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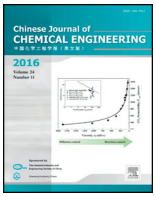

Article

A computational simulation study for techno-economic comparison of conventional and stripping gas methods for natural gas dehydration

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ABSTRACT

In the present work, the conventional natural gas dehydration method (CDM) and stripping gas method (SGM) are technically and economically analyzed, utilizing Aspen HYSYS and Aspen Process Economic Analyzer (APEA), respectively. To optimize the CDM and SGM, the sensitivities of the water content of dry gas, reboiler duty and raw material loss are analyzed against solvent rate and stripping gas rate. The optimized processes are set to achieve a targeted value of water content in dry gas and analyzed at optimized point. The analysis shows that SGM gives 46% lower TEG feed rate, 42% lower reboiler duty and 99.97% pure regenerated TEG. Moreover, economic analysis reveals that SGM has 38% lower annual operating cost compared to CDM. According to results, from both technical and economic point of view, SGM is more feasible for natural gas dehydration compared to CDM.

1. Introduction

Natural gas is among the most important and environmentally friendly fossil fuel. Its importance is increasing significantly in the industrial and domestic sectors [1] as it shares 24% of the total world's energy consumption [2,3]. When extracted, natural gas contains approximately up to 2000 $\mathrm{mg\cdot m^{-3}}$ water content [4], which can lead to several drawbacks including hydrate formations, corrosion of pipelines and reduction in the heat capacity [5]. The water content of dry gas is strictly regulated for pipeline transmission. In general, the limit for water content in natural gas is less than 120 $\mathrm{mg\cdot m^{-3}}$ in the U.S. and less than 70 $\mathrm{mg\cdot m^{-3}}$ in Canada [6]. Therefore, it is imperative to remove water vapors from natural gas before its transmission and combustion [7]. Several methods, such as absorption, adsorption, refrigeration, gas permeation and high ultra-sonic separation, have been used for natural gas dehydration [8]. Among these methods, the absorption *via* solvent is the most commonly adopted method because of its economic and technical benefits [9]. Moreover, tri-ethylene glycol (TEG) is the most widely used solvent for absorption, owing to its low volatility, high hygroscopicity and high thermal stability [10]. TEG dehydration process includes two basic units, namely absorber and regenerator. The regenerator is considered more important as it decides the cost of the whole process [11]. Besides the conventional thermal regeneration method, several methods are focused on intensifying the TEG regeneration process, such as stripping gas [12], Stahl column [13] and cold-finger methods [14]. Among all these methods, the conventional thermal method and the stripping gas method are widely employed in the industry, as they do not require extra equipment and raw materials [6].

Extensive simulation and experimental studies have been carried out to find the most suitable method and optimum parameters for the natural gas dehydration. Mohamadbeigy [15] performed the process simulation of a natural gas dehydration unit and studied the effect of different variables, such as the TEG flow rate, stripping gas flow rate and number of trays of the absorber, to improve the dehydration performance. Jacob [16] conducted similar research for process simulation and optimization of the Niger Delta gas dehydration unit, in terms of decreasing the water content of dry gas. Moreover, as increasing reboiler temperature leads to thermal decomposition of TEG, the results of his study suggested utilization of stripping gas instead of increasing reboiler temperature, to get a high purity of recovered TEG. El-Mawgoud *et al.* [11] revamped the Akik gas dehydration plant to reduce the equipment cost and energy consumptions involved in the process. To that purpose, a simulation model of the existing plant was developed on Aspen HYSYS and three diverse process modifications, based on equipment configuration, were proposed for the optimization of the

