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Modeling of the Coldfinger Water Exhauster for Advanced TEG Regeneration in Natural Gas Dehydration

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The performance of natural gas dehydration using triethylene glycol (TEG) strongly depends on the purity level of TEG in the regeneration unit. Coldfinger is a TEG regeneration technology reported to be capable of increasing TEG purity to levels above 99.8 wt.%, but conceptual models of this equipment appear to be lacking. This work presents a methodology for modeling Coldfinger, where the equipment is represented as two theoretical equilibrium stages operating at different temperatures in the presence of internal vapor recirculation. The key parameters governing the functioning of the equipment are discussed on the basis of a series of simulations carried out for different top temperatures and internal recirculation ratios. The results demonstrate that a regeneration of TEG up to approximately 99.9 wt.% is achievable by injecting small amounts of dry gas, considerably lower than conventional enhanced TEG regeneration by gas stripping.

1. Introduction

Natural gas produced from reservoirs is often saturated with water. In current industrial practice, the concentration of water in the export gas stream should be maintained at low levels, typically in the range of 70 to 120 mg/Nm³, in order to avoid severe operational problems such as water condensation, corrosion and hydrate formation. Absorption by means of triethylene glycol (TEG) is the most common natural gas dehydration method applied to reach required water contents. The efficiency of the absorption process is mainly subjected to the purity levels of TEG attainable in the regeneration stage, which is typically carried out by distillation at ambient pressure and maximum reboiler temperature of 204 °C (TEG degradation onset temperature). Under these conditions, the maximum TEG purity achieved is roughly 99 wt.%. For this reason, several advanced regeneration processes have been implemented in oil and gas production to comply with current water content specifications, which means higher levels of TEG purity and consequently higher efficiency in the gas dehydration process (Gironi et al., 2007a).

One of these processes is the Coldfinger technology, which basically consists of a water exhauster integrated with the basic distillation column and fed by TEG leaving the reboiler. In the exhauster, TEG is further dehydrated by continuous vaporization coupled with partial condensation and removal of the vapor at the top of the equipment, where a cold pipe (i.e. the “cold finger”) is located. It is typically reported that, using this technology, TEG purity around 99.2 to 99.5 wt.% is achievable (GPSA, 2012). Even though the Coldfinger technology was disclosed in 1971 (Reid 1971), to this day available commercial process simulators are not provided with a Coldfinger unit per se and only few studies report models for the Coldfinger unit. For instance, Gironi et al. (2007a) and Øi and Selstø (2002) reported strategies for modeling the water exhauster by means of an external routine and the commercial process simulator Aspen HYSYS®; however, neither of them disclosed a model of the equipment based on its physical principles. Finally, Rahimpour et al. (2013) presented a methodology for modeling an industrial Coldfinger unit, which incorporates the injection of hot stripping gas. Their model is based on segmenting the equipment in sub-systems and coupling heat transfer calculations with phase equilibrium. However, TEG/water ratio in the condensates is taken equal to the value in the vapor, which is apparently not the case for TEG/water mixtures.

This work presents a different approach for modeling the Coldfinger water exhauster, which is represented as a two-equilibrium stage unit with internal recirculation of the vapor. An in-depth study of the Coldfinger

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performance depending on process parameters such as the temperature of the cooling pipe, the internal recirculation ratio and the amount of injected stripping gas is presented.

2. Methodology

2.1 Conceptualization and modeling

The Coldfinger water exhauster, represented in Figure 1a, is an easy-to-install technology that consists of a cooling U-pipe placed in the vapor space of the vessel containing the TEG coming from the reboiler of the regeneration column. Such vessel can be either a separate equipment (surge tank) or an integrated section of the reboiler itself. Additionally, the water exhauster is provided with a tray placed right under the cooling pipe, where the condensate of the vapor mixture in the proximities of the Coldfinger is collected and sent back to the reboiler. TEG from the reboiler enters the Coldfinger at a purity around 98.7-99.0 wt.%, under reboiler conditions of 204 °C and atmospheric pressure (GPSA, 2012), being a water-saturated liquid at the mentioned conditions. Since the bottom section of the Coldfinger operates practically at the same pressure and temperature of the reboiler (GPSA, 2012), a change in the overall system composition is necessary to shift the equilibrium conditions and obtain TEG at higher purity levels. This can be achieved by injection of small quantities of dry gas and recirculation of the uncondensed gas and vapours from the top to the bottom of the equipment. The Coldfinger internal recirculation is driven by natural convection due to the temperature difference between the bottom and the top section of the vessel.

