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MODELLING OF REGENERATION IN TEG NATURAL GAS DEHYDRATION UNITS

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ABSTRACT

This project compares different enhanced TEG regeneration methods through their modeling in a commercial process simulator. Gas dehydration is important for achieving the required sales gas specifications and ensuring safe flow in the export pipelines. Usually the gas dehydration process is performed through the absorption of water vapor from the gas in the triethylene glycol (TEG), which is regenerated afterwards. The traditional regeneration method limits the achievable TEG purity, therefore also restraining the achievable dry gas quality, hence the need for enhanced TEG regeneration methods. The traditional choice was the use of stripping gas, however due to BTEX emission concerns, other enhanced regeneration methods were implemented (Vacuum, Stahl, Drizo, Coldfinger), with mixed experience by the industry.

The different TEG regeneration methods were implemented in Aspen Hysys, a widely used process simulator in the oil and gas industry, with the Glycol Package, based on the Twu-Sim-Tassone (TST) Cubic Equation of State. Based on case studies of the traditional regeneration method with or without stripping gas, it was discovered that the most relevant process parameters are the solvent circulation and the amount of stripping gas. Subsequently, case studies were conducted on each TEG regeneration model with the variation of these two parameters only. The remaining parameters were kept constant. Subsequently, for each case, an optimal set of parameters was chosen, where the required specification was met and the amount of spilled gas minimized. The methods were compared at these optimal set of parameters, based on the amount of spilled gas and the BTEX emissions, indicating the Drizo as the method with the best performance. However, regarding TEG purity, the Stahl method performed the best, achieving the highest value among all methods.

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1. INTRODUCTION

During offshore oil production, the reservoir fluid coming from the well is typically a mixture of three distinct phases: an aqueous phase (produced water), a liquid hydrocarbon phase (oil) and a gas phase with some suspended solids in the mixture. Normally, the three phases must be separated and then further processed in the topside facilities, before being discharged or exported to onshore (*Figure 1*).

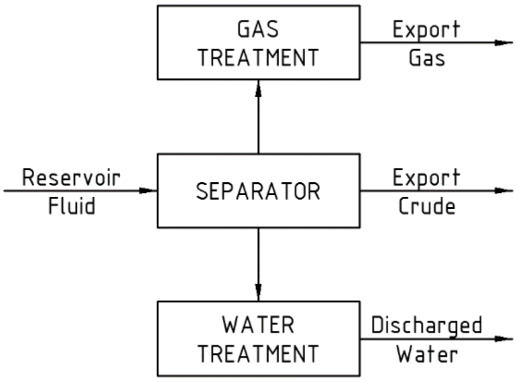

Figure 1 – Topside processes

The separation of the three phases is carried out in 3-phase separators. These vessels slow down the reservoir fluid by reducing its momentum. Then, the phases are separated by means of gravitational force. There are normally three separators on offshore facilities, the first being high pressure, the last being low pressure and the pressure of the middle separator is in between. This arrangement serves to stabilize the crude oil by removing volatile components.

The produced water is treated in water treatment facilities. The objective is to remove the dispersed hydrocarbons from the water to meet environmental regulations for the produced water discharge quality. The water purification facilities mostly consist of hydrocyclones and skimmers.

The produced gas must be recompressed and exported to onshore facilities. The high-pressure (9 - 14 MPa) pipelines [1], used for exporting, lay on the seabed where the fluid can cool down to as low as -1°C [2]. At this low temperature and high pressure, if there is water in the gas phase it may form solid crystalline hydrates with the light hydrocarbons. The hydrates can cause severe damage to the pipelines. The gas phase in the reservoir fluid is saturated with water because it was previously in contact with the brine. Therefore, one of the purpose of the gas treatment is the removal of water from the gas.

On offshore facilities water is removed from the gas by absorbing it from the gas into a polar solvent, usually triethylene-glycol (TEG). The solvent is subsequently regenerated and recycled to minimize the make-up needed. The effectiveness of the gas removal depends on the water content of the regenerated solvent, which is determined by the effectiveness of the regeneration. Below a certain limit of allowed water content, traditional dehydration processes cannot perform and modification to the solvent regeneration process must be considered.

This project focuses on the gas dehydration in offshore facilities, especially on the different methods to regenerate the solvent. In the next section, the traditional dehydration process that is most frequently implemented on offshore facilities is presented and its limitations are underlined. Subsequently, dry gas specifications and the implementation of different enhanced regeneration methods are discussed. Afterwards the problem statement is presented, followed by a presentation of the possible extensions to the traditional solvent regeneration method for enhanced TEG regeneration.

2. GAS DEHYDRATION

The removal of water vapor from the wet-gas can be performed by three distinct processes:

- Absorption of water from natural gas by liquid solvent
- Adsorption of water from natural gas by solid desiccant
- Refrigeration of natural gas along with the addition of hydrate inhibitors

In offshore installations, the first option is the most commonly used [1], therefore the subsequent sections will focus on this type of processes.

2.1. Absorption

During absorption, a gas mixture is contacted by a liquid solvent to selectively remove one or more components (solutes) from the mixture. Absorption is often coupled with a solvent regeneration method, which can either be stripping, the opposite of absorption, or distillation (*Figure 2*). Both absorption and regeneration are carried out in multiple contact trayed or packed columns, where the two phases flow countercurrently. The number of stages in an absorption column is inversely proportional to the amount of solvent required for the process [3]. Typically, new offshore facilities use columns with structured packing, because they allow high gas flow rates. The height of the packing is equivalent to about three to four equivalent theoretical trays [4].

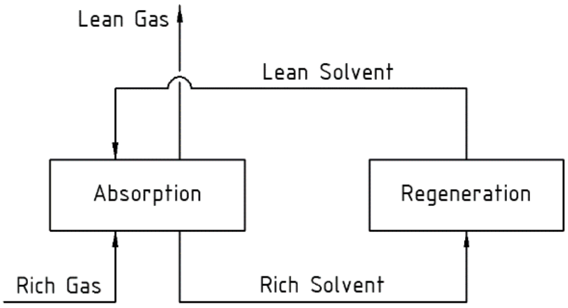

Figure 2 – Schematic of the absorption process coupled with regeneration

Absorption is favored at low temperature and high pressure, however both refrigeration and compression of gases are expensive processes, thus the absorber is normally operated at feed gas temperature and pressure. This is also the case for natural gas dehydration [3].

The choice of solvent depends on the application. Generally, the solvent should meet the following criteria:

- High solubility for the solute to reduce the amount of solvent used
- Low volatility to reduce losses
- Stability to reduce need for make-up
- Non-corrosive
- Low-viscosity for high rate of mass-transfer
- Safe (non-toxic, non-flammable)
- Non-foaming
- Available (inexpensive, or it can be regenerated)

The solvents that meet these criteria are the glycols in the case of gas dehydration. The most popular glycol used for offshore gas processing is the triethylene-glycol (TEG) (*Figure 3*) and its properties are presented in *Table 1*. TEG, a polar solvent, has a high affinity for water, it is non-foaming, safe to use and compared to the other glycols it has low volatility. Because of the TEG high viscosity, other glycols might be considered when the ambient temperature is low.

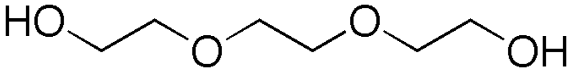

Figure 3 – Chemical structure of triethylene-glycol (TEG)

TEG Properties	
Molecular formula	$C_6H_{14}O_4$
Molecular weight	150.174 g/mol
Appearance	Colorless, odorless liquid
Density	1.1255 g/cm^3
Melting point	-7°C
Boiling point	285°C

Table 1 – TEG Properties [5]

The main advantage of TEG over the other glycols is its relative stability. TEG decomposition only becomes significant at temperatures over 204°C. Nevertheless, the fact that its decomposition starts well below its boiling point (Table 1), still has significant implications on the achievable dry gas quality which will be explained in the following sections.

2.2. Regeneration

As stated in the previous section, the absorption process is often combined with a solvent regeneration process. This is also the case for offshore installations, where it is particularly important to limit the amount of production chemicals that needs to be shipped to and loaded on the platforms.

The regeneration process is traditionally performed either by stripping, distillation or a combination of both (*Figure 4*). Stripping is the inverse of absorption, where lean gas strips the rich solvent from the solute. The process requires high temperature and low pressure to be effective. In the case of distillation, instead of adding a new vapor phase to the system, the new vapor phase is formed in the system by the addition of energy. The latter option is preferred on offshore installations, possibly with the combination of stripping gas.

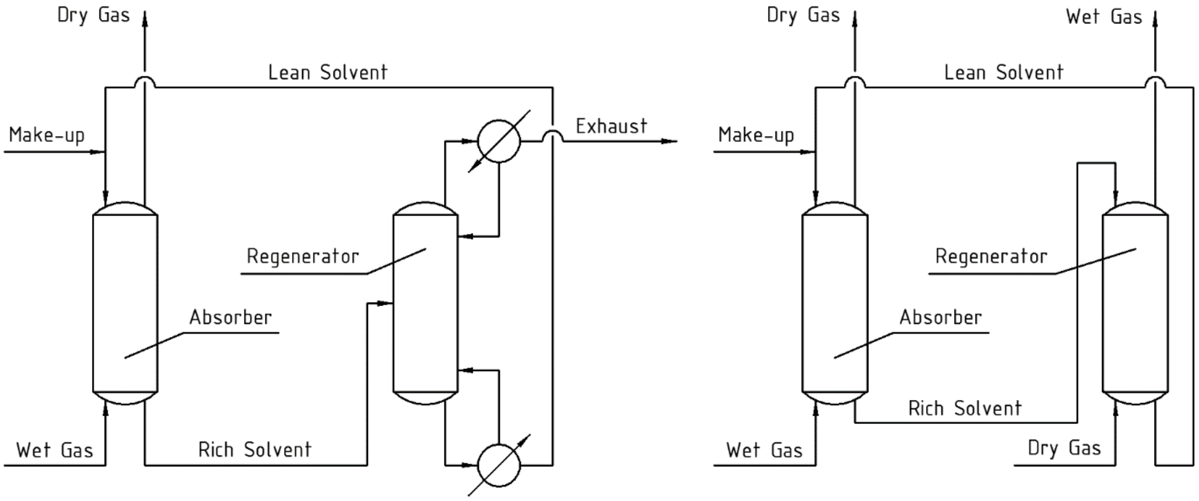

Figure 4 – Regeneration with distillation (to the left) and stripping (to the right)

The distillation is performed in a packed or trayed column *(Figure 5*). The feed is usually preheated to be in vapor-liquid equilibrium, and the feed-stage is somewhere in the middle of the column. The section above the feed stage is called the rectifying section and the section below the feed stage is called the stripping section. At the bottom of the column is the reboiler, where energy is introduced to the system by boiling up the liquid exiting the column at the bottom and then reintroducing the formed vapor phase. On the top of the column there is a condenser, where partial or total condensation of the vapor phase occurs before being refluxed back to the column. The reflux and the boil-up are dependent on each other, with more reflux, more boil-up is also needed, increasing the energy demand too. There is a trade-off between the number of stages in the column and the amount of reflux required to achieve a specified degree of separation.

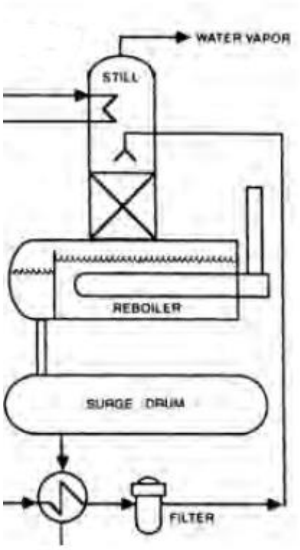

Figure 5 – TEG regeneration with distillation [6]

On offshore installations the usual set-up contains trays or packing equivalent to about three equilibrium stages [7]. At the top of the column there is a partial condenser integrated into the cap of the column. The cooling liquid is generally the rich TEG exiting the absorber. The feed stage is normally located on the first or second stage. The column is normally placed vertically on the top of the reboiler so the liquid coming from the column directly enters the reboiler and vapor from the reboiler directly enters the column.

As stated earlier, TEG starts to decompose at temperatures above 204°C. Consequently, the temperature in the reboiler cannot surpass this value, limiting effectively the degree of TEG purity achievable in the reboiler without the use of stripping gas.

3. SALES GAS SPECIFICATIONS

The objective of the natural gas dehydration is to achieve a water content at or below a specified value. There are no standard specifications for natural gas, thus this value depends on the individual contract between the purchaser and the producer. Typically, maximum allowed water content is between the range of 4-7 lb/MMscf (0.06-0.11 g/Sm^3) [6].

On offshore installations, however, the maximum allowed water content often depends on flow assurance concerns to prohibit water condensation and hydrate formation in the export pipeline. Their risk of occurrence in these pipes is eminent due to the high pressure inside (up to 9-14 MPa) [1] and the low seabed temperature (around -1°C) [2]. Therefore, the maximum allowed water content often needs to be further reduced, sometimes to as low as 2.5 lb/MMscf (0.0375 g/Sm^3)[1]. The exact extent of further water removal is normally specified as a maximum allowable water dew-point. Water-dewpoint is the temperature at a given pressure when the first aqueous phase appear.

As mentioned in the previous section, the reduction of the water content in the wet gas is limited by the water content of the lean solvent, which in turn is limited by the regeneration and the reboiler temperature. If the maximum allowed water content is less than 4 lb/MMscf (0.06 g/Sm^3), then the use of stripping gas is required in the regenerator. However, due to the emission of hazardous air pollutants (HAP), of which the most important are the BTEX compounds (benzene, toluene, ethylbenzene, xylene) [8], the industry has been investigating other methods.

4. BTEX EMISSIONS

During the gas dehydration process, aromatic components are absorbed by the glycol solvent and subsequently emitted to the atmosphere at the regeneration process of the glycol. TEG can absorb significant amounts of aromatic compounds in the gas, specifically Benzene, Toluene, Ethylbenzene and Xylene (BTEX).

The BTEX emissions are considered problematic due to environmental concerns and the fact that they present a safety hazard. Benzene exposure can lead to cancer, toluene affects the reproduction system, ethylbenzene can affect the kidney and xylene exposure can affect the central nervous system.

The Environmental Protection Agency, EPA, limits the emissions for BTEX compounds at 25 tons per year. There is also a limit of 10 tons per year per individual aromatic compound emitted. In order to reduce the emission of BTEX compounds to the atmosphere, they must be incinerated at high temperatures.

As it was mentioned in the section 3, the use of stripping gas increases BTEX emissions, therefore the industry shows a predilection to employ other patented or proprietary methods for TEG regeneration such as the DRIZO and the COLDFINGER [1].

5. ENHANCED TEG REGENERATION METHODS

Enhanced solvent regeneration methods are usually modifications of the original process to achieve lower water content in the solvent (*Figure 6*). Offshore applications favor methods where less additional equipment and less increase in operational costs are required.

