube length extended	6.0000	M

Tube design gauge pressure	1000.001	KPAG
Tube design temperature	340.000	DEG C
Tube operating temperature	340.000	DEG C
Tube corrosion allowance	0.0600	MM
Tube wall thickness	1862739,00	MM
Tube gauge	16,00	BWG
Tube pitch symbol	TRIANGULAR	
Tube pitch	32.000	MM
Tube seal type	SEALW	
TUBE SHEET DATA		
Tube sheet material	A 515	
Tube sheet thickness	28.000	MM
Tube sheet corrosion allowance	3.0001	MM
Channel material	A 515	
HEAD DATA		
Head material Tube side	A 515	
ASA rating Tube side	300,00	CLASS
Head thickness Tube side	7.0002	MM
WEIGHT DATA		
Shell	920,00	KG
Tubes	1300,00	KG
Heads	170,00	KG
Internals and baffles	150,00	KG
Nozzles	180,00	KG
Flanges	420,00	KG
Base ring and lugs	7,00	KG
Tube sheet	80,00	KG
Saddles	48,00	KG
Fittings and miscellaneous	360,00	KG
Total weight	3600,00	KG
VENDOR COST DATA		
Material cost	12630,00	EURO
Shop labor cost	6353,00	EURO
Shop overhead cost	5754,00	EURO
Office overhead cost	2644,00	EURO
Profit	3018,00	EURO
Total cost	30400,00	EURO
Cost per unit weight	929392,00	EUR/KG
Cost per unit area	292.223	EUR/M2

Summary Costs

Item	Material(EUR)	Manpower(EUR)	Manhours
Equipment&Setting	30400.	1966.	40,00
Piping	0.	0.	0,00
Civil	0.	0.	0,00
Structural Steel	0.	0.	0,00
Instrumentation	0.	0.	0,00
Electrical	0.	0.	0,00
Insulation	0.	0.	0,00
Paint	0.	0.	0,00
Subtotal	**30400,00**	**1966,00**	**40,00**

Total material and manpower cost=EUR 32400.

CO2 Cooler

Project : CO2 REMOVAL STUDENT
Scenario : BASECASE

CO2 Cooler

Item Code: DHE FIXED T S
Internal Name : DHE FIXED T S CO2 Cooler

Design Data

Parameter	Value	Units
Item type	FIXED T S	
Number of identical items	1	
GENERAL DESIGN DATA		
TEMA type	BEM	
Heat exchanger design option	STAND	
Heat transfer area	1288.000	M2
Area per shell	644.000	M2
Number of shells	2	
Number of tube passes	1	
Number of shell passes	1	
Vendor grade	HIGH	
SHELL DATA		
Shell material	A285C	
Shell diameter	1025.000	MM
Shell length	9.0000	M
Shell design gauge pressure	1000.001	KPAG
Shell design temperature	340.000	DEG C
Shell operating temperature	340.000	DEG C
Shell corrosion allowance	3.0002	MM
Shell wall thickness	12.000	MM
ASA rating Shell side	300	CLASS
Number of baffles	21	
Shell fabrication type	PLATE	
Expansion joint	NO	
TUBE DATA		

Tube material	A 214	
Number of tubes per shell	897	
Tube outside diameter	25.000	MM
Tube length extended	9.0000	M
Tube design gauge pressure	1000.001	KPAG
Tube design temperature	340.000	DEG C
Tube operating temperature	340.000	DEG C
Tube corrosion allowance	0.0600	MM
Tube wall thickness	1.7000	MM
Tube gauge	16	BWG
Tube pitch symbol	TRIANGULAR	
Tube pitch	32.000	MM
Tube seal type	SEALW	
TUBE SHEET DATA		
Tube sheet material	A 515	
Tube sheet thickness	50.000	MM
Tube sheet corrosion allowance	3.0001	MM
Channel material	A 515	
HEAD DATA		
Head material Tube side	A 515	
ASA rating Tube side	300	CLASS
Head thickness Tube side	7.0002	MM
WEIGHT DATA		
Shell	2800	KG
Tubes	7800	KG
Heads	460	KG
Internals and baffles	930	KG
Nozzles	480	KG
Flanges	1400	KG
Base ring and lugs	19	KG
Tube sheet	400	KG
Saddles	140	KG
Fittings and miscellaneous	1100	KG
Total weight per item	15500	KG
Total weight	31000	KG
VENDOR COST DATA		

Material cost	41257	EURO
Shop labor cost	14537	EURO
Shop overhead cost	13839	EURO
Office overhead cost	6211	EURO
Profit	6607	EURO
Total cost	164900	EURO
Cost per unit weight	5.3194	EUR/KG
Cost per unit area	128.028	EUR/M2
Cost per shell	82450	EUR/SHEL

Summary Costs

Item	Material(EUR)	Manpower(EUR)	Manhours
Equipment&Setting	164900.	4168.	85
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**164900**	**4168**	**85**

Total material and manpower cost=EUR 169100.