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plant. Nemati Rouzbahani *et al.* [17] performed a process simulation study with the aim to optimize a di-ethylene glycol (DEG) natural gas dehydration unit in Iran. A steady-state flowsheet simulator was utilized to develop the simulation model of the dehydration unit and Redlich-Kwong-Soave equation of state with Modified-Huron-Vidal (RKSMHV2 model) mixing rule was applied for simulations. Moreover, they employed sensitivity analysis technique for the parametric optimization of the process. Results from the process simulation and sensitivity analysis suggested an optimum 10% increase in the DEG molar flow rate for 6% reduction of the dry gas dew point, without having any significant increase in the energy consumption and volatile organic compounds emissions. Ghiasi *et al.* [18] utilized an entirely different approach by employing multilayer perceptron (MLP) neural network and least squares support vector machine (LSSVM) algorithm, to predict the optimum stripping gas rate. Experimental results were found in good agreement with predicted results with only less than 0.01% absolute average kelative deviation (AARD). Rahimpour *et al.* [19] studied the Sarkhun gas processing plant and performed the process simulation of the dew point adjustment unit. The objective was to improve the dew points of water and hydrocarbons by optimizing the operating conditions. After optimization, the dew points of water and hydrocarbons exhibit −10 °C to −26 °C and −5 °C to −9 °C reductions, respectively. Although extensive literature is available on the process simulation and optimization of the natural gas dehydration process, none of the researchers focused on process simulation study based on techno-economic comparison of different methods of natural gas dehydration, to present the most suitable method among them.

This study aims to find the feasible method for natural gas dehydration between the conventional dehydration method (CDM) and the stripping gas method (SGM). Technical and economic evaluation has been performed on Aspen HYSYS and Aspen Process Economic Analyzer (APEA), respectively. Firstly, the optimum parameters for the operation of CDM and SGM are found by the application of relative sensitivity function. Next, both optimized processes are made to achieve targeted specifications of outlet dry gas and analyzed at that state. Moreover, economic evaluation is performed for the calculation of total capital and operating costs of both processes. Finally, optimized CDM and SGM are compared from the technical and economic aspect to find the suitable method for natural gas dehydration between them.

Table 1
The wet gas composition used for simulation

	Componet/mol%
Methane (CH_4)	89.70
Ethane (C_2H_6)	3.10
Propane (C_3H_8)	1.48
i-Butane (C_4H_{10})	0.58
n-Butane (C_4H_{10})	0.30
i-Pentane (C_5H_{12})	0.10
n-Pentane (C_5H_{12})	0.05
Water (H_2O)	0.22
Nitrogen (N_2)	0.10
Carbon dioxide (CO_2)	2.82
Others	1.55

2. Process Description

Fig. 1 presents the simple flow diagram of the natural gas dehydration process utilizing TEG as a solvent. It contains two major sections: 1) absorption of water from natural gas using TEG as a solvent in the absorber and 2) regeneration of rich TEG in the regenerator. The Input natural gas composition and the initial operating parameters of the process are provided in Table 1 and Table 2, respectively.

It can be seen from Fig. 1, the wet gas feed enters from the bottom of the absorber and lean TEG feed enters from the top. The solvent flowing downwards absorbs water from the wet gas. The pressure of absorber is set according to the wet gas pressure, which is 110 MPa. After absorption, the dry gas leaves from the top of the absorber and rich TEG leaves from the bottom. The rich TEG then passes through the rich-lean heat exchanger for further increase in temperature. The purpose of the rich-lean heat exchanger is to conserve energy. Afterwards, rich TEG enters the flash column, which removes any trapped gases and volatile components. From the flash column, this rich TEG stream enters regenerator, which consists of a reboiler, a still column and a condenser on the top. The reboiler operates between 175 and 200 °C or usually 10 °C less than TEG decomposition temperature [20]. In the column, the water gets separated from the rich TEG stream by fractional distillation. From the top of the column, water vapors with a mixture of gases leave and a small fraction is condensed back to provide enough reflux that will assist the