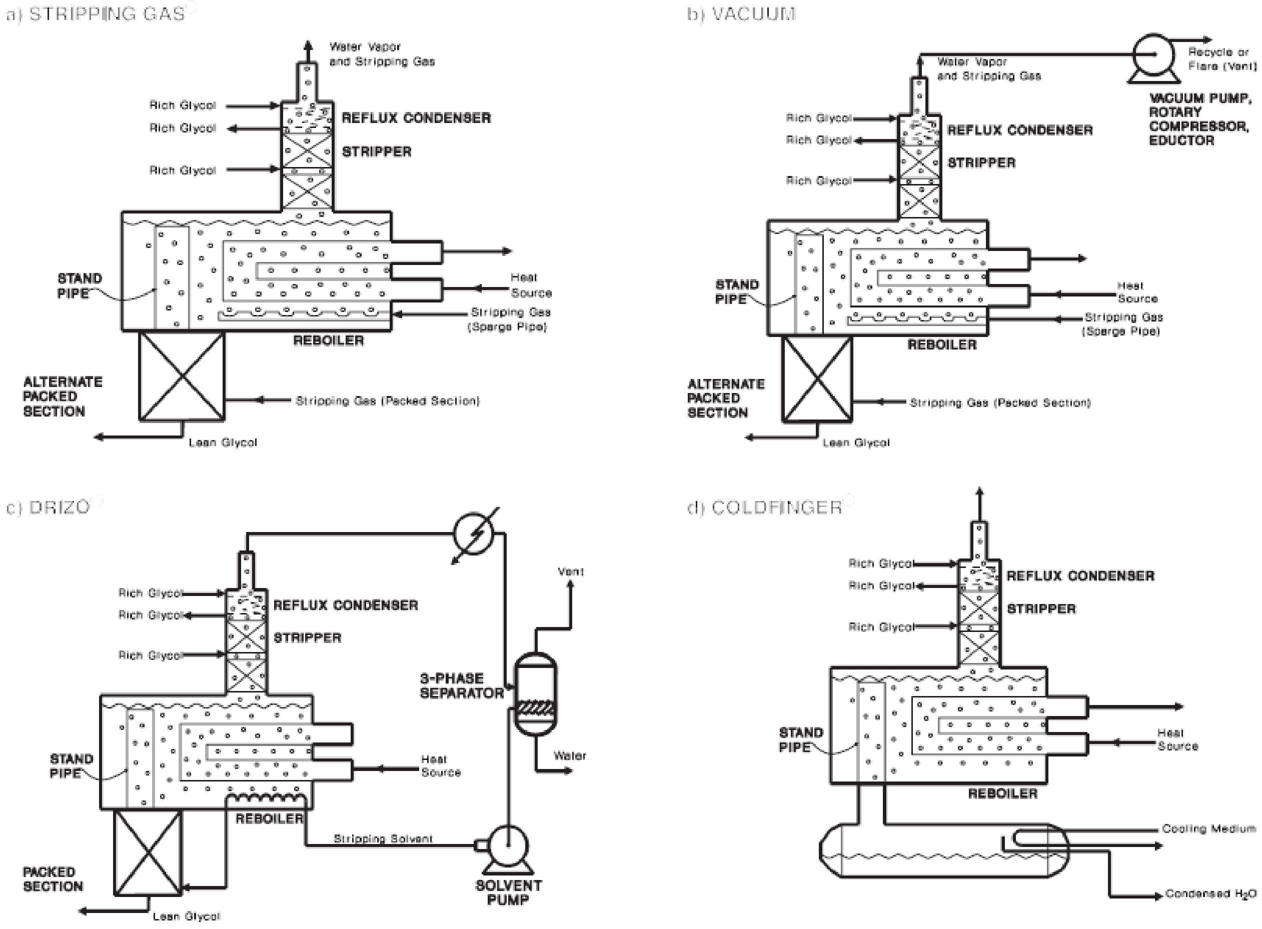

Figure 6 – Enhanced TEG regeneration methods [6]

The addition of stripping gas has already been discussed as the most common method for enhancing the solvent regeneration. The addition of inert gas lowers the partial pressure of water, thereby creating additional drive force for dehydration of the liquid phase. There are two different methods for the stripping gas implementation. The first and simpler method is through the direct injection of the stripping gas to the reboiler through a sparge pipe. The second, alternative, method is to use a separate packed column, usually installed at the bottom of the reboiler and operated as a separate stripping column where the lean solvent is further stripped from water by the dry gas. This second column is called the Stahl-column and it can provide additional equilibrium stages to the purification [9].

A very effective method is to generate vacuum in the regeneration column, thereby lowering the partial pressure of water in the vapor phase and allowing for more water to evaporate from the solvent in the reboiler. The cost associated with this method is the installation of the vacuum pump and its operating cost.

Of the proprietary methods, the two most important are the Drizo and the Coldfinger. Drizo uses its own internally generated stripping medium, a mixture of paraffinic hydrocarbons of the C5+ boiling range and BTEX compounds. These compounds exist as vapor at the reboiler temperature *(Table 1)* and act as an inert stripping gas, however they can be generated by further condensation of the overhead vapor exiting the regenerator. The condensed hydrocarbons are separated from the water and the non-condensable water and then recycled back to the reboiler. As the liquid hydrocarbons build up, they are drawn off as a Natural Gas Liquid product (NGL). This method requires an additional heat exchanger for cooling down the overhead vapor and a three-phase separator to separate the overhead product [6].

Compound	Boiling Point at 101.325 kPa
Benzene	80.1°C
Toluene	110.8°C
Ethylbenzene	136.2°C
Xylene	138.5-144°C

Table 2 – Boling point of BTEX compounds [10]

The Coldfinger consists of a condensing bundle ("cold finger") installed into the vapor space of the surge tank with a tray to recycle the condensed liquids back to the reboiler. In the most common applications, dilute glycol (rich TEG) from the glycol contactor is used as the coolant in the Coldfinger tube bundle. The mechanism of the Coldfinger method is not well understood [11]. According to the Gas Processor's Suppliers Engineering Databook [6], the bundle continuously condenses equilibrium vapor and discharges the condensate through a tray placed under the tube bundle, while the surge tank is half full of hot-lean TEG. The liquid phase then seeks to restore the equilibrium vapor and in doing so, exhausts its trace water before it reaches the Coldfinger surge-tank outlet nozzle. With a limited residence time, the water in the liquid phase is exhausted and the residual liquid (lean TEG) concentration increases. It is claimed that the Coldfinger process does not use stripping gas [6].

Industry experience has been mixed with the Drizo and Coldfinger methods [1]. Further understanding about their mechanisms and effectiveness is required.

6. PROBLEM STATEMENT

In the previous sections an overview of the offshore natural gas dehydration processes and its current challenges was presented. Due to the flow assurance concerns in the export pipelines, the allowed water content is lower than for sales gas. The possible extent of water removal from the wet gas depends on the amount of water contained in the lean TEG, which is related to the effectiveness of the solvent regeneration. In the traditional regeneration process, this is limited by the maximum allowed reboiler temperature. Therefore, to achieve purer regenerated solvent, enhanced TEG regeneration methods must be considered. The traditional choice was the use of stripping gas, but it has become less common due to emission concerns. Thus, other patented and proprietary methods were considered and deployed, such as the Drizo and the Coldfinger. However, the experience of the oil industry regarding these methods has been varied since their effectiveness has not been entirely proven or understood.

To further investigate the enhanced TEG regeneration methods, the resulting problem statement is the following question:

Which enhanced TEG regeneration is the most efficient in terms of utility consumption, hydrocarbon losses, and BTEX emission?

The question is answered using the commercial process simulator Aspen Hysys. As a first step, the different enhanced TEG regeneration methods are modelled based on the information presented in the introduction. Since the aim is to isolate the effect of enhanced TEG regeneration methods, certain process specifications were fixed in all cases, such as the number of stages in the regenerator, absorber, the feed composition and its process conditions. Using these models other process conditions were varied in each case to find the range of conditions at which the gas dehydration meets the specified water content. Subsequently, from the range of the values, an optimal one is chosen to maximize the gas production (and minimize utility consumption). Based on these results a comparison was made between the different methods regarding the amount of spilled gas and the amount of emitted BTEX compounds in each case. The results were further analyzed by collecting additional data for example the amount of TEG circulated, gas burned in the reboiler, hydrocarbon losses and achieved lean TEG purity, to highlight the mechanism in potential efficiency gains.

Part of the project included the design and set-up of an equilibrium model for the Coldfinger enhanced regeneration since it is not included in commercial process simulators. The Coldfinger modelling and the comparison with other enhanced TEG regeneration methods, comprise the novelty aspect of this project.

In the subsequent sections, the models of each method set-up in Hysys and their specifications are introduced, followed by an explanation of the case studies and calculations performed. Finally, the results are presented and analyzed.

7. MODELLING AND PROCESS SIMULATION

7.1. Modelling of the Gas Dehydration and TEG Regeneration Process

A typical feed gas composition, temperature and pressure were selected to model the wet gas inlet in Hysys as shown in *Table 3* and *Table 4*.

Parameter	Value
Temperature	30°C
Pressure	4000 kPa
Mass Flow	236661 kg/h

Table 3 – Wet gas inlet parameters

Component	Mass Fraction
Methane	0.6996
H_2O	0.0011
CO_2	0.0045
Nitrogen	0.0057
n-Hexane	0.0087
n-Pentane	0.0037
n-Heptane	0.0056
i-Pentane	0.0110
n-Butane	0.0295
i-Butane	0.0589
Propane	0.0671
Ethane	0.1006
Benzene	0.0020
E-Benzene	0.0011
Toluene	0.0005
o-Xylene	0.0005

Table 4 – Wet gas inlet composition

The efficiency of a gas dehydration method is measured on the water content presented in the dry gas product and according to the Gas Processors Suppliers Association the water content specification for natural gas limit range from 0.06 to 0.11g/Sm^3[6].

Typical sales gas specifications also limit the water dew point to a maximum of -10°C for flow assurance in export pipelines in the seabed.

The simulation created in Hysys of a standard gas dehydration process by absorption is presented in *Figure 7* and it combines the gas dehydration and the glycol regeneration process. The thermodynamic model selected to represent the phase behavior was the Glycol Package since it provides a more accurate modelling of a TEG dehydration system.

The gas dehydration process consists of the absorption process where the water is removed by using a liquid which is a good solvent of water. Glycol is the most used absorbent, and in this case the triethylen glycol, TEG, was selected since it can be easily regenerated to a higher degree of purity (98-99%) and it presents lower capital and operating costs [4]. Therefore, it offers the best cost benefit relation and it is the most commonly used glycol in natural gas dehydration.

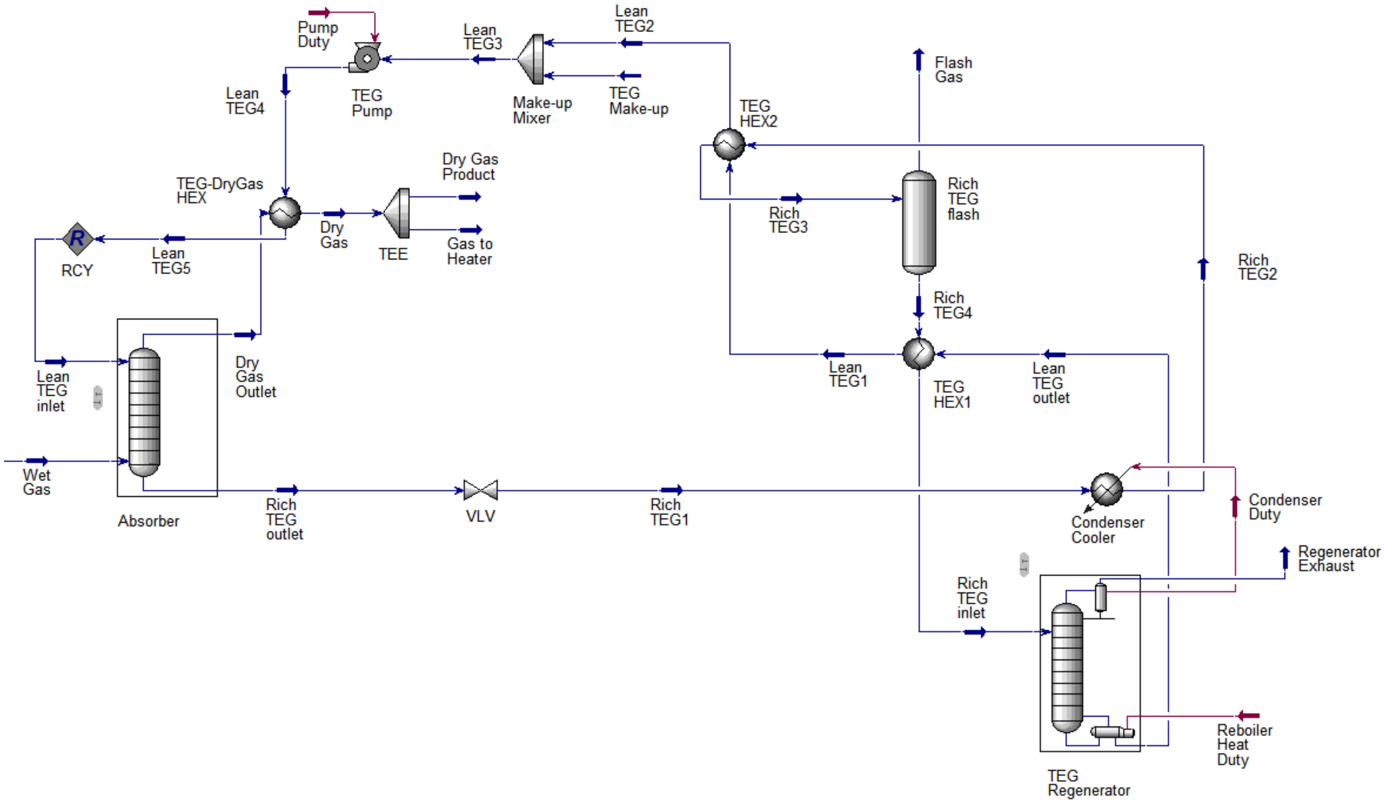

Figure 7 – Gas dehydration and TEG regeneration process

7.2. Process Description - General

The gas dehydration and TEG regeneration process presented in *Figure 7* can be explained by the equipment used.

- Absorber:

The Wet Gas inlet enters the Absorber column at the bottom and the Lean TEG inlet enters at the top, flowing downwards the absorber as it gets in contact with the wet gas that flows upwards. The absorber operates at a pressure of 4000 kPa and the Lean TEG inlet enters the absorber at a temperature of 35°C and pressure of 4000 kPa. The number of stages in the absorption column was fixed as four, since further increasing the number of stages would not produce a significant decrease in dry gas water content. [7]. Detailed analysis and reasoning for the selected number of equilibrium stages follows in section 8.