Separator

Project : CO2 REMOVAL STUDENT
Scenario : BASECASE

SEPARATOR

Item Code: DVT CYLINDER
Internal Name : DVT CYLINDER SEPARATIR

Design Data

Parameter	Value	Units
Item type	CYLINDER	
Number of identical items	1	
EQUIPMENT DESIGN DATA		
Liquid volume	171.100	M3
Design gauge pressure	103.422	KPAG
Design temperature	340.000	DEG C
Operating temperature	340.000	DEG C
Fluid specific gravity	1.0000	
SHELL DATA		
Shell material	A 515	
Diameter option	OD	
Vessel diameter	3.9620	M
Vessel tangent to tangent height	13.870	M
Head type	HEMI	
MECHANICAL DESIGN DATA		
Wind or seismic design	W+S	
Fluid volume	20.000	PERCENT
Weld efficiency	85.000	PERCENT
Base material thickness	8.0003	MM
Corrosion allowance	3.0002	MM
Head thickness Top	8.0002	MM
Head thickness Bottom	8.0002	MM
THICKNESSES REQUIRED		
Thickness for internal pressure	2.2971	MM
Wind or seismic design thickness	3.7500	MM

VESSEL SKIRT DATA		
Skirt material	CS	
Skirt height	5.9000	M
Skirt thickness	10.000	MM
NOZZLE AND MANHOLE DATA		
Nozzle ASA rating	150	CLASS
Nozzle material	A 515	
Nozzle A Quantity	1	
Nozzle A Diameter	350.000	MM DIAM
Nozzle A Location	S	
Nozzle B Quantity	1	
Nozzle B Diameter	400.000	MM DIAM
Nozzle B Location	S	
Nozzle C Quantity	1	
Nozzle C Diameter	300.000	MM DIAM
Nozzle C Location	S	
Nozzle D Quantity	1	
Nozzle D Diameter	200.000	MM DIAM
Nozzle D Location	S	
Nozzle E Quantity	7	
Nozzle E Diameter	50.000	MM DIAM
Nozzle E Location	S	
Number of manholes	1	
Manhole diameter	450	MM
WEIGHT DATA		
Shell	10800	KG
Heads	3100	KG
Nozzles	310	KG
Manholes and Large nozzles	180	KG
Skirt	5800	KG
Base ring and lugs	1100	KG
Ladder clips	90	KG
Platform clips	220	KG
Fittings and miscellaneous	70	KG
Total weight	21700	KG
VENDOR COST DATA		

Material cost	32174	EURO
Shop labor cost	26984	EURO
Shop overhead cost	28539	EURO
Office overhead cost	14909	EURO
Profit	14393	EURO
Total cost	117000	EURO
Cost per unit weight	5.3917	EUR/KG
Cost per unit liquid volume	683.810	EUR/M3

Summary Costs

Item	Material(EUR)	Manpower(EUR)	Manhours
Equipment&Setting	117000.	8632.	175
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**117000**	**8632**	**175**

Total material and manpower cost=EUR 125600.

Appendix 5 Equipment cost estimation for the base case with split-stream performed by Aspen ICARUS

Flue Gas Fan

Project : HIT
Scenario : Split Stream
Flue Gas Fan

Item Code: EFN CENTRIF
Internal Name : EFN CENTRIF Flue Gas Fan

Design Data

Parameter	Value	Units
Item type	CENTRIF	
Material	CS	
Actual gas flow rate	254800.00	M3/H
Speed	1500.000	RPM
Driver power	200.000	KW
Total weight	2600	KG

Summary Costs

Item	Material(EUR)	Manpower(EUR)	Manhours
Equipment&Setting	61500.	5258.	106
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**61500**	**5258**	**106**

Total material and manpower cost=EUR 66800.

Fan Motor

Project : CO2 REMOVAL STUDENT
Scenario : BASECASE

Fan motor

Item Code: EMOTVARY
SPEED
Internal Name : EMOTVARY SPEEDFan motor

Design Data

Parameter	Value	Units
Item type	VARY SPEED	
Low speed	250.000	RPM
High speed	1800.000	RPM
Driver power	300.000	KW
Total weight	2500	KG

Summary Costs

Item	Material(EUR)	Manpower(EUR)	Manhours
Equipment&Setting	55500.	6668.	134
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**55500**	**6668**	**134**

Total material and manpower cost=EUR 62200.

DCC Cooling Tower

Project : HIT

Scenario : SPLIT STREAM

Cooling tower (DCC)

Item Code: DTW DC HE TW

Internal Name : DTW DC HE TW Cooling tower (DCC)

Design Data

Parameter	Value	Units
Item type	DC HE TW	
Number of identical items	1,00	
EQUIPMENT DESIGN DATA		
Liquid volume	1767.025	M3
Design gauge pressure	100.002	KPAG
Design temperature	340.000	DEG C
Operating temperature	121.111	DEG C
COLUMN DATA		
Shell material	A 515	
Diameter option	OD	
Vessel diameter	15.000	M
Vessel tangent to tangent height	10.000	M
Head type	HEMI	
MECHANICAL DESIGN DATA		
Wind or seismic design	W+S	
Weld efficiency	85.000	PERCENT
Base material thickness	12.000	MM
Corrosion allowance	3.1750	MM
THICKNESSES REQUIRED		
Thickness for internal pressure	2521818,00	MM
Wind or seismic design thickness	1745708,00	MM
PACKING DATA		
Number of distributor plates	4,00	
Number of packed sections	2,00	
Section height	1132313,00	M
Cross sectional area	176.714	M2
SECTION 1		
Packing type Section 1	68PVC	
Packing height Section 1	7.0000	M
Packing volume	1237,00	M3