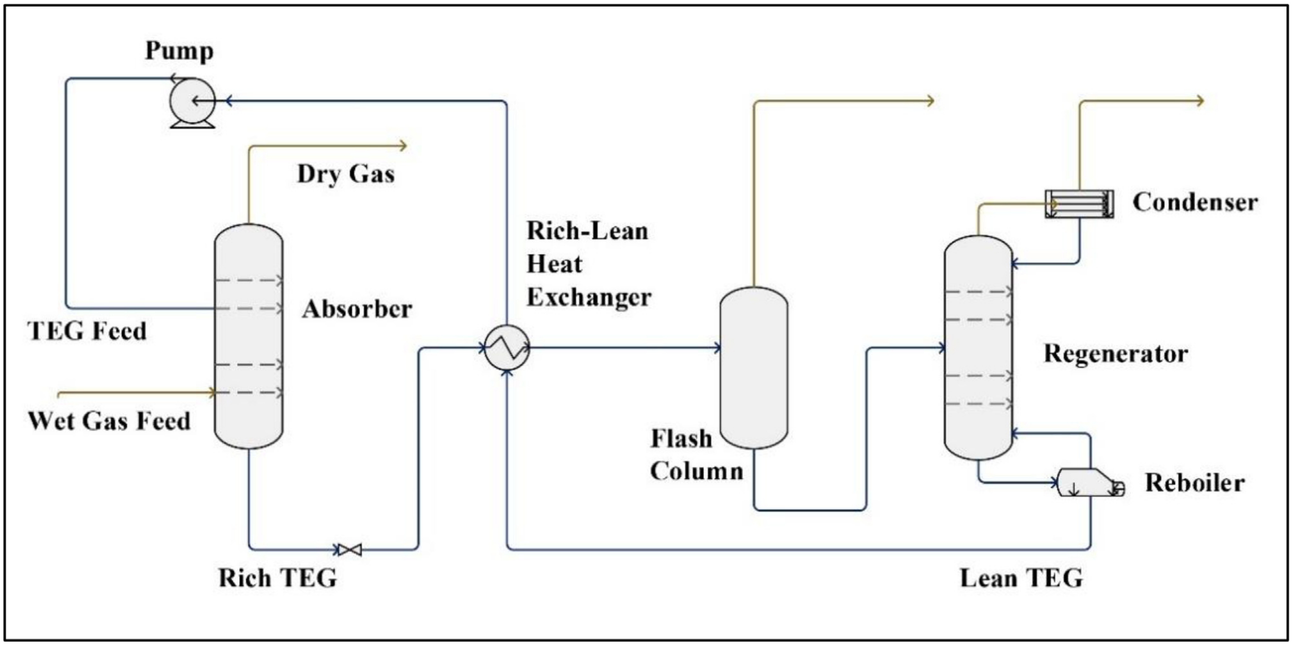

Fig. 1. Simple flow diagram of the natural gas dehydration process.

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Table 2
Initial operating parameters

Stream	Parameter	Value
TEG Feed	Temperature/°C	57.13
	Pressure/MPa	110
	Flow rate/$kg\cdot h^{-1}$	5200
	Purity/wt%	98.86
Wet Gas feed	Temperature/°C	47
	Pressure/MPa	110
	Flow rate/$m^3\cdot d^{-1}$	6518573
	Purity (Water Content)/$mg\cdot m^{-3}$	1765
Stripping gas	Flow rate/$kg\cdot h^{-1}$ ($m^3 h^{-1}$)	43.55
	Temperature/°C	40

fractionation process. From the bottom, Lean TEG leaves which is then recycled back to the absorber by passing through the rich-lean heat exchanger for temperature reduction. A pump is utilized to increase the pressure and maintain the circulation rate of TEG entering the absorber.

Both CDM and SGM have the same equipment configuration, *i.e.*, contactor column for absorption and regenerator for regeneration. The only difference is the injection of a stripping gas stream in the reboiler of the regenerator in SGM. According to Raoult's law, stripping gas decreases the vapor pressure of water vapor and it moves out with the gas stream, resulting in pure TEG [6]. Up to 99.9 wt% pure TEG can be achieved using SGM while CDM gives only up to 98.9 wt% purity [1]. The commonly used stripping gas for the regeneration process is a part of dry gas, leaving the absorber [6].

3. Simulation Model

As mentioned earlier, industrial simulation software, Aspen HYSYS is utilized in the present work. The Aspen Technology recommended glycol property package has been employed for calculations. This property package comprises of TST (Twu-Sim-Tassone) equation of state, which precisely calculates the phase behavior for water-TEG mixture with the critical compressibility factor (Z) equals to 0.296296 [21]. It represents the compressibility more accurately than other methods like the Redlich-Kwong (RK) equation of states, including the Soave modified version, and the Peng and Robinson (PR) equation of state.