Considering the above mentioned, the Coldfinger is modeled as two contiguous compartments where two-stage phase equilibrium takes place, as represented in Figure 1b. The first compartment (bottom section) contains the enhanced regenerated TEG (L_1) in equilibrium with its vapor (V_1) due to the constant injection of stripping gas (G_0) to the liquid stream coming from the reboiler (L_0). The second compartment (top section) receives the vapor coming from the bottom section (V_1), which is partially condensed due to the temperature drop caused by the cold fingers. The liquid condensed on the surface of the cooling pipe and removed from the vessel (L_2) is in equilibrium with the uncondensed vapor (V_2). The natural convection is here represented by considering a continuous reflux of a certain amount of the vapor generated in the second compartment to the first one (V_{2R}). The study is performed considering pure methane as the stripping gas injected at the bottom section and a binary mixture of water-TEG coming from the reboiler, thus obtaining a three-component system inside the Coldfinger formed by methane (1) – water (2) – TEG (3). Although the dry gas available in dehydration units is not pure methane and the liquid stream coming from the reboiler contains also traces of other chemical species, the components other than the three reported above are present in small amount; therefore, they are neglected in this conceptual study. From preliminary simulations, the cooling of the bottom section caused by the mixing of the recirculated uncondensed vapor is seen to be less than 2 °C due to the small amount of the internal recirculated vapor compared to the TEG-rich stream from the reboiler. Consequently, this effect is neglected, and the temperature of the bottom section is fixed at the same temperature of the reboiler (204 °C). The study presented in this work focuses on the effect of the temperature at the top section of the Coldfinger, which depends on the heat power removed from the system, and on the internal recirculation, which depends on the temperature difference between the two sections of the equipment and on its design.

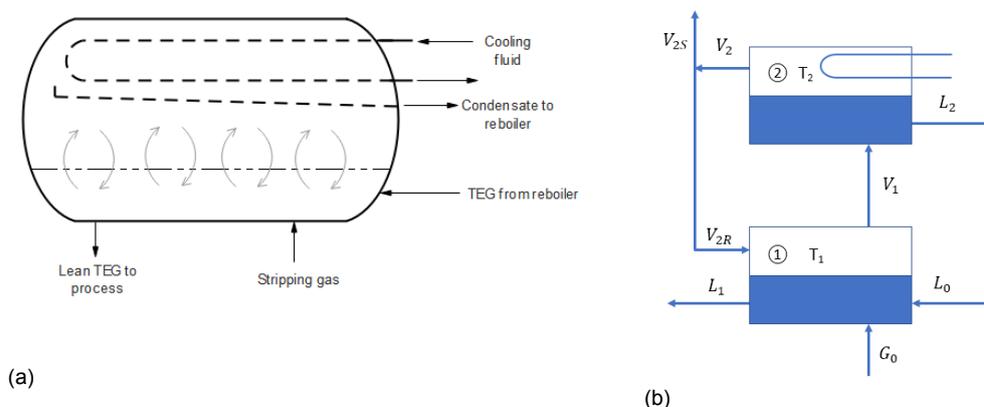


Figure 1: Schematic representation of the Coldfinger water exhauster. (a) Equipment configuration. (b) Conceptual model apparatus.

2.2 Thermodynamic model

The thermodynamic model used for the Coldfinger water exhauster is based on the Peng-Robinson equation of state (EOS) and the classic form of the quadratic mixing rules (van der Waals mixing rules). The critical parameters and acentric factor of the three components of the system under study are shown in Table 1. Data for methane are taken from Perry (1999), whereas data for water and TEG are taken from Gironi et al. (2010).

Table 1: Critical parameters and acentric factors for CH₄ (1), water (2) and TEG (3).

Component	Pc, MPa	Tc, K	Acentric factor
Methane, CH ₄	4.59	190.564	0.011
Water, H ₂ O	22.12	647.3	0.344
TEG	3.958	806.3	0.563

The binary interaction parameters (κ_{12}) were taken or regressed from available literature data. Gironi et al. (2007b, 2010) reported a linear relation of κ_{12} with respect to temperature for the TEG-water binary system, which is used in this work. For the CH₄-water and CH₄-TEG binary systems, the binary interaction parameters were obtained by regression of experimental data of solubility of CH₄ reported in previous works, considering the minimization of the objective function (ϕ) presented in Eq(1).

$$\phi = \sum_{i=1}^N (x_{exp} - x_{calc})_i^2 \quad (1)$$

where, x_{exp} and x_{calc} are the experimental and calculated mole fractions of CH₄ in the liquid phase, respectively; the subscript i stands for the i -th experimental data, while N represents the total number of experimental data.