The Rich TEG outlet leaving the absorber is sent to the regenerator process, but first it undergoes a pressure valve (VLV) for reducing the pressure to 700 kPa.

- Flash Separator (Rich TEG flash)

After the pressure reduction valve, there is a Rich TEG separator for separating the hydrocarbon rich gas from the rich TEG (Rich TEG4 stream).

There is a small TEG loss in the separator that will be taken into consideration for the make-up stream later in the TEG regeneration process.

- Heat exchangers

The heat exchangers used were designed for lowering the energy consumption of the process, therefore using the Lean TEG stream to heat the Rich TEG stream while using the Rich TEG stream to cool down the Lean TEG stream.

The Rich TEG stream needs to be heated before (TEG HEX2) and after (TEG HEX1) the flash separation through glycol-glycol heat exchangers.

The TEG HEX1 is necessary for heating the Rich TEG stream before it enters the distillation column for the regeneration process of the TEG.

The gas-glycol heat exchanger (TEG-DryGas HEX) uses the Dry Gas stream for cooling the Lean TEG stream that enters the Absorber.

The glycol-glycol heat exchangers have a specified pressure drop on the tube side of 150 kPa, however for the gas-glycol heat exchanger no pressure drop was taken into account.

- TEG Regenerator

The TEG Regenerator is a still column on the top of a reboiler for regenerating the TEG and has a low number of stages (three), since the increase of the number of stages does not reflect in an increase of TEG purity [7]. Analysis and reasoning for the selected number of stages is further explained on the case studies section. The column separates the water from the TEG (*Figure 8*) and it operates at a low pressure of 110 kPa and at high temperature. The Rich TEG Inlet entering the column has a temperate of 160°C [4].

The column is equipped with a condenser that through a reflux stream improves the TEG regeneration process. The reflux ratio set was 0.1 for minimizing TEG losses [7].

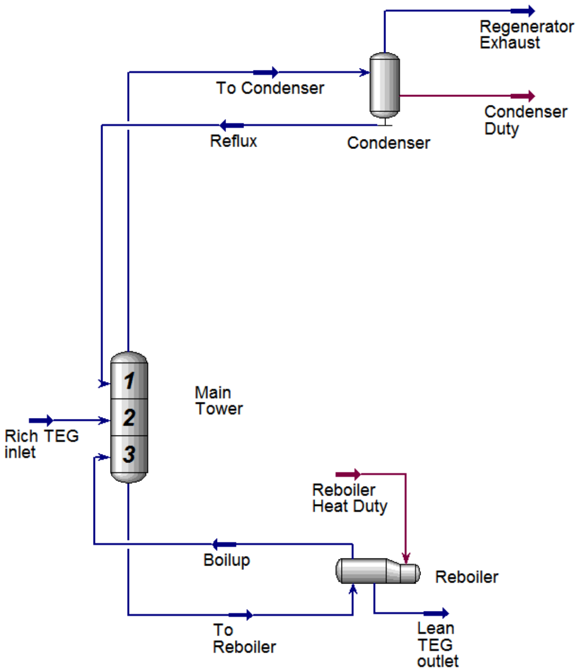

Figure 8 – TEG regenerator column design

As mentioned before, the reboiler operating temperature was set to 204°C to avoid the TEG thermal degradation and the pressure was set as 110 kPa.

During the TEG regenerator process there is a TEG loss at the Regenerator Exhaust stream that is included in the make-up stream for the TEG flow.

- TEG Pump

Since the TEG Regenerator operates at low pressure (110 kPa) and the Absorber operates at high pressure (4000 kPa), it was needed to add a pump for increasing the pressure of the Lean TEG stream before entering the Absorber, allowing the Rich TEG stream to flow. The pump provides the required increase in pressure.

- Condenser cooler

The Condenser Cooler is used for preheating the Rich TEG stream and the operational pressure drop of the Rich TEG stream is 100 kPa.

- Make-up Mixer

Through the gas dehydration and TEG regeneration process there are TEG losses that need to be accounted for. A Make-up Mixer was inserted for mixing the Lean TEG2 with the TEG make-up stream. The TEG loss was calculated as the sum of the losses encountered at the Dry Gas stream, the Flash Gas stream exiting The Rich TEG Flash and the Regenerator Exhaust stream leaving the TEG Regenerator. The Dry Gas stream presents the biggest TEG loss of the entire process.

- Recycler (RCY)

A recycler was introduced for recycling the Lean TEG stream before entering the Absorber.

- TEE, splitter

The Dry Gas stream is split into two streams, the Dry Gas Product and the Gas to Heater stream. The split amount is calculated based on the lower heating value of the dry gas and the required heat duty in the reboiler. In the cases where a stripping gas stream is added to the TEG Regenerator column, the tee splits the Dry Gas into an additional stream, becoming a three-way splitter.

7.2.1. Vacuum Regeneration

In the model for regenerating the rich TEG in a vacuum distillation column, the pressure of the reboiler and the condenser were set at 500mmHg (66.66 kPa) [6]. There is also an additional pump and compressor installed (*Figure 9*), to increase the pressures of the exhaust and lean TEG streams exiting the TEG regenerator back to 110 kPa, as there is no vacuum-pump option available in Hysys.

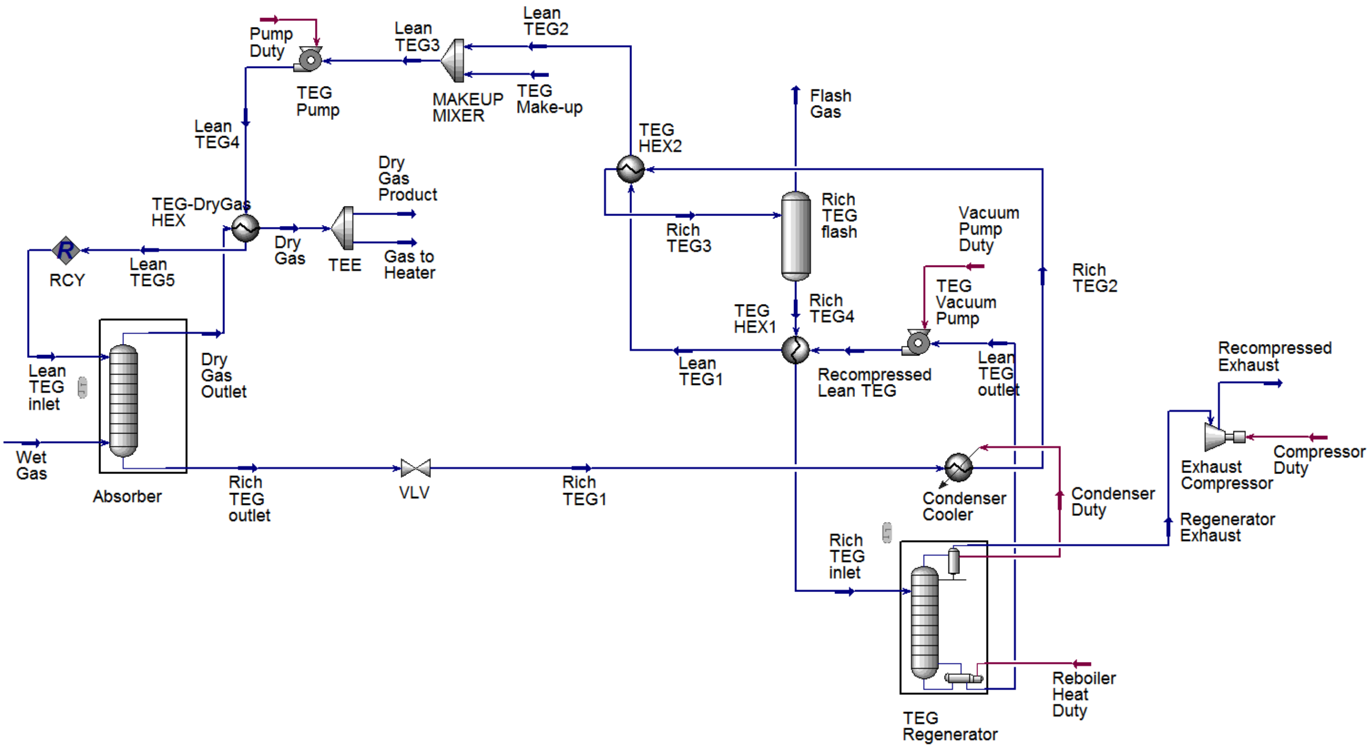

Figure 9 - Gas dehydration and TEG regeneration process with Vacuum

7.2.2. Gas Stripping

The gas used for stripping is split from the produced Dry Gas stream (*Figure 10*). The pressure of the Stripping Gas stream is reduced to 110 kPa (VLV-100), then recycled (RCY-1) into the Stripping Gas Inlet stream that enters the Reboiler in the TEG Regenerator Column (*Figure 11*).

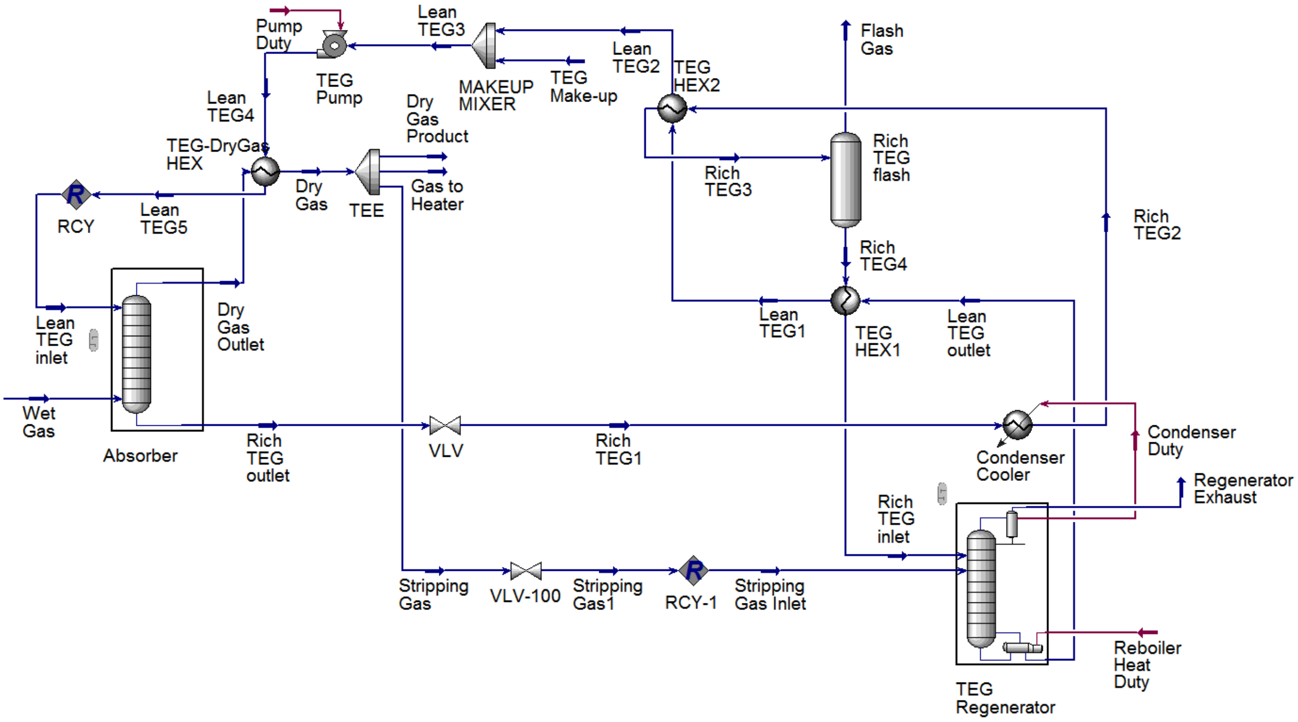

Figure 10 - Gas dehydration and TEG regeneration process with Stripping Gas

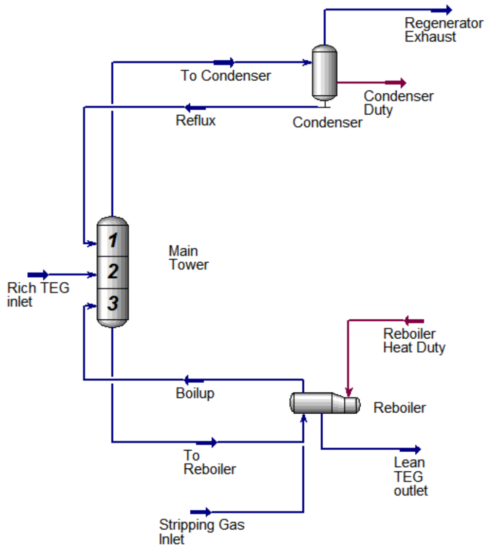

Figure 11 - TEG regenerator column design with focus on Stripping Gas inlet

7.2.3. Stahl Column

The lean TEG stream exiting the TEG Regenerator Column is further purified in an additional three-stage stripping column (Stahl Column, *Figure 12*). Similarly to the Stripping Gas Model, the gas used for stripping is split from the produced Dry Gas stream, its pressure is reduced to 110 kPa (VLV-1). The Stripping Gas Inlet stream enters at the bottom stage of the Stahl Column. The wet stripping gas exiting the column is recycled to the reboiler of the TEG Regeneration Column.