The glycol package has the essential pure and binary interaction parameters for components usually used in the dehydration process. It is adjusted to present precise phase behavior of dehydration process components, particularly for the binary system of TEG-water. The Glycol package utilizes the Cavett model for calculations of enthalpy and entropy [22]. It is applicable over the range of pressures, component concentration and temperatures encountered in a typical water-TEG system. The precision of expected hydrocarbons solubility in the aqueous phase is predicted to lie within the improbability of experiments [22]. Table S1 represents the equilibrium water content prediction in lb. H_2O/MMSCF for a wet gas stream in interaction with 99.5% (by mass) TEG, using the Glycol property package, while Table S2 represents the prediction of the dew point temperatures of water-vapor in equilibrium with TEG solutions, from the TST equation of state in comparison with the GPSA recommended model for TEG dehydration [23]. Tables S1 and S2 are evincing the validity of TST equation of state used in glycol package, which shows that the glycol package can predict accurate results and can be used for developing a TEG dehydration simulation model.

4. Results and Discussions

4.1. Sensitivity analysis

Operating parameters of CDM and SGM are optimized using the sensitivity analysis technique. During this simulation study, independent and dependent parameters are under investigation. Independent parameters are the number of trays for absorber, TEG feed rate and stripping gas feed rate, while the dependent parameters are water content of dry gas, reboiler duty, TEG loss, methane loss and TEG purity at regenerator bottom. To find the most suitable values, independent parameters are optimized by modifying and observing their effects on dependent parameters.

Sensitivity analysis is an effective method for validating engineering works, simulations and understanding their primary systems. It is a unique technique, but until now, only a few researchers have utilized it. In this technique, one can observe the effect on dependent parameters by changing the independent parameters to inspect the performance of the process. The result of sensitivity analysis will help in determining the most sensitive parameters which affect the performance of the process. The relative-sensitivity function is another technique to perform optimization. If it is desired to analyze the effects of different operating parameters, one should use relative-sensitivity functions. Eq. (1) represents the relative sensitivity of the dependent parameter (F) to the