For the system CH₄-TEG, Jou et al. (1987) reported several T-P-x experimental data for different values of temperature ranging from 298.15 to 398.15 K and pressures up to 20 MPa. Regarding the system CH₄-water, two sets of experimental data were analyzed. The first set comprises the values reported by Chapoy et al. (2004), who reported several T-P-x experimental data at low temperatures ranging from 275.11 to 313.11 K and pressures up to 18 MPa. The second set of experimental data comprises the experimental T-P-x values reported by Culberson and McKetta (1951), which corresponds to measurements at temperatures from 298.15 to 410.93 K and pressures up to 68.95 MPa. After minimization of the objective function of each set of data for the system CH₄-water, the values of the calculated κ_{12} were very close, leading to neglect the overall effect of such difference and consider the results obtained with the experimental values from Culberson and McKetta (1951). As a result, a linear relation of κ_{12} with temperature for the binary systems CH₄-TEG and CH₄-water is found, with an average absolute deviation (AAD) of 0.0021 and 0.000085, respectively. The values of the binary interaction parameters for the ternary system considered for modeling the Coldfinger water exhauster are summarized in Table 2.

Table 2: Functions of the binary interaction parameters for the CH₄-water-TEG system.

Binary System	$\kappa_{12}(T)$
CH ₄ -water	$k(T) = 0.00251 T - 1.05038$
CH ₄ -TEG	$k(T) = 0.00030 T + 0.1328$
TEG-water	$k(T) = 0.000482 T - 0.3935$

Temperature in K.

With the selected thermodynamic model for the system TEG-water, the calculated TEG purity of the liquid leaving the reboiler (and entering the bottom section of the Coldfinger) at 204 °C and atmospheric pressure is 99.0 wt.%, which is in line with the value of TEG purity typically obtained in the Oil & Gas industry, corresponding to 98.7-99.0 wt.% (GPSA, 2012).

3. Results and Discussion

The performance of the Coldfinger water exhauster was analyzed with respect to the internal vapor recirculation (α) and the gas-to-liquid feed ratio (β), defined as:

$$\alpha = \frac{V_{2R}}{V_2} \quad (2)$$

$$\beta = \frac{G_0}{L_0} \quad (3)$$

In addition, the performance was also analyzed as a function of the temperature of the top section (T_2). The internal vapor recirculation was varied on four levels, ranging from 0 to 0.8. The base case of analysis corresponds to $\alpha = 0$, where no vapor from the top section recirculates to the bottom section, representing a conventional single-stage stripping process. The gas-to-liquid feed ratio was varied from 0.001 to 0.01, values that are substantially lower than the ones typically used for enhanced regeneration of TEG by gas stripping. Finally, T_2 was varied from 204 °C, equivalent to no heat removal in the top section, down to 34 °C. The minimum temperature is consistent with the use of cold water as an external cooling agent through the Coldfinger.

The further TEG enrichment due to the Coldfinger is clearly seen, as compared to the base case (conventional stripping). For the minimum and maximum values of β under analysis (0.001 – 0.01), it is seen from Figure 3 that the purity of the enhanced regenerated TEG decreases as the temperature at the top section of the equipment increases. In addition, the shape of the curves shows that the Coldfinger process is not efficient when there is only little cooling of the vapor in the top section. This behavior is reproduced for all the values of internal vapor recirculation considered, except for $\alpha = 0$ where the regenerated TEG purity remains constant and independent from T_2 due to the absence of vapor recirculation.

Additionally, the effect of the gas-to-liquid feed ratio in the performance of the Coldfinger was analyzed for two given values of top temperature. As it can be seen in Figure 4, the purity of TEG increases as β and α increase as well. Furthermore, Figure 4 presents the purity of the liquid TEG leaving the reboiler of the regeneration column. It is clearly seen the significant enhancement in TEG purity achieved by means of the Coldfinger regeneration process. The maximum purity of TEG obtained by this means is 99.86 wt.%, corresponding to the case where the temperature at the top section is 34 °C (assumed maximum cooling), $\alpha = 0.8$ and $\beta = 0.01$.

From Figure 4 it can also be seen that, for a given TEG purity, the amount of stripping gas necessary to inject into the Coldfinger is considerably less than the amount needed in a single-stage stripping process, or $\alpha = 0$. For instance, for a TEG purity of 99.6 wt.% and T_2 of 34 °C, it would be necessary to inject into the Coldfinger a flow of dry gas equivalent to 0.2 % of the liquid feed (TEG entering the reboiler) considering an internal vapor recirculation of 0.8; while the same TEG purity (99.6 wt.%) would be achieved in a single-stage process by injecting a significant flow of dry gas equivalent to 0.8 % of the liquid feed.