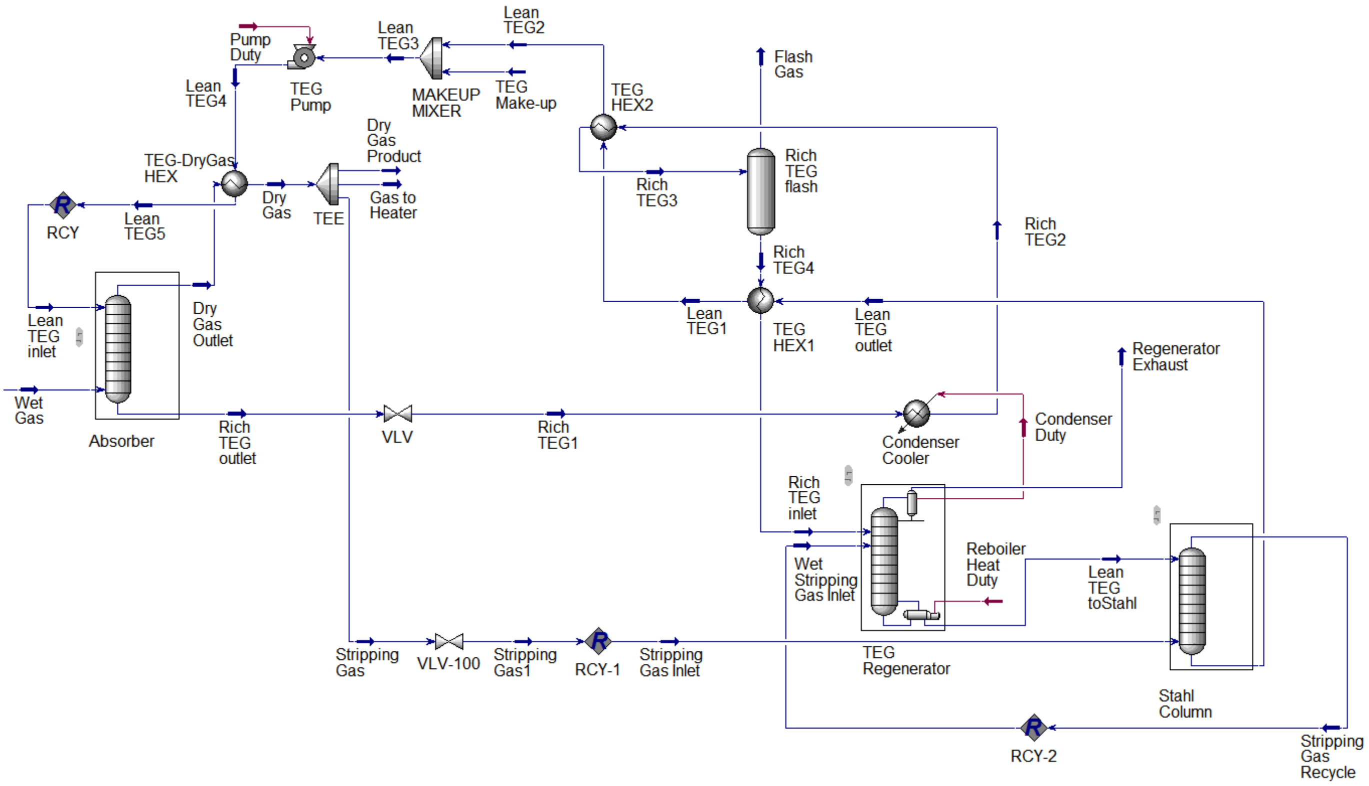

Figure 12 - Gas dehydration and TEG regeneration process with Stahl Column

7.2.4. Drizo

The heavy hydrocarbons (C4+) and water are condensed from the TEG Regenerator overhead and separated (Drizo Condenser and 3-Phase Separator, *Figure 14*). The hydrocarbon condensates are superheated and vaporized in the reboiler of the TEG Regenerator (*Figure 13*). A portion (10% of the molar flow) of the hydrocarbon condensates are split and drawn to prevent large accumulation in the recycled system (NGL product).

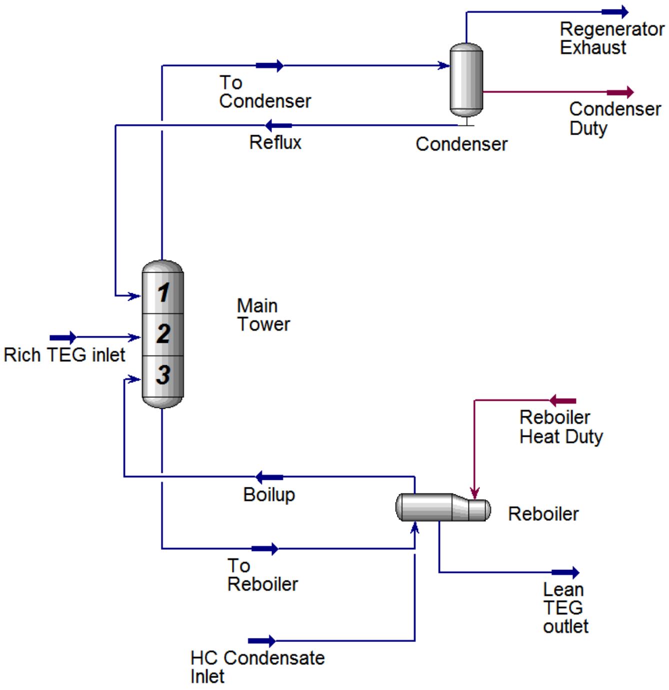

Figure 13 - TEG regeneration process with Drizo with focus on hydrocarbon condensate inlet

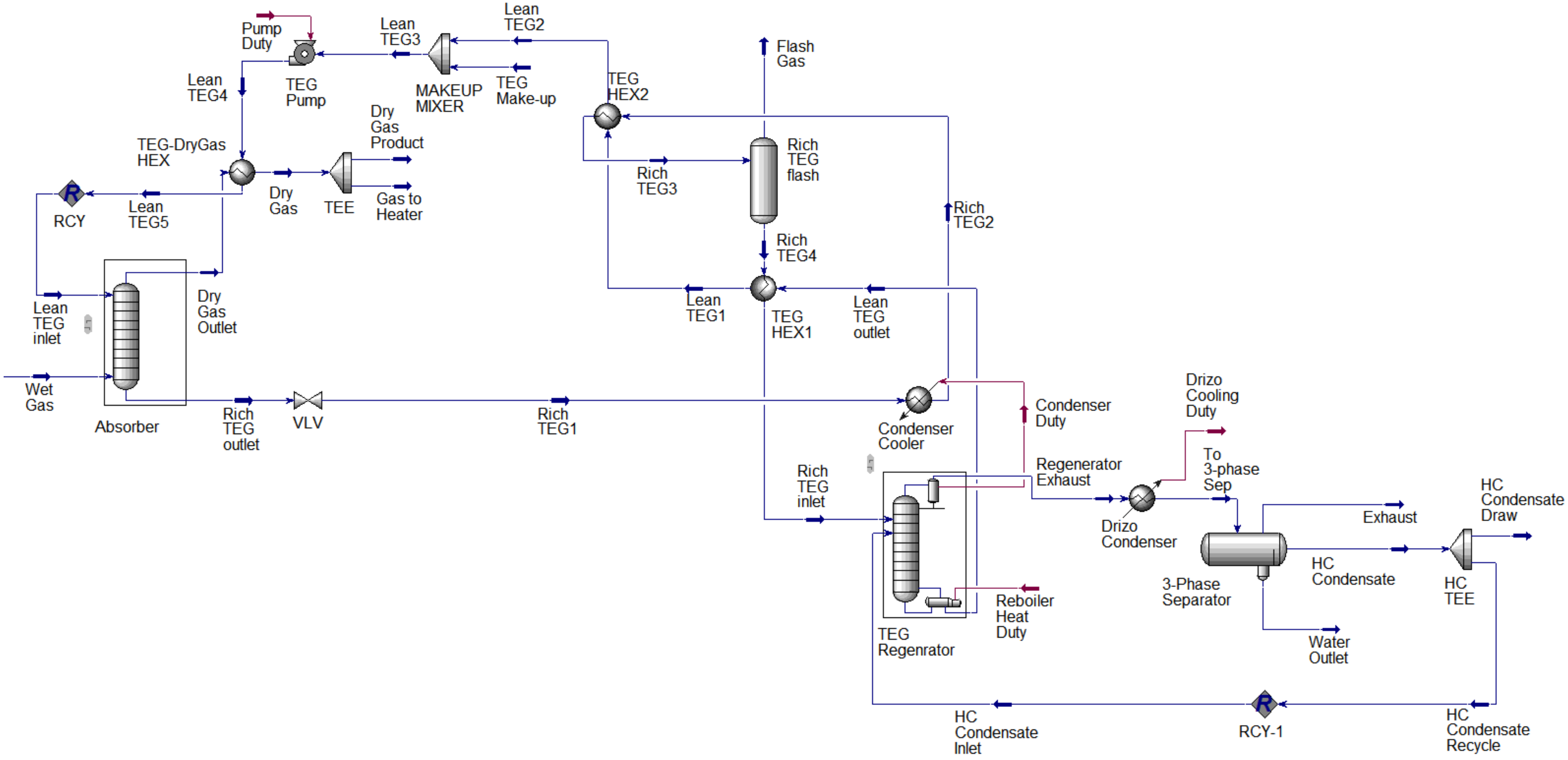

Figure 14 - Gas dehydration and TEG regeneration process with Drizo

7.2.5. Coldfinger – Model

As it was explained in the previous section, the Coldfinger operates through the condensation of some of the vapor near the cold bundle that is installed in the surge-tank thereby cooling it down and removing some of the water and TEG from it. The cold vapor is then replaced by hot vapor coming from the lean TEG liquid.

The liquid lean TEG exiting the reboiler is a bubble-point liquid, meaning that vapor needs to be formed first. This cannot be achieved by merely removing heat from the system, therefore a sufficiently large pressure-drop in the surge tank or the addition of stripping gas must occur. Since the surge tank and the reboiler are integrated into one compact vessel, it is unlikely that significant pressure difference exists between the two parts. Thus, leaving the latter option: the introduction of the vapor phase by some amount of stripping gas.

The surge tank with the Coldfinger apparatus is modelled as two units of equilibrium flash vessel and a heat exchanger (*Figure 15*). The first unit represents the liquid flowing from the reboiler as it is contacted by the stripping gas and the vapor recycled from the reboiler. The streams exiting this units are the further purified lean TEG stream, hot vapor rising to the Coldfinger bundle and the tray installed in the top of the surge tank. The top of the surge tank represents the second equilibrium unit, and it consists of two parts. The vapor leaving the liquid is then partially condensed by the Coldfinger bundle, which is represented as a heat exchanger and then flashed in a flash vessel which represents the liquid tray, and the top part of the surge tank. The cooling liquid is the Rich TEG leaving the absorber.

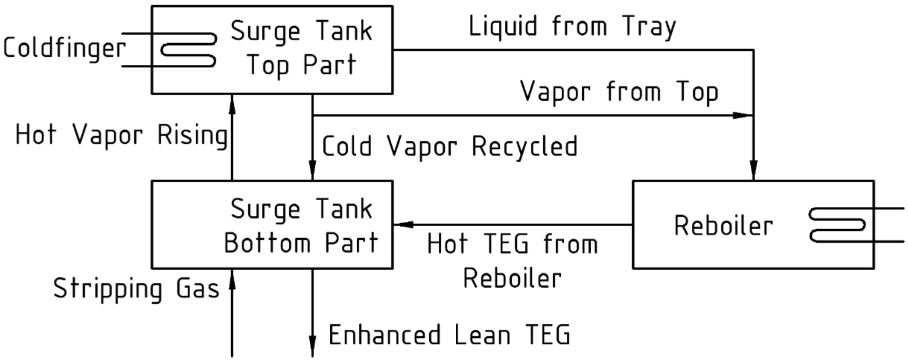

Figure 15 – Coldfinger Model

The implementation of the above model in Hysys is represented in *Figure 16* and a deeper analysis is presented in *Section 10*.

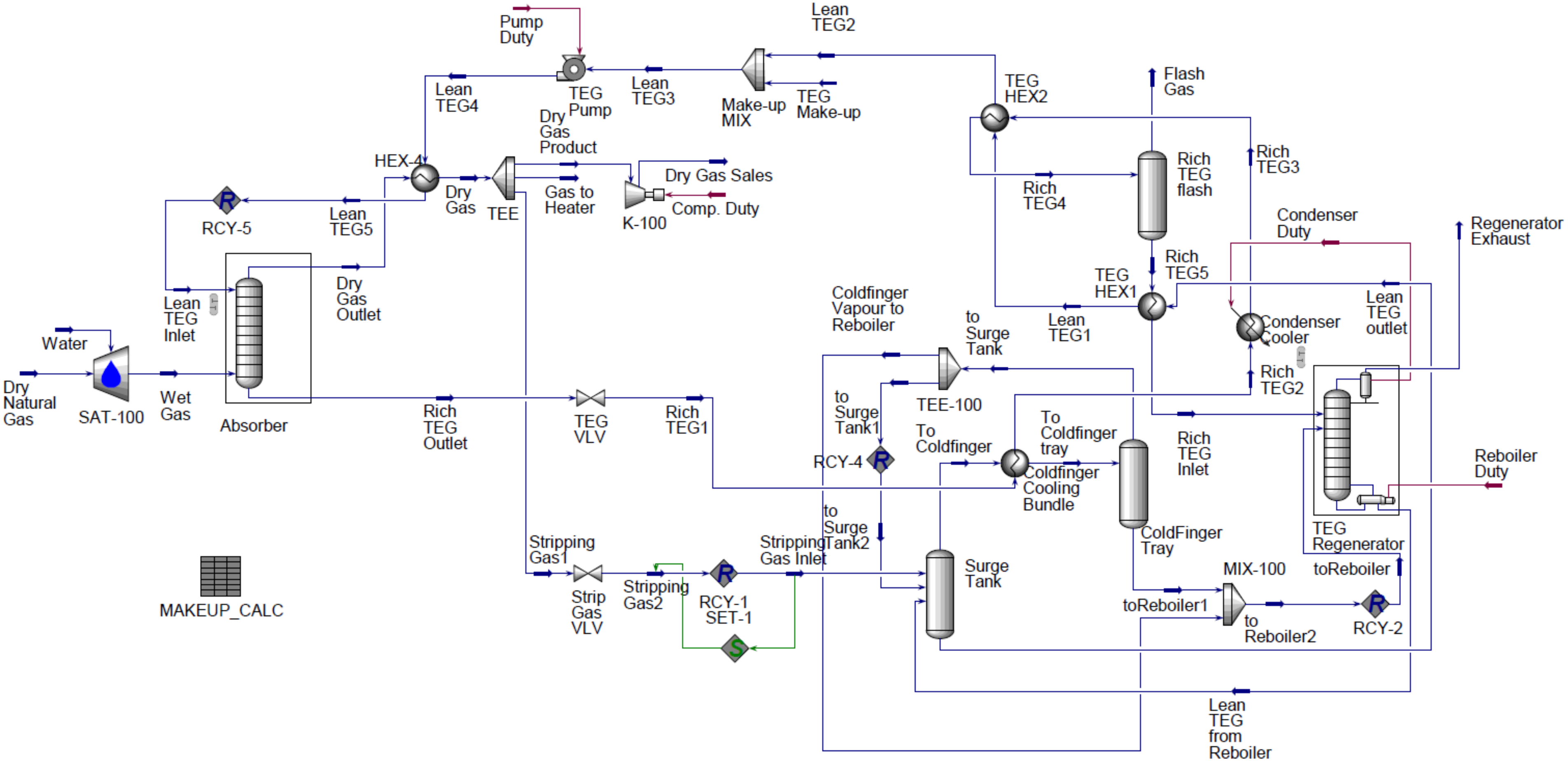

Figure 16 - Gas dehydration and TEG regeneration process with Coldfinger

7.3. The Glycol Package and The Twu-Sim-Tassone Cubic Equation of State

Cubic Equations of State are often used in oil and gas applications for performing phase equilibria calculations, nevertheless they may present problems for predicting the phase behavior of polar systems [12]. Thus, for gas dehydration and TEG regeneration processes modelled in Hysys, the Glycol Package is recommended as the thermodynamic model, since it provides a better representation of purities of lean TEG, TEG circulation rates, dew points and water content on the gas stream [13]. The Glycol package can be applicable in the ranges of temperature, pressure and components concentration necessary in gas dehydration systems with TEG regeneration. The Glycol Package is based on the Twu-Sim-Tassone (TST) Cubic Equation of State extended with experimental parameters for more precise and consistently determination of phase behavior of TEG-water-natural gas systems [14].