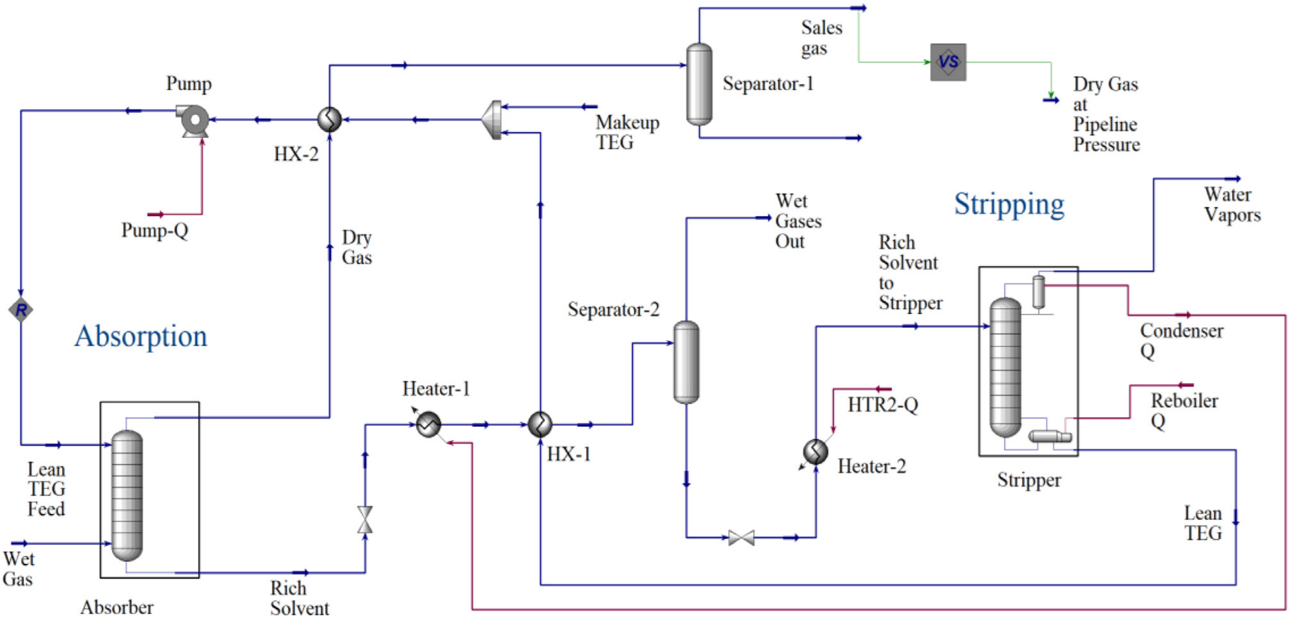

Fig. 2. Aspen HYSYS Process flow diagram of CDM.

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independent parameter (α), calculated at the normal operating point [24].

$$\bar{S}_{\alpha}^{F}=\left.\frac{\partial F}{\partial \alpha}\right|_{\mathrm{NOP}}\times\frac{\alpha_0}{F_0}\approx\frac{F\ \text{Change in percentage}}{\alpha\ \text{Change in percentage}} \tag{1}$$

Where, $\bar{S}_{\alpha}^{F}$ is relative sensitivity of dependent parameter 'F' to independent parameter 'α'. Subscript 'NOP' indicates that all parameters and functions are at normal operating points. The detailed calculation and algorithm of calculating '$\bar{S}_{\alpha}^{F}$' are provided in supporting information Section 2. Relative sensitivity is a dimensionless function. Thus, for a multi-variable process, it can be utilized to analyze the relative influence of given operating parameters.

4.1.1. Conventional dehydration method (CDM)

Firstly, the operating parameters of CDM are investigated to optimize the process. The initial parameters for feed are given in Table 2. The number of trays for absorber and regenerator is 5 and 3, respectively; as these values are found to be most feasible for the process (the detailed result is shown in supporting information Section 3). The reboiler temperature is fixed at 200 °C. The process flow diagram (PFD) of CDM has been shown in Fig. 2.

TEG feed rate is one of the most critical parameters determining the performance of the process. The goal is to reduce the water content value in the dry gas to the maximum extent, which requires a higher TEG feed rate. However, increasing the TEG feed rate will increase the TEG and methane losses, which resultantly increase the cost of raw material loss. In this case study, different flow rates of TEG are employed to observe the effect on the water content of dry gas, reboiler duty and raw material loss. The result is noticeable; increasing the TEG feed rate decreases the water content, as it will have more capacity to absorb water. However, this increase will also raise the heat duty, as more solvent will result in more heat duty in reboiler. Furthermore, the rise in TEG rate will result in higher TEG and methane losses. The reason for higher TEG loss is entrainment caused by wet gas. However, these losses become constant at the equilibrium point. On the other hand, methane losses increase exponentially, as more TEG rate will result in the absorption of a part of methane and other gases. Fig. 3(a), (b) and (c) depict these effects, respectively.

The relative sensitivities of all dependent parameters against the TEG feed rate have been calculated for CDM by Eq. (1). The detailed calculation and algorithm are provided in supporting information Section 2. Fig. 4 shows the relationship between relative sensitivities of dependent parameters and the TEG feed rate for CDM. From Fig. 4, the sensitivity of water content of dry gas increases promptly at the start and reaches its peak at around 1000 $\mathrm{kg\cdot h^{-1}}$ of TEG feed. Afterwards, it rapidly starts decreasing and finally became constant at about 4000 $\mathrm{kg\cdot h^{-1}}$.

In case of reboiler heat duty, its sensitivity is almost constant, which depicts that increasing the feed rate will linearly increase the heat duty. The sensitivity of methane loss increases in the start and then became constant after 2500 $\mathrm{kg\cdot h^{-1}}$. In the case of TEG losses, sensitivity is quite high in the beginning and then gradually starts decreasing, until it became constant at around 2500 $\mathrm{kg\cdot h^{-1}}$ of feed rate. From Fig. 4, the water content of dry gas is the most sensitive parameter to the change in the TEG rate. Furthermore, the sensitivity of water content is decreasing after 1000 $\mathrm{kg\cdot h^{-1}}$ and almost becoming constant at 4000 $\mathrm{kg\cdot h^{-1}}$. However, at 4000 $\mathrm{kg\cdot h^{-1}}$, the reboiler duty and raw material losses are high. Moreover, from Fig. 3(a), there is no significant decrease in water content after 2500 $\mathrm{kg\cdot h^{-1}}$. So, increasing the rate will come at the expense of high reboiler duty and raw material losses. Therefore, the optimum TEG feed rate is 2500 $\mathrm{kg\cdot h^{-1}}$. At this rate, the water content of dry gas is 58.84 $\mathrm{mg\cdot m^{-3}}$ (from Fig. 3(a)) which is considerably below standard limit.