Packing volume per unit height	176.716	M3/M
VESSEL SKIRT DATA		
Skirt material	CS	
Skirt height	1132497,00	M
Skirt thickness	25.000	MM
NOZZLE AND MANHOLE DATA		
Nozzle ASA rating	150,00	CLASS
Nozzle material	A 515	
Nozzle A Quantity	4,00	
Nozzle A Diameter	1200.000	MM DIAM
Nozzle A Location	S	
Nozzle B Quantity	6,00	
Nozzle B Diameter	50.000	MM DIAM
Nozzle B Location	S	
Number of manholes	2,00	
Manhole diameter	900.000	MM
PROCESS DESIGN DATA		
WEIGHT DATA		
Shell	44400,00	KG
Trays and supports	36400,00	KG
Heads	50000,00	KG
Nozzles	28,00	KG
Manholes and Large nozzles	3400,00	KG
Skirt	88200,00	KG
Base ring and lugs	11100,00	KG
Ladder clips	80,00	KG
Platform clips	260,00	KG
Fittings and miscellaneous	70,00	KG
Total weight less packing	233900,00	KG
VENDOR COST DATA		
Packing cost	364972,00	EURO
Material cost	558676,00	EURO
Field fabrication cost	145217,00	EURO
Fabrication labor	12998,00	HOURS
Shop labor cost	116136,00	EURO
Shop overhead cost	120400,00	EURO
Office overhead cost	159873,00	EURO
Profit	165127,00	EURO
Total cost	1630400,00	EURO
Cost per unit weight	2850871,00	EUR/KG

Cost per unit height or length	232914.28	EUR/M
Cost per unit volume	1318.018	EUR/M3
Cost per unit area	9226.182	EUR/M2

Summary Costs

Item	Material(EUR)	Manpower(EUR)	Manhours
Equipment&Setting	1630400.	64077.	1300,00
Piping	0.	0.	0,00
Civil	0.	0.	0,00
Structural Steel	0.	0.	0,00
Instrumentation	0.	0.	0,00
Electrical	0.	0.	0,00
Insulation	0.	0.	0,00
Paint	0.	0.	0,00
Subtotal	**1630400,00**	**64077,00**	**1300,00**

Total material and manpower cost=EUR 1694500.

Absorber

Project : CO2 REMOVAL STUDENT
Scenario : SPLIT STREAM

Absorber

Item Code: DTW PACKED
Internal Name : DTW PACKED Absorber

Design Data

Parameter	Value	Units
Item type	PACKED	
Number of identical items	1	
EQUIPMENT DESIGN DATA		
Application	ABSORB	
Liquid volume	8255.200	M3
Design gauge pressure	100.002	KPAG
Design temperature	340.000	DEG C
Operating temperature	305.000	DEG C
COLUMN DATA		
Shell material	A 515	
Diameter option	OD	
Vessel diameter	17.330	M
Vessel tangent to tangent height	35.000	M
Head type	HEMI	
MECHANICAL DESIGN DATA		
Wind or seismic design	W+S	
Weld efficiency	85.000	PERCENT
Thickness Average	13.200	MM
Corrosion allowance	3.1750	MM
THICKNESSES REQUIRED		
Thickness for internal pressure	13.581	MM
Wind or seismic design thickness	14.078	MM
PACKING DATA		
Number of distributor plates	6	
Number of packed sections	3	

Section height	8.0000	M
Cross sectional area	235.878	M2
SECTION 1		
Packing type	2.0SPR	
Total packing height	24.000	M
Packing volume	5661	M3
Packing volume per unit height	235.879	M3/M
VESSEL SKIRT DATA		
Skirt material	CS	
Skirt height	9.5000	M
Skirt thickness	45.000	MM
NOZZLE AND MANHOLE DATA		
Nozzle ASA rating	150	CLASS
Nozzle material	A 515	
Nozzle A Quantity	4	
Nozzle A Diameter	1200.000	MM DIAM
Nozzle A Location	S	
Nozzle B Quantity	9	
Nozzle B Diameter	50.000	MM DIAM
Nozzle B Location	S	
Number of manholes	7	
Manhole diameter	900.000	MM
PROCESS DESIGN DATA		
WEIGHT DATA		
Shell	197500	KG
Trays and supports	70300	KG
Heads	103800	KG
Nozzles	40	KG
Manholes and Large nozzles	6100	KG
Skirt	184000	KG
Base ring and lugs	24900	KG
Ladder clips	180	KG
Platform clips	470	KG
Fittings and miscellaneous	70	KG
Total weight less packing	587400	KG
VENDOR COST DATA		

Packing cost	21942959	EURO
Material cost	1144378	EURO
Field fabrication cost	371390	EURO
Fabrication labor	46197	HOURS
Shop labor cost	235173	EURO
Shop overhead cost	243620	EURO
Office overhead cost	339076	EURO
Profit	350106	EURO
Total cost	24626701	EURO
Cost per unit weight	41.925	EUR/KG
Cost per unit height or length	1026112.	EUR/M
Cost per unit volume	4350.165	EUR/M3
Cost per unit area	104404.55	EUR/M2

Summary Costs

Item	**Material(EUR)**	**Manpower(EUR)**	**Manhours**
Equipment&Setting	24626700.	188079.	3817
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**24626700**	**188079**	**3817**

Total material and manpower cost=EUR 24814800.

Water wash

Project : CO2 REMOVAL STUDENT
Scenario : SPLIT STREAM

Water wash

Item Code: DTW PACKED
Internal Name : DTW PACKED Absorber

Design Data

Parameter	Value	Units
Item type	PACKED	
Number of identical items	1	
EQUIPMENT DESIGN DATA		
Application	ABSORB	
Liquid volume	2358.683	M3
Design gauge pressure	100.002	KPAG
Design temperature	340.000	DEG C
Operating temperature	305.000	DEG C
COLUMN DATA		
Shell material	A 515	
Diameter option	OD	
Vessel diameter	17.330	M
Vessel tangent to tangent height	10.000	M
Head type	HEMI	
MECHANICAL DESIGN DATA		
Wind or seismic design	W+S	
Weld efficiency	85.000	PERCENT
Base material thickness	15.000	MM
Corrosion allowance	3.1750	MM
THICKNESSES REQUIRED		
Thickness for internal pressure	9.1044	MM
Wind or seismic design thickness	9.5660	MM
PACKING DATA		
Number of distributor plates	2	
Cross sectional area	235.878	M2