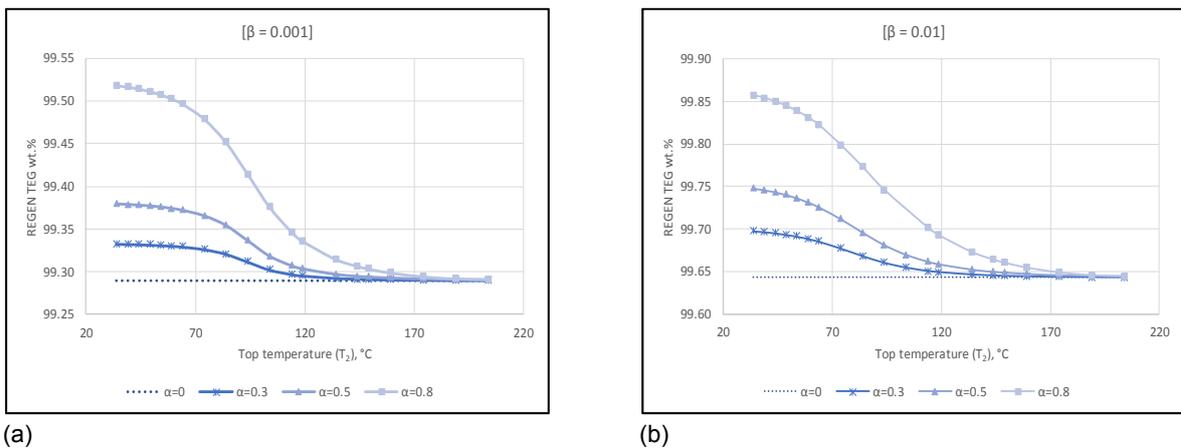


Figure 3: Influence of the temperature of the top section (T_2) on regenerated TEG purity obtained with the Coldfinger process, for different values of internal vapor recirculation (α) (a) $\beta = 0.001$ (b) $\beta = 0.01$.

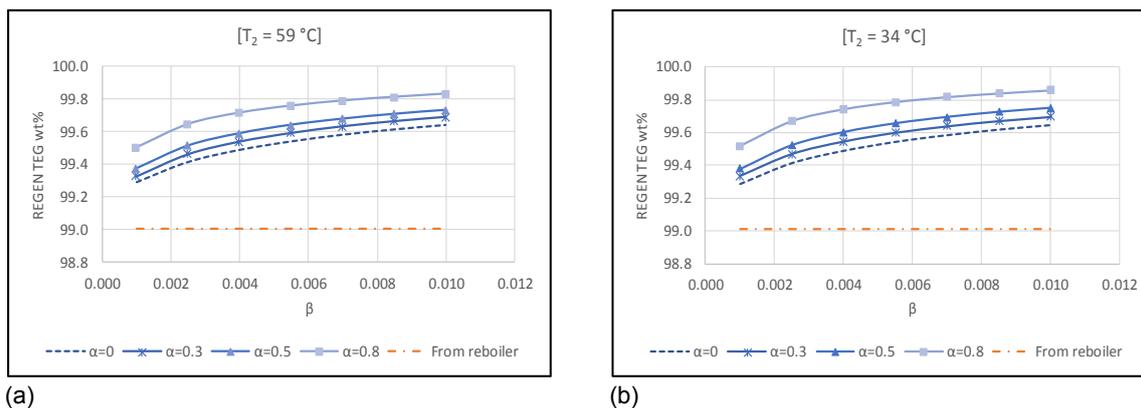


Figure 4: Variation of TEG purity (wt.%) as function of β for different values of internal vapor recirculation. (a) Top section temperature of 59°C . (b) Top section temperature of 34°C .

The effect of the temperature of the top section of the equipment can be analyzed through the composition of the recirculating vapor from the top to the bottom section and the amount of specific heat removed by the cooling pipe (expressed per kilogram of liquid feed). The heat removed from the system was calculated through an energy balance in the top section of the equipment for a steady state process. Latent heats of vaporization and heat capacities for each component of the ternary system were taken from Yaws (1999). Considering the conditions of α and β at which the maximum TEG purity is achieved, Figure 5a presents the mass fraction of methane as function of the top section temperature. It can be seen that the amount of methane present in the recirculating vapor decreases as T_2 increases up to a value of top temperature where it remains practically constant. This behavior demonstrates that, at lower top section temperatures, more water is condensed and removed from the Coldfinger and more methane will recirculate to the bottom section enhancing the stripping effect of the injected dry gas, for a given dry gas inlet in the bottom section.