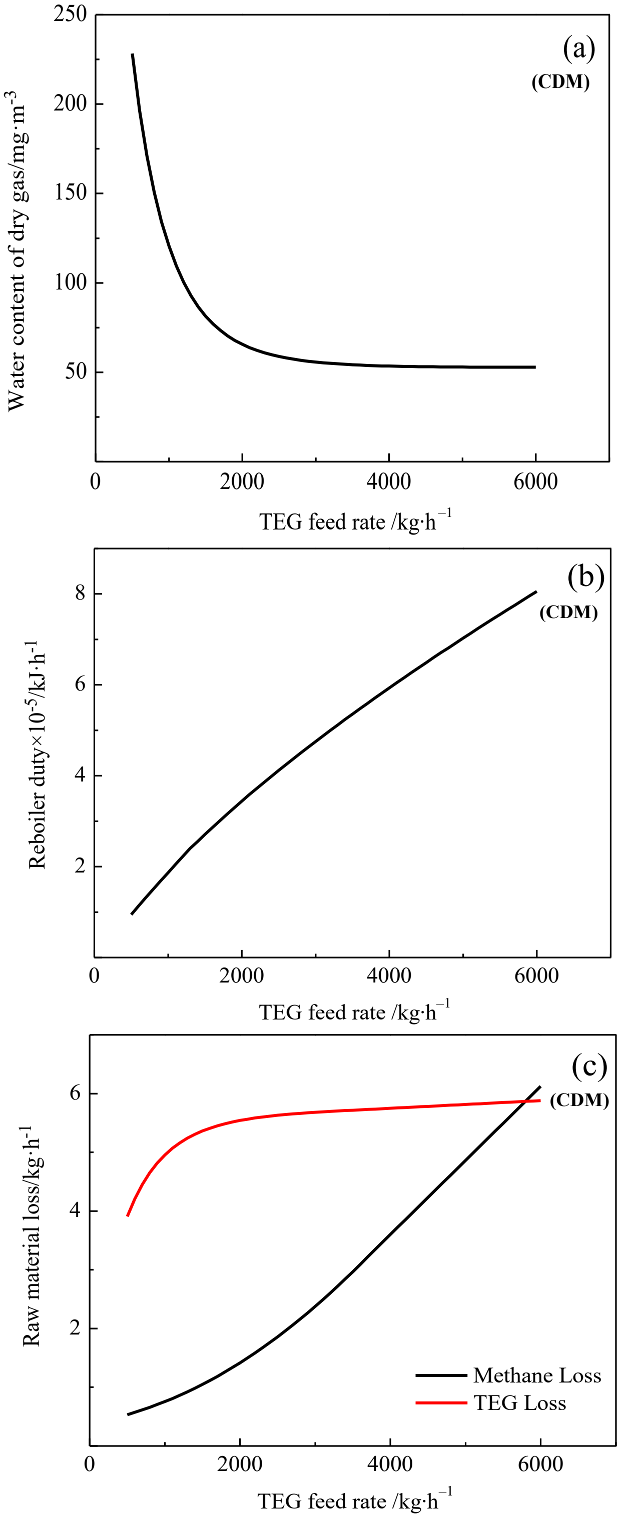

Fig. 3. Effect of TEG feed rate on (a) water content of dry gas; (b) Reboiler duty; (c) TEG and Methane losses for CDM.