SECTION 1		
Packing type	2.0SPR	
Total packing height	5.0000	M
Packing volume	1179	M3
Packing volume per unit height	235.879	M3/M
VESSEL SKIRT DATA		
Skirt material	CS	
Skirt height	9.5000	M
Skirt thickness	28.000	MM
NOZZLE AND MANHOLE DATA		
Nozzle ASA rating	150	CLASS
Nozzle material	A 515	
Nozzle A Quantity	4	
Nozzle A Diameter	1200.000	MM DIAM
Nozzle A Location	S	
Nozzle B Quantity	6	
Nozzle B Diameter	50.000	MM DIAM
Nozzle B Location	S	
Number of manholes	4	
Manhole diameter	900.000	MM
PROCESS DESIGN DATA		
WEIGHT DATA		
Shell	64100	KG
Trays and supports	23500	KG
Heads	74100	KG
Nozzles	28	KG
Manholes and Large nozzles	4500	KG
Skirt	114100	KG
Base ring and lugs	14300	KG
Ladder clips	80	KG
Platform clips	260	KG
Fittings and miscellaneous	70	KG
Total weight less packing	295000	KG
VENDOR COST DATA		
Packing cost	4571450	EURO
Material cost	592339	EURO

Field fabrication cost	177506	EURO
Fabrication labor	13540	HOURS
Shop labor cost	152147	EURO
Shop overhead cost	157610	EURO
Office overhead cost	183532	EURO
Profit	189417	EURO
Total cost	6024000	EURO
Cost per unit weight	20.420	EUR/KG
Cost per unit height or length	1204800.	EUR/M
Cost per unit volume	5107.703	EUR/M3
Cost per unit area	25538.66	EUR/M2

Summary Costs

Item	**Material(EUR)**	**Manpower(EUR)**	**Manhours**
Equipment&Setting	6024000.	81343.	1651
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**6024000**	**81343**	**1651**

Total material and manpower cost=EUR 6105300.

Rich Pump

Project : CO2 REMOVAL STUDENT
Scenario : SPLIT STREAM

Rich Pump

Item Code: DCP CENTRIF
Internal Name : DCP CENTRIF Rich Pump

Design Data

Parameter	Value	Units
Item type	CENTRIF	
Number of identical items	1	
EQUIPMENT DESIGN DATA		
Casing material	CS	
Design temperature	120.000	DEG C
Design gauge pressure	350.000	KPAG
Fluid head	60.000	M
ASA rating	150	CLASS
Driver power	1000.000	KW
Speed	1500.000	RPM
Driver type	MOTOR	
Motor type	TEFC	
Pump efficiency	82.000	PERCENT
Seal type	SNGL	
PROCESS DESIGN DATA		
Liquid flow rate	1299.000	L/S
Fluid density	1000.004	KG/M3
Fluid viscosity	1.0000	MPA-S
Power per liquid flow rate	0.7698	KW/L/S
Liquid flow rate times head	77939	L/S -M
WEIGHT DATA		
Pump	5200	KG

Motor	2500	KG
Base plate	1100	KG
Fittings and miscellaneous	930	KG
Total weight	9700	KG
VENDOR COST DATA		
Motor cost	88010	EURO
Material cost	11186	EURO
Shop labor cost	72227	EURO
Shop overhead cost	73671	EURO
Office overhead cost	41667	EURO
Profit	45940	EURO
Total cost	332700	EURO
Cost per unit weight	34.299	EUR/KG
Cost per unit liquid flow rate	256.120	EUR/L/S
Cost per unit power	332.700	EUR/KW

Summary Costs

Item	**Material(EUR)**	**Manpower(EUR)**	**Manhours**
Equipment&Setting	332700.	18231.	368
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**332700**	**18231**	**368**

Total material and manpower cost=EUR 350900.

Rich/Lean heat exchanger

Project : CO2 REMOVAL STUDENT
Scenario : SPLIT STREAM

Rich/Lean HX

Item Code: DHE FLOAT HEAD
Internal Name : DHE FLOAT HEADHeae Exchanger - BaseCase

Design Data

Parameter	Value	Units
Item type	FLOAT HEAD	
Number of identical items	1	
GENERAL DESIGN DATA		
TEMA type	BES	
Heat exchanger design option	STAND	
Heat transfer area	57205.00	M2
Area per shell	1144.100	M2
Number of shells	50	
Number of tube passes	2	
Number of shell passes	1	
Vendor grade	HIGH	
SHELL DATA		
Shell material	A285C	
Shell diameter	1400.000	MM
Shell length	10.100	M
Shell design gauge pressure	1000.001	KPAG
Shell design temperature	340.000	DEG C
Shell operating temperature	340.000	DEG C
Shell corrosion allowance	3.0002	MM
Shell wall thickness	12.000	MM
ASA rating Shell side	300	CLASS
Number of baffles	18	
Shell fabrication type	PLATE	