7.3.1. The TST Cubic Equation of State

The TST CEOS permits a better estimate of liquid densities for heavy hydrocarbons and polar components [15]. The estimation of vapor pressure is also more accurate with TST CEOS and it is represented by the following equation[16]:

$$P = \frac{RT}{v-b} - \frac{a}{(v+3b)(v-0.5b)} \quad \textit{Eq. 1}$$

The values of the attractive term (*a)*, the repulsive term (*b)*, and the compressibility factor (Z) at the critical point (*c*) are respectively:

$$a_c = 0.470507\frac{R^2T_c^2}{P_c} \quad \textit{Eq. 2}$$

$$b_c = 0.0740740\frac{RT_c}{P_c} \quad \textit{Eq. 3}$$

$$Z_c = 0.2962 \quad \textit{Eq. 4}$$

The values of Z_c for the Soave Redlich Kwong (SRK) ($Z_c = 0.333$) and for Peng Robinson (PR) ($Z_c = 0.3074$) are larger than the TST value, which is under 0.3, being closer to the real value of most substances [16].

Since *a* is a function of the temperature, it can be calculated from:

$$a(T) = \propto (T) a_c \qquad \text{Eq. 5}$$

Where the alpha function, $a(T)$, is a function of reduced temperature and the Twu alpha function is represented as:

$$\propto = T_r^{N(M-1)} e^{L(1-T_r^{NM})} \qquad \text{Eq. 6}$$

The alpha function parameters L, M and N used to correlate the vapor pressure of a component are unique for each component and can be calculated from the regression vapor pressure data of the pure component [16].

7.3.2. The TST mixing rules

The ability of a cubic equation of state to predict phase equilibria of mixtures is related to the mixing rule applied [12]. For the parameters *a* and *b*, the TST zero-pressure mixing rule can be defined as [16]:

$$a^* = b^* \left[\frac{a_{vdw}^*}{b_{vdw}^*} + \frac{1}{C_r} \left(\frac{A_0^E}{RT} - \frac{A_{0vdw}^E}{RT} \right) \right] \qquad \text{Eq. 7}$$

$$b = b_{vdw} \qquad \text{Eq. 8}$$

The zero-pressure mixing rule assumes that the reduced liquid volume can be either constant or suffer no variation as the one calculated from a cubic equation of state using the van der Waals mixing rule for its *a* and *b* parameters [12].

A_0^E represents the excess Helmholtz free energies at zero pressure and A_{0vdw}^E indicates that it is evaluated from the cubic equation of state using the van der Waal's mixing rules [16].

C_r is a function of *r*, meaning the reduced liquid volume at zero pressure and can be expressed as:

$$C_r = \frac{1}{w-u} \ln \left(\frac{r+w}{r+u} \right) \qquad \text{Eq. 9}$$

Where *u* and *w* are constants that depend on the equation of state. For the TST cubic equation of state *u* is 3 and *w* is -0.5.

a^* and $b^*$are defined by equations:

$$a^* = \frac{Pa}{R^2 T^2} \qquad \text{Eq. 10}$$

$$b^* = \frac{Pb}{RT} \qquad \textit{Eq. 11}$$

The *a* and *b* parameters evaluated using van der Waals mixing rules, respectively a_{vdw} and b_{vdw} are calculate by the following equations:

$$a_{vdw} = \sum_i \sum_j x_i x_j \sqrt{a_i a_j}(1 - k_{ij}) \qquad \textit{Eq. 12}$$

$$b_{vdw} = \sum_i \sum_j x_i x_j \left[\frac{1}{2}(b_i + b_j)\right] \qquad \textit{Eq. 13}$$

8. CASE STUDIES

Before comparing the different TEG regeneration methods the most significant process variables were established and separated from the remainder. The solvent flowrate in the absorber, the used stripping gas (if applicable), the reflux rate in the regeneration column and the number of equilibrium stages in the absorber were identified as potentially influencing key process parameters such as the amount of TEG make-up needed, heat in the reboiler, and hydrocarbon losses in the flash gas and the regenerator exhaust. Case studies were performed on the base case with or without stripping to gain better understanding of the effect of these variables and to isolate the important variables for the following comparison of the different TEG regeneration methods.

8.1. Determination of important process parameter

Initially, the effect of the number of equilibrium stages in the absorber was determined by isolating the unit from the rest of the process (*Figure 17*). The simulation was performed by varying the TEG flowrate, the number of equilibriums stages in the absorption column and by saving the calculated water content in the dry gas. The remaining process parameters were kept constant (*Table 5*).

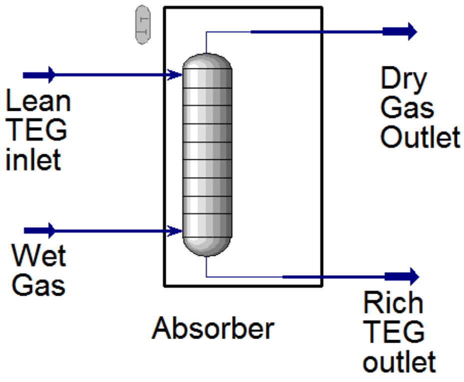

Figure 17 – Absorber inlets and outlets

Fixed Parameters	**Values**	**Units**
Solvent Water content	0.1; 1	wt%
Feed composition and condition	*See Section 7.1*	
Independent variables		
Solvent to Feed Ratio	0.005 - 0.045	kg/kg
Number of Equilibrium Stages	2 - 10	-
Dependent variables		
Water content in the dry gas		g/Sm^3

Table 5 – Process parameters – Absorption column

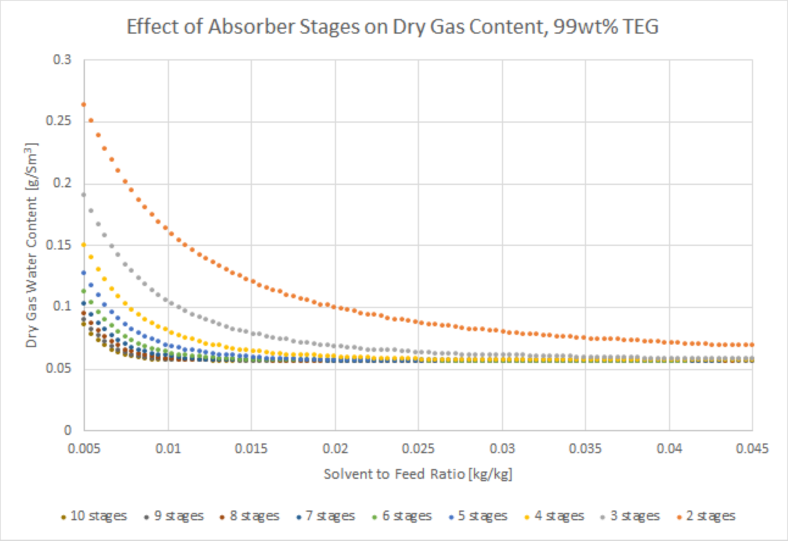

Figure 18 – Effect of absorber stages on dry gas content at 99wt% TEG

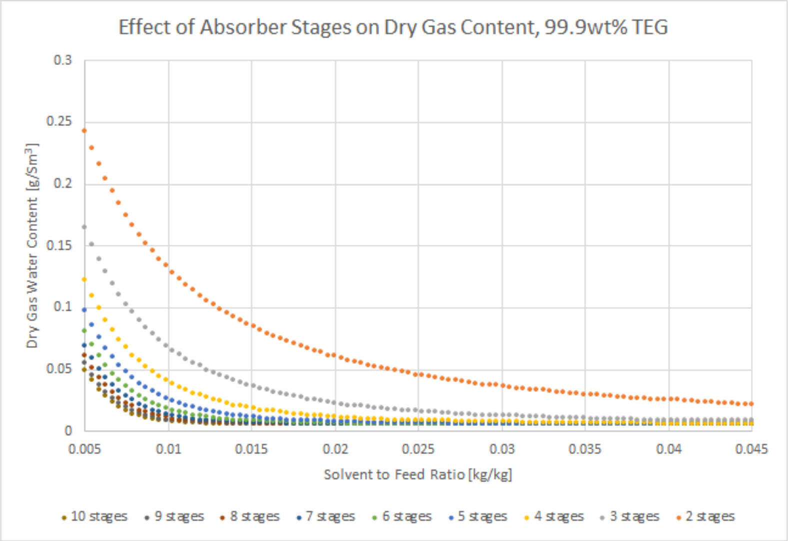

Figure 19 – Effect of absorber stages on dry gas content at 99.9wt% TEG

Figure 18 and *Figure 19* indicate that there is no significant improvement in the dry gas quality increasing the number of equilibrium stages over four. Therefore, in the subsequent case-studies the number of stages was set to N=4.

The effect of the reflux ratio was investigated in the traditional TEG regeneration process (*Table 6*). The reflux ratio cannot improve the lean TEG quality in the bottom product, since this function belongs to the temperature in the reboiler. However, it influences the amount of TEG lost in the overhead vapor. Consequently, the needed TEG make-up was investigated as a function of the solvent circulation and the reflux ratio in the regeneration column of initially three equilibriums stages. The TEG-make-up was calculated by summing up the losses in the column exhaust, the flash gas, and the dry gas.

Fixed Parameters	**Values**	**Units**
Reboiler Temperature	204	°C
Number of Stages in the Regenerator	3	-
Independent variables		
Reflux Ratio	0.0125, 0.1, 0.2	mol/mol
Solvent to Feed Ratio	0.005 - 0.045	kg/kg
Dependent variables		
TEG Make-up		kg/h

Table 6 – Process parameters – Effect of reflux ratio

As it can be seen on *Figure 20*, increasing the reflux ratio above 0.1 gives no further decrease in the required TEG make-up. From the literature [3] it is known, that there is a trade-off between the required reflux ratio and the number of stages. However, the reflux ratio is already very low, so it is not reasonable to increase the number of stages in the column to decrease the reflux ratio. The number of equilibrium stages set as one and two were experimented, however with the given specifications, convergence was not obtained for the regenerator column. Therefore, the number of equilibrium stages were kept at 3 in the subsequent case studies, and the reflux ratio at 0.1, which also corresponds to values found in the literature [7].

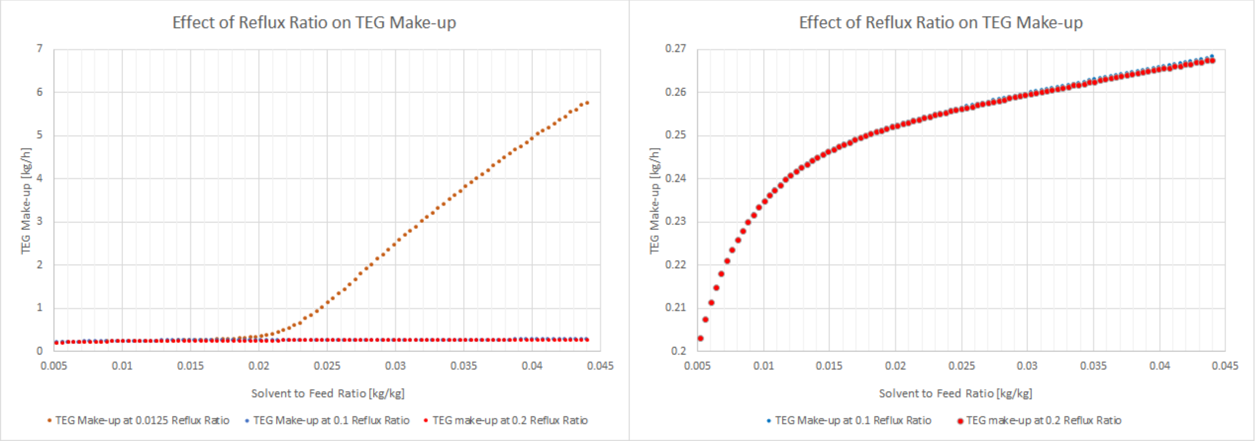

Figure 20 – Effect of reflux ratio on TEG make-up

Finally, the effect of the stripping gas flowrate and the solvent circulation was studied (*Table 7*). Both the stripping gas flowrate and the solvent flowrate were varied. The dependent variables were the following: dry gas water content, heat used in the reboiler, hydrocarbon losses in the separator and the regenerator exhaust.