Figure 5b shows the purity of enhanced regenerated TEG as a function of the specific heat removed. The results show that, as the amount of heat removed increases, more water is removed from TEG and its purity level increases, with the whole process becoming efficient in the “vertical” region of the S-shaped curve. At low values of heat removal, which correspond to high top temperatures as marked in the plot, the regeneration of TEG increases in a very small amount, meaning that the heat removal is not efficient since it is leading to poor condensation of water from the recirculating vapor. However, as more heat is removed, there is a considerable increase of the TEG purity. In this region, the condensation degree of the vapor at the proximities of the cooling pipe is effective and a significant amount of water is removed from the recirculating vapor. Finally, TEG purity increases up to a point where it shows an asymptotic trend, meaning that additional heat removal is not effective in further improving TEG regeneration.

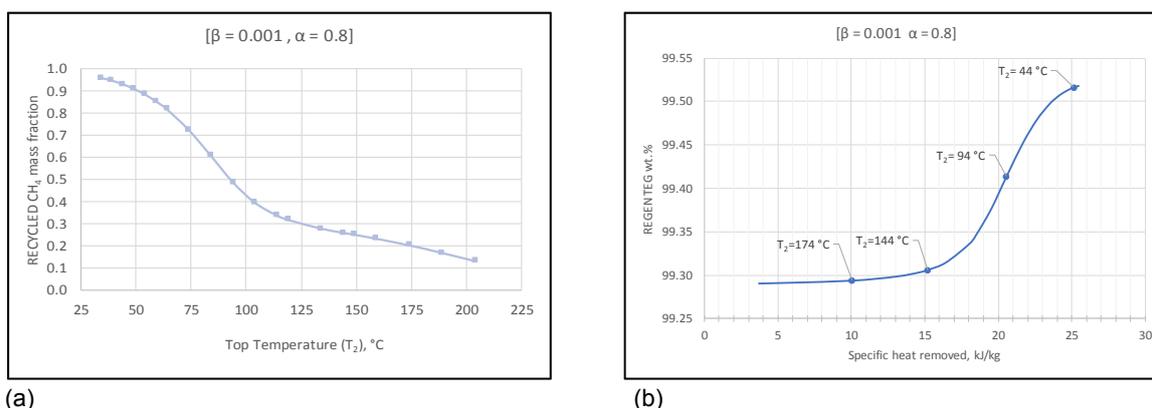


Figure 5: Influence of the top section temperature on the Coldfinger process for $\beta = 0.001$ and $\alpha = 0.8$. (a) Mass fraction of CH_4 in the recirculated vapor. (b) Purity of TEG (wt.%) as a function of the specific heat removed from the top section (per kilogram of feed).

4. Conclusions

Conceptual modeling of the Coldfinger water exhauster is successfully achieved by representing the equipment as a two-stage phase equilibrium system with internal recirculation of the vapor and different stage temperatures. Operating on simplified ternary system (CH₄-water-TEG), it is shown how the Coldfinger technology is able of increasing the purity of TEG up to approximately 99.9 wt.% in the regeneration process by using only a small fraction of the dry gas that would be needed in a single-stage stripping process. For instance, a TEG purity of 99.86 wt.% is obtained using the Coldfinger technology, considering an internal vapor recirculation ratio of 0.8 and a temperature of the top section of 34 °C, with an amount of stripping gas of approximately 1 % of the liquid feed entering the Coldfinger, whereas the same TEG purity could be achieved in a single-stage stripping regeneration process with an injection of stripping gas corresponding to 5 % of the liquid feed leaving the reboiler. This result is an example of quantification of the advantage of Coldfinger over the conventional stripping process.

Through the in-depth study of the parameters influencing the performance of the Coldfinger, it is seen that the internal vapor recirculation, along with the constant condensation of water on the surface of the cooling coil, exerts a strong influence on the achievable levels of TEG dehydration. These parameters are, in fact, the key conceptual parameters to explain the extent of the enhanced TEG regeneration with small amounts of injected dry gas. The heat removed from the top section of the apparatus shows, as well, that the purity of TEG depends strongly on the condensation capacity of the cooling pipe.

The results presented in this work demonstrate that it is possible to explain the behavior of the Coldfinger water exhauster based on thermodynamics. Consequently, the presented approach is suggested as a Coldfinger model for the conceptual design of the unit, to be implemented as a starting point for the equipment design.

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