Expansion joint	NO	
TUBE DATA		
Tube material	A 214	
Number of tubes per shell	1593	
Tube outside diameter	25.000	MM
Tube length extended	9.0000	M
Tube design gauge pressure	690.000	KPAG
Tube design temperature	120.000	DEG C
Tube operating temperature	120.000	DEG C
Tube corrosion allowance	0.0600	MM
Tube wall thickness	1.7000	MM
Tube gauge	16	BWG
Tube pitch symbol	TRIANGULAR	
Tube pitch	32.000	MM
Tube seal type	SEALW	
TUBE SHEET DATA		
Tube sheet material	A 515	
Tube sheet thickness	65.000	MM
Tube sheet corrosion allowance	3.0001	MM
Channel material	A 515	
FLOATING HEAD DATA		
Head material Tube side	A 515	
Floating head thickness	7.0002	MM
SHELL SIDE HEAD DATA		
Head material Shell side	A285C	
ASA rating Shell side	300	CLASS
Head thickness Shell side	12.000	MM
HEAD DATA		
Head material Tube side	A 515	
ASA rating Tube side	150	CLASS
Head thickness Tube side	7.0002	MM
WEIGHT DATA		
Shell	4300	KG
Tubes	13900	KG
Heads	930	KG
Internals and baffles	1700	KG

Nozzles	430	KG
Flanges	2000	KG
Base ring and lugs	39	KG
Tube sheet	950	KG
Saddles	230	KG
Fittings and miscellaneous	1600	KG
Total weight per item	26100	KG
Total weight	1305000	KG
VENDOR COST DATA		
Material cost	63364	EURO
Shop labor cost	21940	EURO
Shop overhead cost	21352	EURO
Office overhead cost	9353	EURO
Profit	9910	EURO
Total cost	6296000	EURO
Cost per unit weight	4.8245	EUR/KG
Cost per unit area	110.060	EUR/M2
Cost per shell	125920	EUR/SHEL

Summary Costs

Item	Material(EUR)	Manpower(EUR)	Manhours
Equipment&Setting	6296000.	51657.	1048
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**6296000**	**51657**	**1048**

Total material and manpower cost=EUR 6347700.

Desorber

Project : CO2 REMOVAL STUDENT
Scenario : SPLIT STREAM

Desorber

Item Code: DTW PACKED
Internal Name : DTW PACKED Absorber

Design Data

Parameter	Value	Units
Item type	PACKED	
Number of identical items	1	
EQUIPMENT DESIGN DATA		
Application	ABSORB	
Liquid volume	581.816	M3
Design gauge pressure	200.000	KPAG
Design temperature	200.000	DEG C
Operating temperature	165.000	DEG C
COLUMN DATA		
Shell material	A 515	
Diameter option	OD	
Vessel diameter	4.9690	M
Vessel tangent to tangent height	30.000	M
Head type	HEMI	
MECHANICAL DESIGN DATA		
Wind or seismic design	W+S	
Fluid volume	20.000	PERCENT
Weld efficiency	85.000	PERCENT
Thickness Average	9.7732	MM
Corrosion allowance	3.1750	MM
THICKNESSES REQUIRED		
Thickness for internal pressure	4.5211	MM
Wind or seismic design thickness	8.4988	MM
PACKING DATA		
Number of distributor plates	6	
Number of packed sections	3	

Section height	2.0000	M
Cross sectional area	19.392	M2
SECTION 1		
Packing type	2.0SPR	
Total packing height	6.0000	M
Packing volume	116	M3
Packing volume per unit height	19.392	M3/M
VESSEL SKIRT DATA		
Skirt material	CS	
Skirt height	7.5000	M
Skirt thickness	18.000	MM
NOZZLE AND MANHOLE DATA		
Nozzle ASA rating	150	CLASS
Nozzle material	A 515	
Nozzle A Quantity	1	
Nozzle A Diameter	500.000	MM DIAM
Nozzle A Location	S	
Nozzle B Quantity	1	
Nozzle B Diameter	450.000	MM DIAM
Nozzle B Location	S	
Nozzle C Quantity	1	
Nozzle C Diameter	600.000	MM DIAM
Nozzle C Location	S	
Nozzle D Quantity	1	
Nozzle D Diameter	750.000	MM DIAM
Nozzle D Location	S	
Nozzle E Quantity	8	
Nozzle E Diameter	50.000	MM DIAM
Nozzle E Location	S	
Number of manholes	6	
Manhole diameter	900.000	MM
PROCESS DESIGN DATA		
WEIGHT DATA		
Shell	35900	KG
Trays and supports	7900	KG
Heads	4900	KG

Nozzles	160	KG
Manholes and Large nozzles	3800	KG
Skirt	16700	KG
Base ring and lugs	2300	KG
Ladder clips	150	KG
Platform clips	400	KG
Fittings and miscellaneous	70	KG
Total weight less packing	72300	KG
VENDOR COST DATA		
Packing cost	451000	EURO
Material cost	143651	EURO
Field fabrication cost	75517	EURO
Fabrication labor	3172	HOURS
Shop labor cost	34188	EURO
Shop overhead cost	35387	EURO
Office overhead cost	49087	EURO
Profit	50671	EURO
Total cost	839500	EURO
Cost per unit weight	11.611	EUR/KG
Cost per unit height or length	139916.67	EUR/M
Cost per unit volume	7215.050	EUR/M3
Cost per unit area	43290.55	EUR/M2

Summary Costs

Item	**Material(EUR)**	**Manpower(EUR)**	**Manhours**
Equipment&Setting	839500.	34584.	702
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**839500**	**34584**	**702**

Total material and manpower cost=EUR 874100.