4.1.2. Stripping gas method (SGM)

The next technique is to include stripping gas in the process, to observe its effect on the purity of TEG and to evaluate the overall performance for process optimization. In this study, a part of dry gas from the top of the absorber is utilized for stripping in the regenerator. The PFD is shown in Fig. 5. The Process is like CDM, except a new stripping gas stream is introduced in the regenerator from reboiler. Initial input

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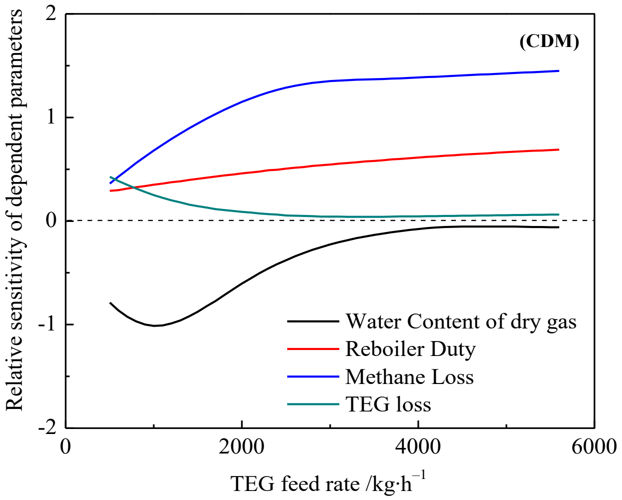

Fig. 4. TEG feed rate *vs.* relative sensitivities of dependent parameters for CDM.

parameters for SGM are the same as CDM and are shown in Table 2. Likewise, for this case study, 5 number of trays for absorber and the same wet gas feed is used. The number of trays for regenerator is 3 and the reboiler temperature is fixed at 200 °C.

4.1.2.1. Effect of TEG feed rate. The impact of TEG feed rate on the water content of dry gas, reboiler heat duty and raw material loss is investigated. Fig. 6(a), (b) and (c) show the effect of TEG feed rate on these dependent variables, respectively. It is apparent from Fig. 6(a), by increasing the TEG feed rate, the water content of dry gas will decrease. In Fig. 6(b), increase in TEG feed rate is linearly increasing heat duty of reboiler, as more solvent will result in more stripping duty. Next, the effect of TEG feed rate on TEG losses and methane losses is observed. As discussed in CDM, increasing TEG rate will result in less entrainment and more flooding in the absorber.

Therefore, there is a rise in TEG loss from start and then loss becomes almost constant after 2000 $\mathrm{kg \cdot h^{-1}}$ feed rate. On the other hand, methane losses are increasing exponentially. Fig. 6(c) shows the effect of TEG feed rate on TEG and methane losses for SGM. The trends are exactly like CDM. Similarly, for SGM, the relative sensitivities of all dependent parameters have been plotted against the TEG feed rate in Fig. 7.

It is evident from the figure that the water content of dry gas is the most sensitive parameter. Here, 2000 $\mathrm{kg \cdot h^{-1}}$ is the most sensitive feed rate for water content value, and after this point, sensitivity starts decreasing. Moreover, the heat duty of the reboiler shows almost constant sensitivity. Methane losses are increasing with an increase in sensitivity and then became constant after 2500 $\mathrm{kg \cdot h^{-1}}$. For TEG losses, sensitivity decreases from the start and then reaches a constant value at around 2500 $\mathrm{kg \cdot h^{-1}}$. These trends depict that the water content of dry gas is the most sensitive parameter to the change in TEG rate. Hence, it will determine the optimum TEG feed rate. From Fig. 7, the sensitivity of water content is highest at 2000 $\mathrm{kg \cdot h^{-1}}$, then became zero at around 3900 $\mathrm{kg \cdot h^{-1}}$ and finally became constant after 5000 $\mathrm{kg \cdot h^{-1}}$. However, from Fig. 6, increasing TEG feed rate above 2500 $\mathrm{kg \cdot h^{-1}}$ will not decrease water content effectively but will result in more heat duties, operating cost and raw material losses. Besides, at 2500 $\mathrm{kg \cdot h^{-1}}$ water content of dry gas is 15.48 $\mathrm{mg \cdot m^{-3}}$, which is well below the limit. Therefore, 2500 $\mathrm{kg \cdot h^{-1}}$ is the optimum feed rate for SGM.