Fixed Parameters	**Values**	**Units**
Reflux Ratio in the Regenerator	0.1	-
Number of Stages in the Regenerator	3	-
Number of Stages in the Absorber	4	
Independent variables		
Solvent to Feed Ratio	0.005 - 0.045	kg/kg
Stripping Gas Flow	0.04225 – 0.84509	wt‰ of feed gas
Dependent variables		
Dry Gas Water Content		g/Sm^3
Reboiler Heat Duty		kJ/h
Regenerator Overhead HC losses		kg/h
Flash Gas HC losses		kg/h

Table 7 – Process parameters – Effect of Stripping Gas and TEG circulation

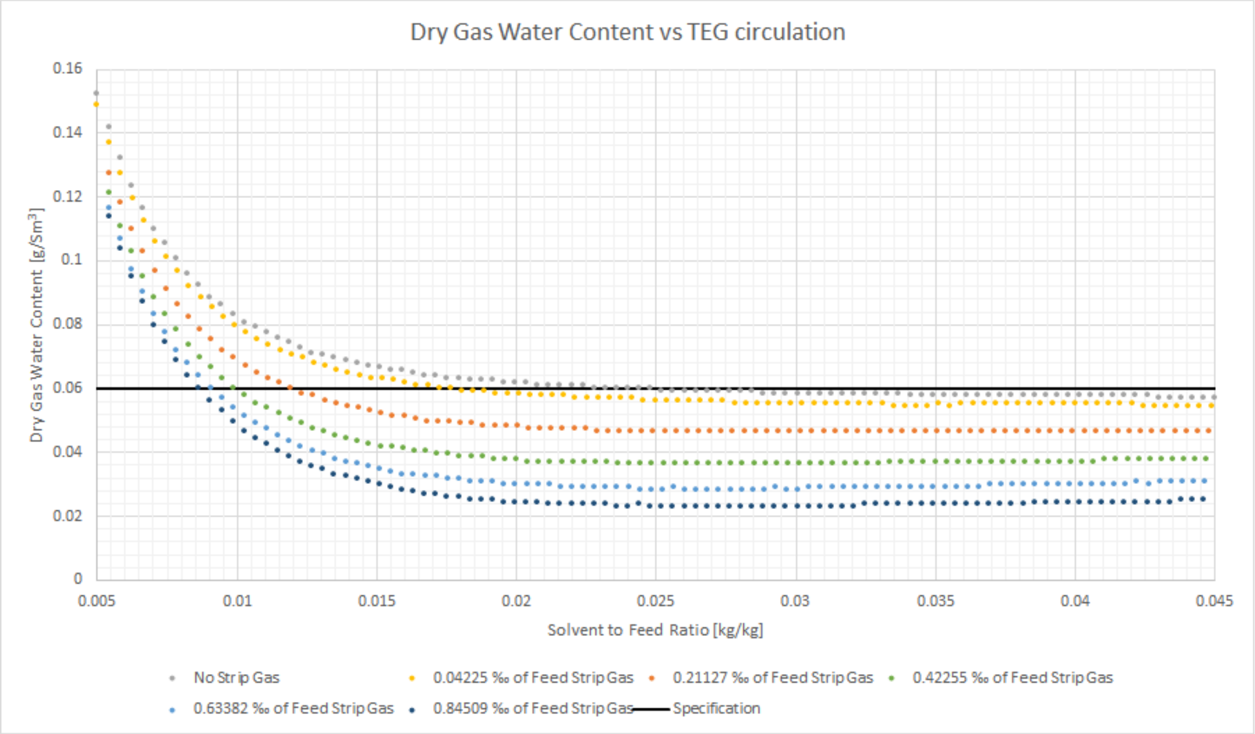

Figure 21 – Dry gas water vs TEG circulation

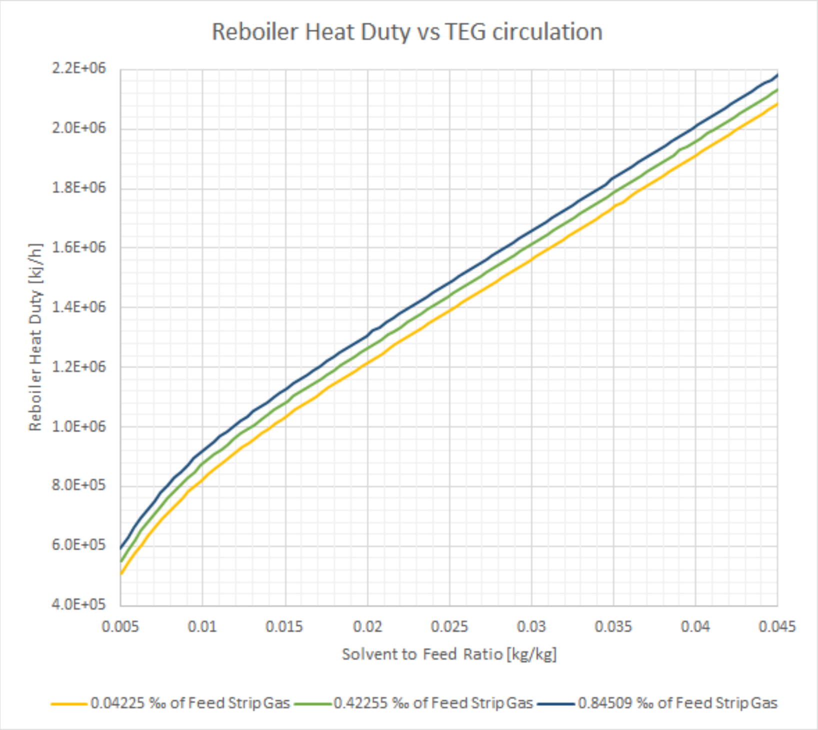

Figure 22 - TEG circulation effect on reboiler heat duty

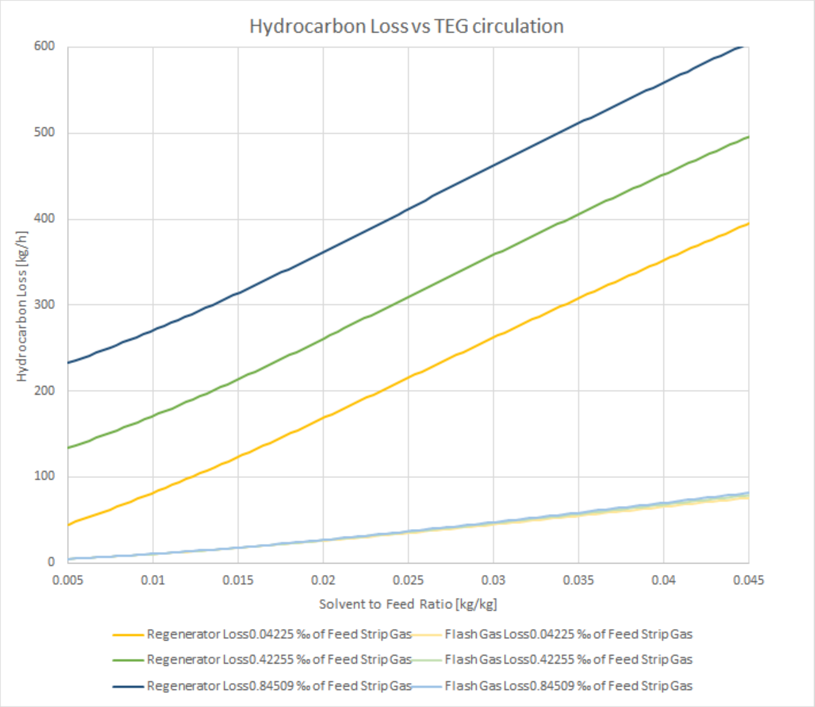

Figure 23 – TEG circulation effect on hydrocarbon loss

Figure 21, Figure 22 and *Figure 23* suggest that the solvent circulation and the amount of stripping gas used has a significant effect on the process parameters. The water content of the dry gas can be decreased significantly both by increasing the amount of stripping gas used and by increasing the rate of solvent circulation. The heat duty requirement in the reboiler appears to be directly correlated with the solvent circulation but not with the stripping gas flow rate. The same holds true for the hydrocarbon losses in the separator flash gas. Nevertheless, the hydrocarbon losses in the column exhaust depends both on the solvent circulation and the stripping gas rate. In conclusion, the process parameters that have major effect on the losses and utility consumption are the solvent circulation and the stripping gas flowrate.

8.2. Comparison of different solvent regeneration methods

Having identified the major process parameters: the stripping gas flow rate and the solvent circulation, the case studies were setup by varying the lean TEG Inlet mass flowrate (kg/h) of the absorber and the stripping gas flow rate (if applicable to the process) as the independent variable (*Table 8*).

In case of the solvent circulation all values were recalculated to solvent to feed ratio, as the feed flow rate was constant in all cases. The solvent to feed ratio studied ranged from 0.005 to 0.045. In the models where stripping gas was utilized (Gas Stripping, Stahl, Coldfinger), the amount of stripping gas ranged between 0.04225-0.84509 wt‰ of feed gas (1-200 kg/h) for the Gas Stripping and Stahl Column applications and 0.04225-0.12675 wt‰ of feed gas (1-30 kg/h) for the Coldfinger modelling.

Independent variables	Values	Units
Solvent to Feed Ratio	0.005 - 0.045	kg/kg
Stripping Gas Flow	0.04225 - 0.84509	wt‰ of feed gas
Stripping Gas Flow (Coldfinger)	0.04225 - 0.12675	wt‰ of feed gas

Table 8 – Independent variables

The following parameters were fixed for all cases:

Fixed Parameters	Values	Units
Reflux Ratio in the Regenerator	0.1	-
Number of Stages in the Regenerator	3	-
Number of Stages in the Absorber	4	
Reboiler Temperature	204	°C
Absorber Pressure	4000	kPa
Regenerator Pressure	110	kPa
Regenerator Pressure (Vacuum)	500	mmHg
Pressure drop in heat exchanger	150	kPa

Table 9 – Fixed parameters

The dependent variables for all cases were the following:

Dependent Variables	Units
Dry Gas Product - Flowrates	kg/h, Sm^3/h, kgmole/h
Dry Gas Product - Water content	wt%, mole% -> g/Sm^3
Dry Gas Product - Water dew point at 8275 kPa	°C
Reboiler Heat Duty	kJ/h
Dry Gas burned to heat the Reboiler (Gas to Heater)	kg/h, Sm^3/h, kgmole/h
TEG Make-up	kg/h
TEG Circulation Pump Duty	kW
Lean TEG outlet - Water and TEG content	wt%
Streams exiting the dehydration process	
Flash Gas - Flowrate for each component	kg/h, kgmole/h
Regenerator Exhaust - Flowrate for each component	kg/h, kgmole/h

Table 10 – Dependent variables

The additional process variables monitored and collected for the different enhanced TEG regeneration processes are shown in *Table 11* to *Table 14.*

Vacuum Distillation	
Additional Dependent Variables	**Units**
Vacuum Pump Duty	kW
Compressor Duty	kW

Table 11 – Vacuum distillation parameters

Gas Stripping and Stahl Column	
Additional Dependent Variables	**Units**
Stripping Gas – Flowrates	kg/h -> wt‰ of feed gas

Table 12 – Gas stripping and Stahl Column parameters

Drizo	
Additional Dependent Variables	**Units**
Condenser Duty (Drizo Cooling Duty)	kJ/h
HC Condensate Regenerator Inlet flowrate*	kg/h
Streams exiting the dehydration process	
NGL product (HC Condensate Draw)	kg/h
	*to monitor accumulation

Table 13 – Drizo parameters

Coldfinger	
Additional Dependent Variables	***Units***
Stripping Gas – Flowrates	kg/h -> wt‰ of feed gas
Recycled Stream (to SurgeTank2) flowrate*	kg/h
	*to monitor accumulation

Table 14 – Coldfinger parameters

The obtained data were used to determine the optimal solvent to feed ratio and the stripping gas amounts for maximum dry gas production, regarding the specified constraint that the water dew point of the dry gas at 8275 kPa must be at or below -10°C in each case of TEG regeneration model. As it was stated earlier, the Dry Gas Product value considers all major operational expenses, such as the amount of gas burned to heat the reboiler, the gas used for stripping purposes and the subsequent losses in the column overhead vapor. BTEX emissions were also calculated, but the processes were not optimized for minimal BTEX emission.

9. RESULTS

The two gas quality specifications investigated in this work are the following:

- The dry gas water content must be less than 0.06 g/Sm^3 (4 lb/MMscf) for sales gas
- The dry gas water dew point must not reach -10°C at 8275 kPa for export in offshore pipeline

The sales gas water content specifications were possible to be met in all cases, including the base case (*Figure 24*) without any enhanced TEG regeneration method used. However, the water dew point specifications could only be achieved through the application of enhanced TEG regeneration methods (*Figure 25*).

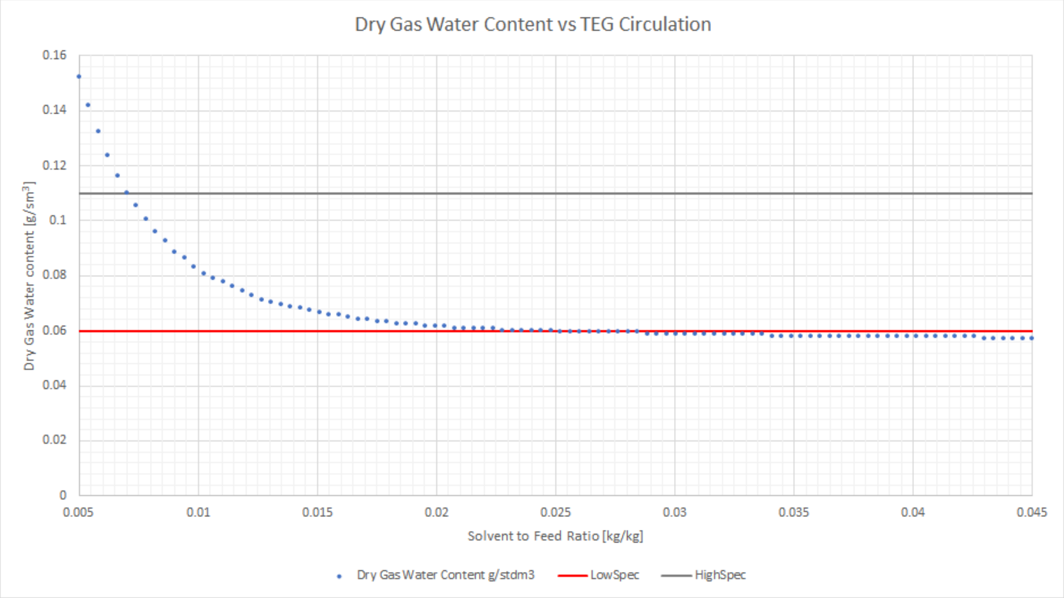

Figure 24 - Base case water content as function of TEG circulation

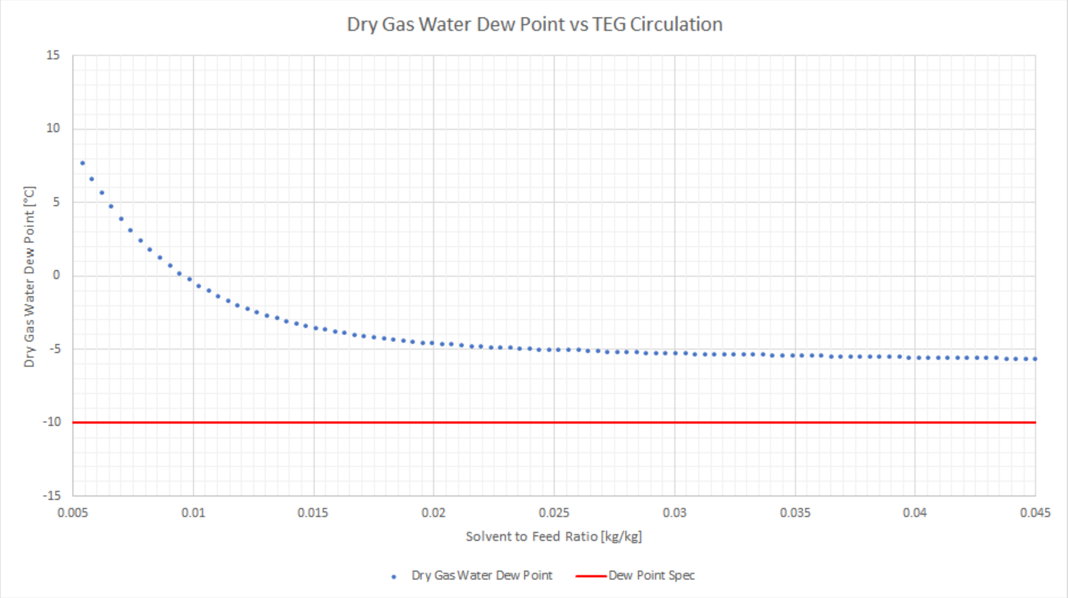

Figure 25 - Water dew point as function of TEG circulation

A comparison between the different regeneration methods, which satisfy the export specifications, regarding the optimized produced dry gas quantity can be seen in *Figure 26*. Since the utilities are covered by using some of the produced gas for heating the reboiler and as a stripping gas (and the subsequent loss in the overhead vapor), the less gas spilled for a given method the higher the gas production rate will be for a given feed. Most of the gas loss occurs in the regenerator exhaust in each case, thus methods where this loss can be minimized performed well. For example, even though the Drizo process consumes the most gas to heat the reboiler, this is by far compensated by the decreased hydrocarbon loss in the regenerator exhaust, consequently causing it to be the best performing enhanced TEG regeneration method of the five. It is followed by the Stahl, as the second-best option. The Coldfinger is slightly better than the Vacuum, because it has marginally less losses and less need for gas to heat. The traditional stripping gas injected to the reboiler performs the poorest of the five enhanced TEG regeneration methods, due to the relatively high losses in the regenerator exhaust.