Reboiler

Project : CO2 REMOVAL STUDENT
Scenario : SPLIT STREAM

Reboiler

Item Code: DRB KETTLE
Internal Name : DRB KETTLE Reboiler

Design Data

Parameter	Value	Units
Item type	KETTLE	
Number of identical items	1	
GENERAL DESIGN DATA		
TEMA type	BKT	
Heat exchanger design option	STAND	
Heat transfer area	4345.525	M2
Area per shell	362.127	M2
Number of shells	12	
Number of tube passes	2	
Number of shell passes	1	
Vendor grade	HIGH	
SHELL DATA		
Shell material	A285C	
Shell diameter	1150.000	MM
Shell length	11.300	M
Shell design gauge pressure	1000.001	KPAG
Shell design temperature	340.000	DEG C
Shell operating temperature	340.000	DEG C
Shell corrosion allowance	3.0002	MM
Shell wall thickness	12.000	MM
ASA rating Shell side	300	CLASS
Number of baffles	23	
Shell fabrication type	PLATE	
Expansion joint	NO	
TUBE DATA		

Tube material	A 214	
Number of tubes per shell	505	
Tube outside diameter	25.000	MM
Tube port diameter	787.000	MM
Tube length extended	9.0000	M
Tube design gauge pressure	200.000	KPAG
Tube design temperature	200.000	DEG C
Tube operating temperature	200.000	DEG C
Tube corrosion allowance	0.0600	MM
Tube wall thickness	1.7000	MM
Tube gauge	16	BWG
Tube pitch symbol	TRIANGULAR	
Tube pitch	32.000	MM
Tube seal type	SEALW	
TUBE SHEET DATA		
Tube sheet material	A 515	
Tube sheet thickness	38.000	MM
Tube sheet corrosion allowance	3.0001	MM
Channel material	A 515	
PROCESS DESIGN DATA		
Duty	54.833	MEGAW
Heat of vaporization	350.000	KJ/KG
Vaporization	90.000	PERCENT
Specific gravity tower bottoms	0.5000	
Molecular weight Bottoms	100.000	
HEAD DATA		
Head material Tube side	A 515	
ASA rating Tube side	150	CLASS
Head thickness Tube side	7.0002	MM
WEIGHT DATA		
Shell	3900	KG
Tubes	4400	KG
Heads	290	KG
Internals and baffles	640	KG
Nozzles	300	KG
Flanges	400	KG

Base ring and lugs	31	KG
Tube sheet	190	KG
Saddles	170	KG
Fittings and miscellaneous	930	KG
Total weight per item	11300	KG
Total weight	135600	KG
VENDOR COST DATA		
Material cost	24816	EURO
Shop labor cost	12547	EURO
Shop overhead cost	11564	EURO
Office overhead cost	4727	EURO
Profit	5113	EURO
Total cost	705200	EURO
Cost per unit weight	5.2006	EUR/KG
Cost per unit area	162.282	EUR/M2
Cost per shell	58766	EUR/SHEL

Summary Costs

Item	**Material(EUR)**	**Manpower(EUR)**	**Manhours**
Equipment&Setting	705200.	6199.	126
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**705200**	**6199**	**126**

Total material and manpower cost=EUR 711400.

Lean Pump

Project : CO2 REMOVAL STUDENT
Scenario : SPLIT STREAM

Lean Pump

Item Code: DCP CENTRIF
Internal Name : DCP CENTRIF Lean Pump

Design Data

Parameter	Value	Units
Item type	CENTRIF	
Number of identical items	1	
EQUIPMENT DESIGN DATA		
Casing material	CS	
Design temperature	120.000	DEG C
Design gauge pressure	150.000	KPAG
Fluid head	60.000	M
ASA rating	150	CLASS
Driver power	475.000	KW
Speed	1500.000	RPM
Driver type	MOTOR	
Motor type	TEFC	
Pump efficiency	82.000	PERCENT
Seal type	SNGL	
PROCESS DESIGN DATA		
Liquid flow rate	658.300	L/S
Fluid density	1000.004	KG/M3
Fluid viscosity	1.0000	MPA-S
Power per liquid flow rate	0.7216	KW/L/S
Liquid flow rate times head	39498	L/S -M
WEIGHT DATA		
Pump	1900	KG
Motor	1500	KG

Base plate	410	KG
Fittings and miscellaneous	350	KG
Total weight	4200	KG
VENDOR COST DATA		
Motor cost	54189	EURO
Material cost	4787	EURO
Shop labor cost	26767	EURO
Shop overhead cost	27301	EURO
Office overhead cost	19218	EURO
Profit	21239	EURO
Total cost	153500	EURO
Cost per unit weight	36.548	EUR/KG
Cost per unit liquid flow rate	233.176	EUR/L/S
Cost per unit power	323.158	EUR/KW

Summary Costs

Item	Material(EUR)	Manpower(EUR)	Manhours
Equipment&Setting	153500.	12045.	243
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**153500**	**12045**	**243**

Total material and manpower cost=EUR 165500.

Lean Cooler

Project : CO2 REMOVAL STUDENT
Scenario : SPLIT STREAM

Lean Cooler

Item Code: DHE FLOAT HEAD
Internal Name : DHE FLOAT HEADLean Cooler

Design Data

Parameter	Value	Units
Item type	FLOAT HEAD	
Number of identical items	1	
GENERAL DESIGN DATA		
TEMA type	BES	
Heat exchanger design option	STAND	
Heat transfer area	988.800	M2
Area per shell	329.600	M2
Number of shells	3	
Number of tube passes	2	
Number of shell passes	1	
Vendor grade	HIGH	
SHELL DATA		
Shell material	A285C	
Shell diameter	775.000	MM
Shell length	9.8000	M
Shell design gauge pressure	1000.001	KPAG
Shell design temperature	340.000	DEG C
Shell operating temperature	340.000	DEG C
Shell corrosion allowance	3.0002	MM
Shell wall thickness	12.000	MM
ASA rating Shell side	300	CLASS
Number of baffles	25	
Shell fabrication type	PLATE	
Expansion joint	NO	
TUBE DATA		

Tube material	A 214	
Number of tubes per shell	459	
Tube outside diameter	25.000	MM
Tube length extended	9.0000	M
Tube design gauge pressure	690.000	KPAG
Tube design temperature	340.000	DEG C
Tube operating temperature	340.000	DEG C
Tube corrosion allowance	0.0600	MM
Tube wall thickness	1.7000	MM
Tube gauge	16	BWG
Tube pitch symbol	TRIANGULAR	
Tube pitch	32.000	MM
Tube seal type	SEALW	
TUBE SHEET DATA		
Tube sheet material	A 515	
Tube sheet thickness	40.000	MM
Tube sheet corrosion allowance	3.0001	MM
Channel material	A 515	
FLOATING HEAD DATA		
Head material Tube side	A 515	
Floating head thickness	7.0002	MM
SHELL SIDE HEAD DATA		
Head material Shell side	A285C	
ASA rating Shell side	300	CLASS
Head thickness Shell side	12.000	MM
HEAD DATA		
Head material Tube side	A 515	
ASA rating Tube side	150	CLASS
Head thickness Tube side	7.0002	MM
WEIGHT DATA		
Shell	2300	KG
Tubes	4000	KG
Heads	290	KG
Internals and baffles	740	KG
Nozzles	130	KG
Flanges	710	KG

Base ring and lugs	13	KG
Tube sheet	220	KG
Saddles	90	KG
Fittings and miscellaneous	800	KG
Total weight per item	9300	KG
Total weight	27900	KG
VENDOR COST DATA		
Material cost	23903	EURO
Shop labor cost	11240	EURO
Shop overhead cost	10461	EURO
Office overhead cost	4383	EURO
Profit	4779	EURO
Total cost	164300	EURO
Cost per unit weight	5.8889	EUR/KG
Cost per unit area	166.161	EUR/M2
Cost per shell	54766	EUR/SHEL

Summary Costs

Item	**Material(EUR)**	**Manpower(EUR)**	**Manhours**
Equipment&Setting	164300.	5751.	117
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**164300**	**5751**	**117**

Total material and manpower cost=EUR 170100.

Condenser

Project : CO2 REMOVAL STUDENT
Scenario : SPLIT STREAM

Condenser

Item Code: DHE FIXED T S
Internal Name : DHE FIXED T S Condenser

Design Data

Parameter	Value	Units
Item type	FIXED T S	
Number of identical items	1,00	
GENERAL DESIGN DATA		
TEMA type	BEM	
Heat exchanger design option	STAND	
Heat transfer area	79.550	M2
Number of shells	1,00	
Number of tube passes	1,00	
Number of shell passes	1,00	
Vendor grade	HIGH	
SHELL DATA		
Shell material	A285C	
Shell diameter	525.000	MM
Shell length	6.0000	M
Shell design gauge pressure	1000.001	KPAG
Shell design temperature	340.000	DEG C
Shell operating temperature	340.000	DEG C
Shell corrosion allowance	3.0002	MM
Shell wall thickness	12.700	MM
ASA rating Shell side	300,00	CLASS
Number of baffles	16,00	
Shell fabrication type	PIPE	
Expansion joint	NO	
TUBE DATA		
Tube material	A 214	
Number of tubes per shell	218,00	
Tube outside diameter	25.000	MM
Tube length extended	6.0000	M

Tube design gauge pressure	1000.001	KPAG
Tube design temperature	340.000	DEG C
Tube operating temperature	340.000	DEG C
Tube corrosion allowance	0.0600	MM
Tube wall thickness	1862739,00	MM
Tube gauge	16,00	BWG
Tube pitch symbol	TRIANGULAR	
Tube pitch	32.000	MM
Tube seal type	SEALW	
TUBE SHEET DATA		
Tube sheet material	A 515	
Tube sheet thickness	28.000	MM
Tube sheet corrosion allowance	3.0001	MM
Channel material	A 515	
HEAD DATA		
Head material Tube side	A 515	
ASA rating Tube side	300,00	CLASS
Head thickness Tube side	7.0002	MM
WEIGHT DATA		
Shell	920,00	KG
Tubes	1300,00	KG
Heads	170,00	KG
Internals and baffles	150,00	KG
Nozzles	180,00	KG
Flanges	420,00	KG
Base ring and lugs	7,00	KG
Tube sheet	80,00	KG
Saddles	48,00	KG
Fittings and miscellaneous	360,00	KG
Total weight	3600,00	KG
VENDOR COST DATA		
Material cost	12630,00	EURO
Shop labor cost	6353,00	EURO
Shop overhead cost	5754,00	EURO
Office overhead cost	2644,00	EURO
Profit	3018,00	EURO
Total cost	30400,00	EURO
Cost per unit weight	929392,00	EUR/KG
Cost per unit area	292.223	EUR/M2

Summary Costs

Item	Material(EUR)	Manpower(EUR)	Manhours
Equipment&Setting	30400.	1966.	40,00
Piping	0.	0.	0,00
Civil	0.	0.	0,00
Structural Steel	0.	0.	0,00
Instrumentation	0.	0.	0,00
Electrical	0.	0.	0,00
Insulation	0.	0.	0,00
Paint	0.	0.	0,00
Subtotal	**30400,00**	**1966,00**	**40,00**