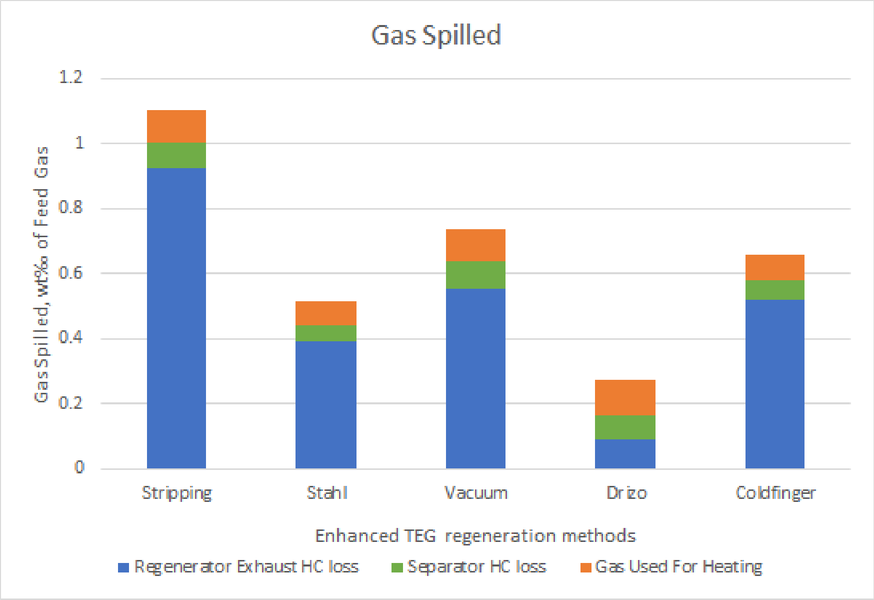

Figure 26 – Amount of spilled gas in different enhanced TEG regeneration methods

Another concern of the dehydration process is the amount of hazardous air pollutants (HAP) released, with special focus towards the BTEX compounds, as the necessity of meeting the regulations presents additional costs. *Figure 27* shows that the gas stream exiting the Rich TEG Flash Separator contains only a small amount of BTEX compounds, as the separator is operated at 90°C. Most of the BTEX compounds exiting the dehydration process originates from the vapor stream of the regenerator exhaust. Vacuum regeneration and direct gas stripping produce the highest amounts, followed by the Coldfinger and Stahl methods. The exhaust stream of the Drizo process contains the lowest BTEX quantities, as the procedure recirculates these for solvent stripping.

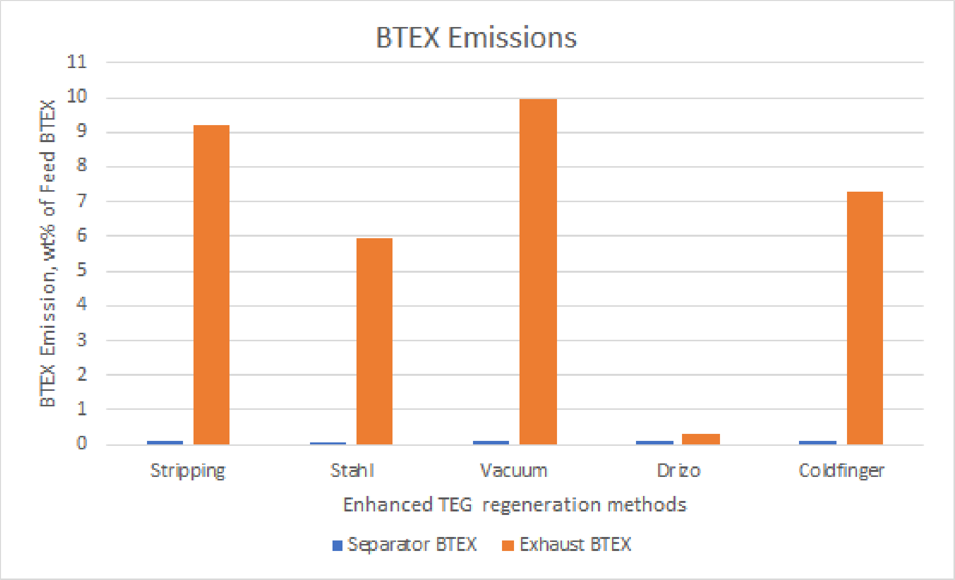

Figure 27 – BTEX emissions in the separator and exhaust

In the next section, these results are analyzed to explain the differences in performance between the methods.

10. ANALYSES

In the previous section, it was established that the best performing method in terms of produced gas and BTEX emissions in the regenerator exhaust was the Drizo method, closely followed by Stahl (*Figure* 27). In this section, the explanations are presented.

It could be seen on *Figure 26* that except for the Drizo method, most of the spilled gas originates from the regenerator exhaust loss. In comparison, the gas burned to heat the reboiler is significantly less and it is not the reason for the main difference in effectiveness between the different enhanced TEG regeneration methods. Thus, the factors influencing the hydrocarbon loss in the regenerator exhaust are further investigated.

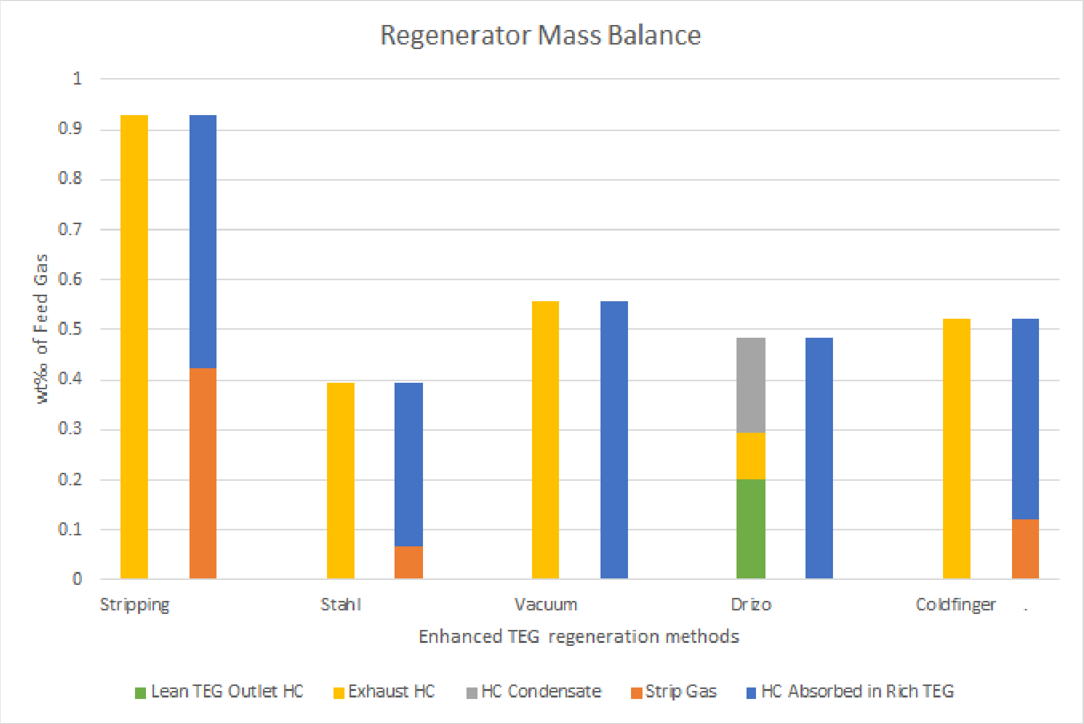

Figure 28 - Regenerator mass balance. Left: outlets, right: inlets

The mass balance of the regenerator indicates (*Figure 28*) that the exhaust loss in the Drizo process is lower because of the condensation and recirculation of the overhead vapor, leading to the Drizo as the best performing process. The mass balance also suggests that about half of the condensed liquid hydrocarbon resides in the lean TEG stream exiting the regenerator while the other half is being drawn of as hydrocarbon condensate.

Furthermore, it can be understood that the exhaust loss can come from two sources. One is the consumed stripping gas, corresponding to the literature [1]. The other source is the gas absorbed in the rich TEG stream. Hence, in the other cases of enhanced TEG regeneration, the magnitude of this loss depends on these two amounts.

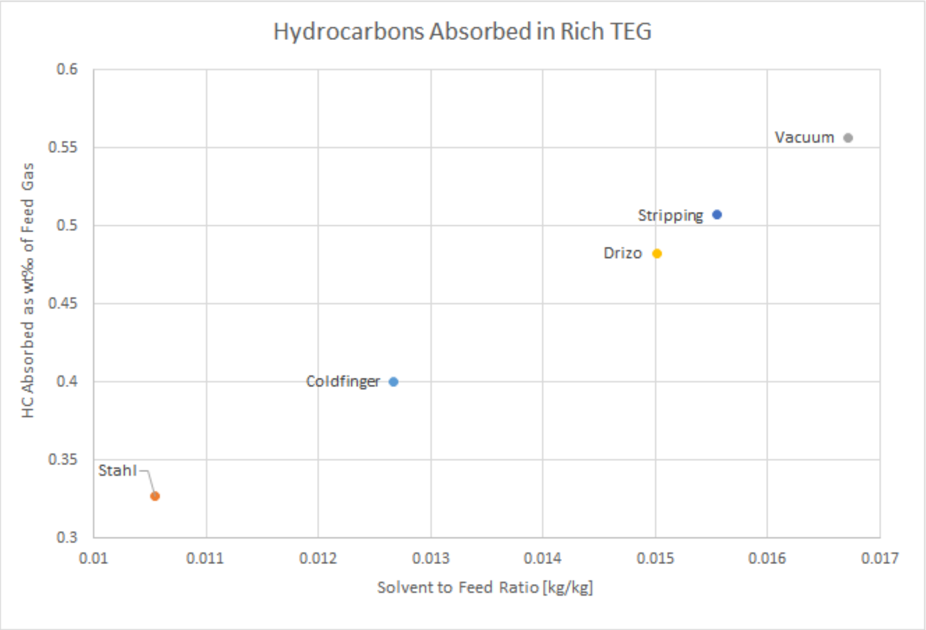

Figure 29 – Hydrocarbons absorbed in the rich TEG

The amount of absorbed hydrocarbon in the rich TEG is directly proportional to the solvent to feed ratio in the absorber (*Figure 29*). This denotes that those methods that require less solvent circulation have less losses in the regenerator exhaust exiting from this source. Comparing the lean TEG purity between the different cases *(Figure 30*), the needed solvent to feed ratio in the absorber, to reach the same dry gas specifications in each case, is decreasing proportionally with increased lean TEG purity (*Figure 30*). Therefore, those methods that achieve leaner TEG have less losses in the regenerator exhaust due to less absorbed hydrocarbons in the rich TEG. However, it can also be perceived that these gains can be offset by the increased need of stripping gas as it is the case for the simple stripping method.

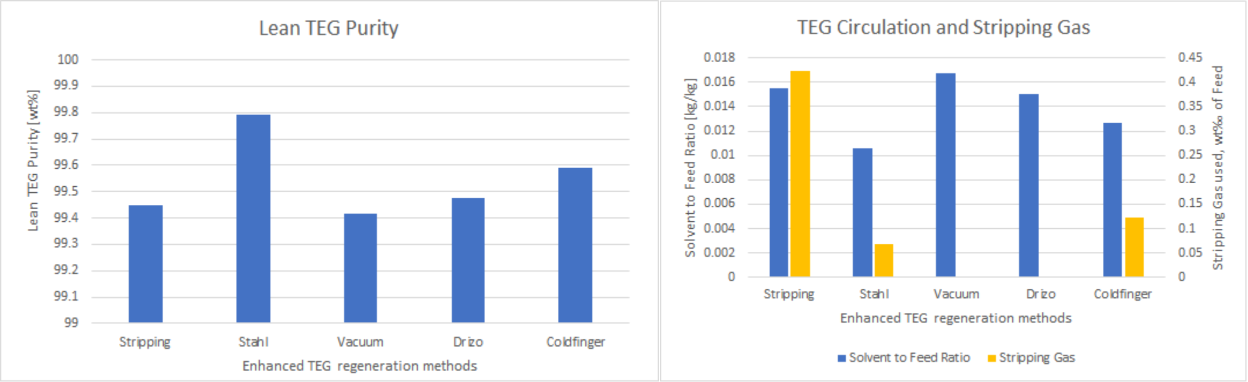

Figure 30 – Lean TEG purity, TEG circulation and stripping gas for different enhanced TEG regeneration methods

Overall the stripping method performs the poorest, because of the relatively high TEG circulation and the large amount of stripping gas required. Except for the Drizo, the methods that achieved higher TEG purity in the optimum value without increased need of stripping gas, are the more efficient methods, since they also require less solvent. This is the case of the Stahl and the Coldfinger methods.

10.1. Coldfinger Model

According to the model developed in this project, the Coldfinger method does indeed improve the quality of the lean TEG, thereby allowing for a more efficient dehydration. To gain insight into the Coldfinger mechanism component mass balances were constructed (*Figure 31*) for the liquid part of the surge tank and for the vapor part around the Coldfinger, based on the results of the Hysys simulation at optimal conditions.

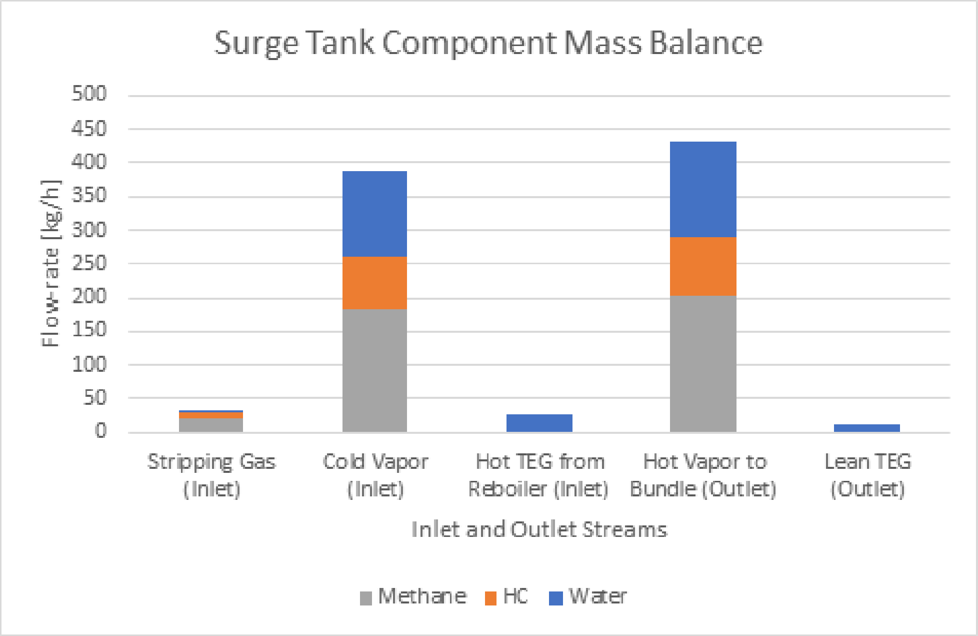

Figure 31 – Coldfinger surge tank component mass balance

It can be inferred from the surge tank mass balance (*Figure 31*), that the enhanced quality of lean TEG originates from the significant build-up of recirculating vapor (approximately 20 times the amount of mass flow of the stripping gas inlet) between the liquid and the vapor part. This vapor contains significant amount of inert gas (mainly methane) which lowers the partial pressure of water in the vapor phase.

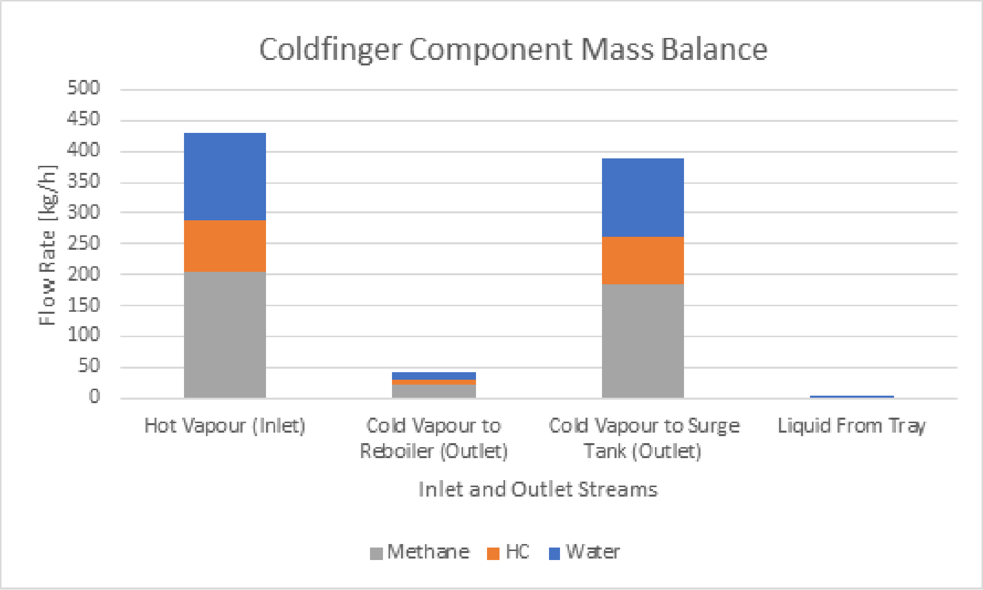

Figure 32 – Coldfinger component mass balance

It can also be seen from the mass balance for the Coldfinger (*Figure 32*) that most of the water is being removed by the vapor that is not being recirculated to the liquid. In comparison, the water being removed in the liquid tray is negligible. Therefore, it can be concluded that the effect of the Coldfinger is to create a drive force for the recirculation by lowering the temperature of the rising hot vapor on top (in this case from 197.5°C to 195.7°C) and allowing for the buildup of the inert gases by recirculation.

One disadvantage of the model developed in this work is that it does not account for the role of the magnitude of the temperature difference on the amount of gases being recycled. For that accurate sizing of the surge tank would be needed as well as convection models for the exchanging vapors.

10.2. BTEX Emission Analysis

As mentioned in the results, the best performing method is the Drizo regarding the BTEX emissions and the amount of gas spilled. The BTEX compounds are condensed, half of them are recycled to the lean TEG stream and half of them are recovered in the hydrocarbon condensate.

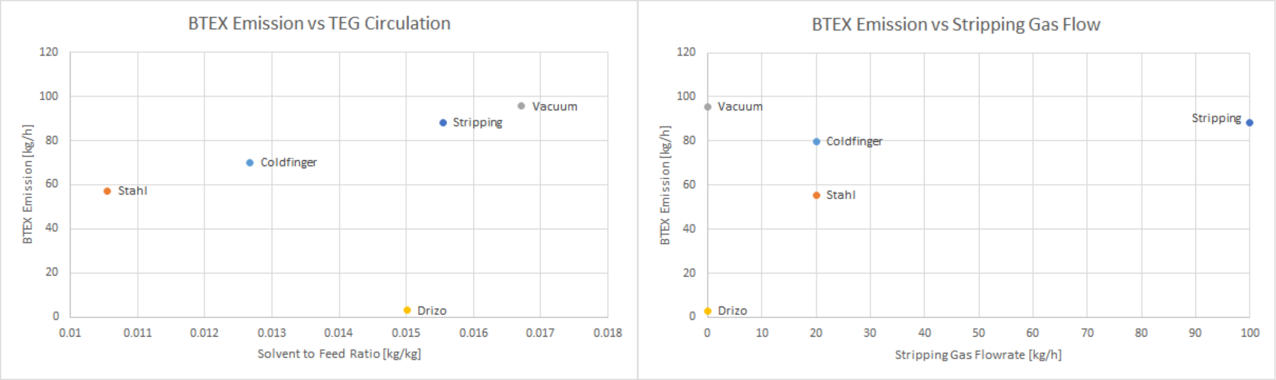

Figure 33 – BTEX emissions regarding TEG circulation and stripping gas flow

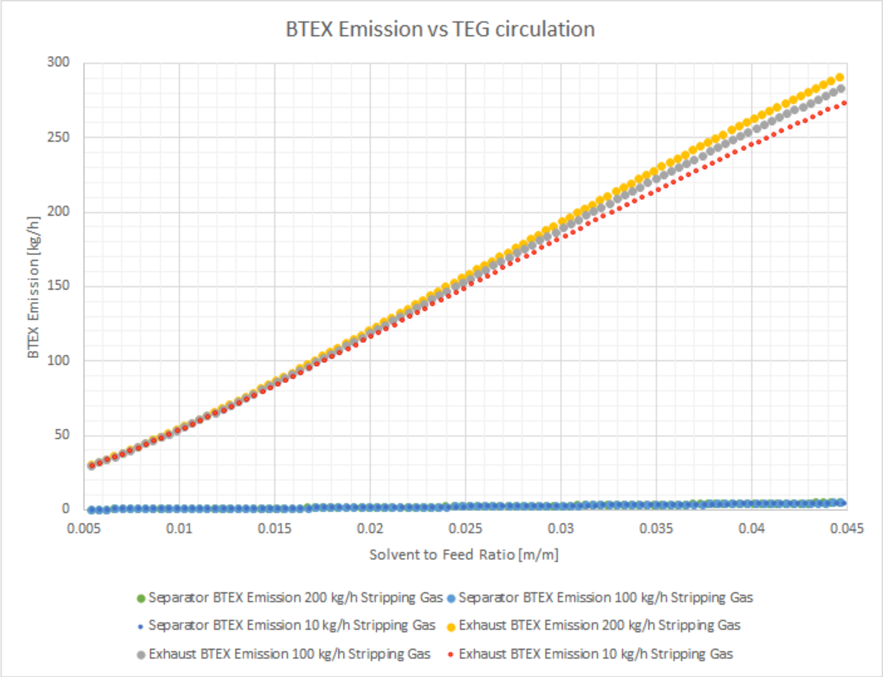

Figure 34 – BTEX emissions vs TEG circulation

In the other cases (*Figure 33* and *Figure 34*), it was noticed, that the BTEX emission is a function of the solvent circulation, but it is not related to the stripping gas consumption. The more solvent required in the absorber, the more of the BTEX compounds are absorbed in it and subsequently emitted in the regenerator overhead vapor.

Apart from the Drizo method, the rate of BTEX emission are very high compared to the allowed specifications mentioned in *Section 4*, demanding additional measures to be taken for its limitation, such as installation of additional equipment.

10.3. Equipment and additional utility costs

This section addresses the possible operational costs and the needed investment in extra equipment for the different TEG enhanced regeneration methods previously discussed.

The utility cost for the TEG circulation in the glycol pump is not included because the work required by the equipment is considered negligible when compared to other utility costs, moreover with a more advanced pump design, most of it could be recoverable. For the same reason, additional cooling duties related to the Drizo process were not considered.

One major utility cost not previously considered is the maintenance of the vacuum since vacuum pumps are not implemented in Hysys. Accounting for this additional cost, it is reasonable to assume that the enhanced TEG regeneration with vacuum presents a higher cost when compared to the simple stripping method.

Method	Additional Equipment
Stripping	None
Stahl	Packed stripping column
Vacuum	Vacuum Pump
Drizo	Condenser
Coldfinger	Coldfinger Bundle, Tray

Table 15 – Additional equipment requirements for enhanced TEG regeneration methods

Concerning investment in extra equipment, it can be seen that the Drizo, the vacuum, the Stahl and the Coldfinger methods require extra equipment, but not of the same magnitude (*Table 15*). The Coldfinger bundle, for example, is just a small addition to the surge tank, requiring considerably less investment when compared to the other methods. However, as stated in the previous section, given the high BTEX emission in all cases except the Drizo, an additional condenser would be required in all other methods in order to condense and collect the BTEX compounds. This makes the equipment cost associated with the Drizo process lower when compared with the other methods.

11. CONCLUSION

Natural gas is saturated with water as it comes out of the reservoir, therefore, different offshore processes need to be applied for the gas dehydration, avoiding consequently problems caused by the wet gas such as corrosion or gas hydrate formation.

The modelling of the gas dehydration and different TEG regeneration methods was successfully completed in Hysys. The Glycol Package based on the Twu-Sim-Tassone CEOS was selected since the simulation is based on a non-ideal liquid mixture of water-glycol.

The simulation of the TEG regeneration process required more attention when fixing the operating parameters since otherwise the column presented convergence problems. Thus, during the simulation in Hysys it was necessary to experiment with different parameters before reaching a consistent convergence of the columns.

Even though the simulator does not provide a specific Coldfinger unit, a method for modelling the Coldfinger was suggested in this thesis. With the modelling of the Coldfinger was possible to compare the different TEG regeneration methods, meaning the base case, vacuum distillation, direct gas stripping, stripping in a separate (Stahl) column, the Drizo and the Coldfinger. It was also found that Coldfinger enhance TEG purity by the accumulation of significant amount of recirculating inert gas in the surge tank.

Several aspects could be considered when deciding what is the best model for implementation, such as the dry gas production, the amount of gas spilled, the operational costs, the equipment implementation costs, the demanded area, the amount of TEG make-up needed and the energy consumption. Therefore, to provide an answer to the question of which is the best method, it is strongly dependent on the variables included for analyses.

The specifications used throughout this work include the sale gas specifications (dry gas water content must be less than 0.06 g/Sm^3) and the specification for export in offshore pipeline (dry gas water dew point must not reach -10°C at 8275 kPa). With the exclusion of the base case, the other remaining TEG regeneration methods met the specifications with the right operating parameters.

When considering the amount of gas spilled during the processes, it was revealed that this value is mostly determined by the amount of hydrocarbon in the vapor exhausted from the regenerator. Hence, the Drizo presents the best results because these hydrocarbons are condensed and partly recycled.

In the other cases, the decisive factor was the TEG purity and the amount of stripping gas required. With increasing TEG purity less solvent was required to achieve the specifications, leading to less hydrocarbons absorbed in the solvent and reaching the exhaust. The amount of losses in the regenerator exhaust proportionally increases with the amount of stripping gas used.

The highest lean TEG purity obtained was in the Stahl method, indicating low TEG recirculation and relatively low amount of stripping gas requirement. The Coldfinger performed well regarding both the solvent circulation and the amount of stripping gas needed. The vacuum and stripping methods achieved approximately the same TEG purity, thus requiring the same amount of solvent. Nevertheless, the stripping method required a significant amount of stripping gas, generating the highest hydrocarbon loss in the regenerator exhaust. It is imperative to mention that the vacuum method requires the maintenance of vacuum, which presents itself as an additional operating cost that was not accounted for in this report. Regarding necessary additional equipment, it was found that the Coldfinger method needs the least amount of new equipment after the conventional stripping method for operating.

An additional focal aspect of this thesis was the emission of BTEX compounds in each method. The Drizo was clearly the best choice in this aspect, with very low emissions, and it is due to the configuration of the process itself: condensation and recirculation of the vapor stream of the regenerator exhaust for solvent stripping. Considering the high BTEX emissions in the other cases, it implies that these methods would require additional investment in equipment to condense and collect these compounds.

The reliability of the model is related to the attained lean TEG purities. For the base case the achieved purity was 98,9 % by weight, which corresponds to values found in the literature. The highest lean TEG purity obtained was with the Stahl method, 99.79 % by weight followed by the Coldfinger, 99.59% by weight. The Drizo, Stripping and Vacuum methods obtained respectively of 99.47, 99.45 and 99.42 % by weight TEG purity. The Coldfinger values were in the vicinity of the suggested literature value of 99.7% by weight TEG purity [6]. Despite the literature suggesting that the Drizo method can achieve TEG purity levels as high as 99.99 % by weight [6], those values were not reached in this simulation.

12. FUTURE WORK AND IMPROVEMENTS

The simulation created in this thesis was based on simplified models. Therefore, more intrinsic aspects of the design such as sizing of units were not addressed in this work.

Even though there were no convergence problems with the absorber and TEG regenerator columns, there were temperature cross issues in the heat exchangers, occurring at very low lean TEG flow rates. It is recommended that a series of heat exchangers should be implemented in order to avoid this issue in the future. The matter was not addressed in this simulation since it did not affect the final results and there were time constrains.

The Hysys simulation presented used the Glycol Package. It could be interesting to perform the simulation with other CEOS to see the differences between different packages provided by Hysys, since the Glycol Package supposedly works better for non-ideal liquid mixtures containing significant amount of water and TEG.

The implementation of the Coldfinger apparatus in Hysys is suggested since it is not provided in the process simulator program.

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