CO2 Cooler

Project : CO2 REMOVAL STUDENT
Scenario : SPLIT STREAM

CO2 Cooler

Item Code: DHE FIXED T S
Internal Name : DHE FIXED T S CO2 Cooler

Design Data

Parameter	Value	Units
Item type	FIXED T S	
Number of identical items	1	
GENERAL DESIGN DATA		
TEMA type	BEM	
Heat exchanger design option	STAND	
Heat transfer area	679.700	M2
Number of shells	1	
Number of tube passes	1	
Number of shell passes	1	
Vendor grade	HIGH	
SHELL DATA		
Shell material	A285C	
Shell diameter	1050.000	MM
Shell length	9.0000	M
Shell design gauge pressure	1000.001	KPAG
Shell design temperature	340.000	DEG C
Shell operating temperature	340.000	DEG C
Shell corrosion allowance	3.0002	MM
Shell wall thickness	12.000	MM
ASA rating Shell side	300	CLASS
Number of baffles	21	
Shell fabrication type	PLATE	
Expansion joint	NO	
TUBE DATA		
Tube material	A 214	

Number of tubes per shell	947	
Tube outside diameter	25.000	MM
Tube length extended	9.0000	M
Tube design gauge pressure	1000.001	KPAG
Tube design temperature	340.000	DEG C
Tube operating temperature	340.000	DEG C
Tube corrosion allowance	0.0600	MM
Tube wall thickness	1.7000	MM
Tube gauge	16	BWG
Tube pitch symbol	TRIANGULAR	
Tube pitch	32.000	MM
Tube seal type	SEALW	
TUBE SHEET DATA		
Tube sheet material	A 515	
Tube sheet thickness	55.000	MM
Tube sheet corrosion allowance	3.0001	MM
Channel material	A 515	
HEAD DATA		
Head material Tube side	A 515	
ASA rating Tube side	300	CLASS
Head thickness Tube side	7.0002	MM
WEIGHT DATA		
Shell	2900	KG
Tubes	8200	KG
Heads	490	KG
Internals and baffles	970	KG
Nozzles	560	KG
Flanges	1500	KG
Base ring and lugs	19	KG
Tube sheet	460	KG
Saddles	150	KG
Fittings and miscellaneous	1200	KG
Total weight	16500	KG
VENDOR COST DATA		
Material cost	43199	EURO
Shop labor cost	15949	EURO

Shop overhead cost	15262	EURO
Office overhead cost	6599	EURO
Profit	6991	EURO
Total cost	88000	EURO
Cost per unit weight	5.3333	EUR/KG
Cost per unit area	129.469	EUR/M2

Summary Costs

Item	**Material(EUR)**	**Manpower(EUR)**	**Manhours**
Equipment&Setting	88000.	2315.	47
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Subtotal	**88000**	**2315**	**47**

Total material and manpower cost=EUR 90300.

Separator

Project : CO2 REMOVAL STUDENT
Scenario : SPLIT STREAM

SEPARATOR

Item Code: DVT CYLINDER
Internal Name : DVT CYLINDER SEPARATIR

Design Data

Parameter	Value	Units
Item type	CYLINDER	
Number of identical items	1	
EQUIPMENT DESIGN DATA		
Liquid volume	171.100	M3
Design gauge pressure	103.422	KPAG
Design temperature	340.000	DEG C
Operating temperature	340.000	DEG C
Fluid specific gravity	1.0000	
SHELL DATA		
Shell material	A 515	
Diameter option	OD	
Vessel diameter	3.9620	M
Vessel tangent to tangent height	13.870	M
Head type	HEMI	
MECHANICAL DESIGN DATA		
Wind or seismic design	W+S	
Fluid volume	20.000	PERCENT
Weld efficiency	85.000	PERCENT
Base material thickness	8.0003	MM
Corrosion allowance	3.0002	MM
Head thickness Top	8.0002	MM
Head thickness Bottom	8.0002	MM
THICKNESSES REQUIRED		
Thickness for internal pressure	2.2971	MM
Wind or seismic design thickness	3.7500	MM

VESSEL SKIRT DATA		
Skirt material	CS	
Skirt height	5.9000	M
Skirt thickness	10.000	MM
NOZZLE AND MANHOLE DATA		
Nozzle ASA rating	150	CLASS
Nozzle material	A 515	
Nozzle A Quantity	1	
Nozzle A Diameter	350.000	MM DIAM
Nozzle A Location	S	
Nozzle B Quantity	1	
Nozzle B Diameter	400.000	MM DIAM
Nozzle B Location	S	
Nozzle C Quantity	1	
Nozzle C Diameter	300.000	MM DIAM
Nozzle C Location	S	
Nozzle D Quantity	1	
Nozzle D Diameter	200.000	MM DIAM
Nozzle D Location	S	
Nozzle E Quantity	7	
Nozzle E Diameter	50.000	MM DIAM
Nozzle E Location	S	
Number of manholes	1	
Manhole diameter	450	MM
WEIGHT DATA		
Shell	10800	KG
Heads	3100	KG
Nozzles	310	KG
Manholes and Large nozzles	180	KG
Skirt	5800	KG
Base ring and lugs	1100	KG
Ladder clips	90	KG
Platform clips	220	KG
Fittings and miscellaneous	70	KG
Total weight	21700	KG
VENDOR COST DATA		

Material cost	32174	EURO
Shop labor cost	26984	EURO
Shop overhead cost	28539	EURO
Office overhead cost	14909	EURO
Profit	14393	EURO
Total cost	117000	EURO
Cost per unit weight	5.3917	EUR/KG
Cost per unit liquid volume	683.810	EUR/M3

Summary Costs

Item	Material(EUR)	Manpower(EUR)	Manhours
Equipment&Setting	117000.	8632.	175
Piping	0.	0.	0
Civil	0.	0.	0
Structural Steel	0.	0.	0
Instrumentation	0.	0.	0
Electrical	0.	0.	0
Insulation	0.	0.	0
Paint	0.	0.	0
Subtotal	**117000**	**8632**	**175**

Total material and manpower cost=EUR 125600.