4.1.2.2. Effect of stripping gas rate. Stripping gas rate is having a significant effect on TEG purity and TEG losses. For this case study, the 3 trays for the regenerator and optimum TEG feed rate of 2500 $\mathrm{kg \cdot h^{-1}}$ have been used. Rich TEG stream is being added at 180 °C into the regenerator. Stripping gas has been injected from the reboiler that flows upward in the column. Fig. 8 shows the relation of stripping gas rate with TEG purity and TEG losses. In this case, increasing stripping gas rate will increase TEG purity. The reason is apparent; more stripping gas suppresses the vapor pressure of water vapor and forces it to travel more towards the top, into the condenser [6]. TEG purity increase in the start with an increase in stripping gas rate and then almost became constant after 300 $\mathrm{kg \cdot h^{-1}}$ of stripping rate (378.7 $\mathrm{m^3 \cdot h^{-1}}$). Next, the effect of stripping gas rate on TEG loss is investigated. For fixed rich TEG feed, the increase in stripping gas rate will increase the loss of TEG from the top of the column due to entrainment. The relation between TEG loss and stripping gas rate is shown in Fig. 8. Higher the stripping gas rate higher will be the TEG losses.

To find the optimum stripping gas rate, the sensitivities of TEG purity and TEG losses against the stripping gas rate have been observed. In this case, the TEG feed and rich TEG temperatures are fixed. Fig. 9 depicts the relative sensitivities of TEG losses and TEG purity for SGM. According to the figure, TEG purity is the most sensitive parameter showing a peak at

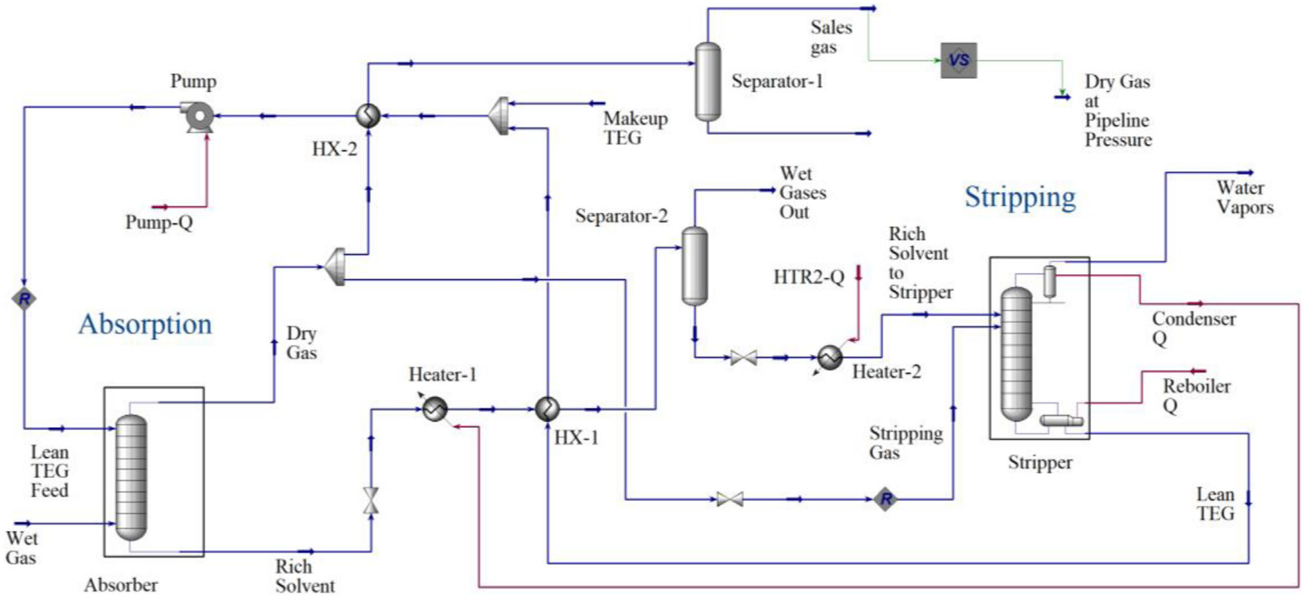

Fig. 5. Aspen HYSYS process flow diagram of SGM.

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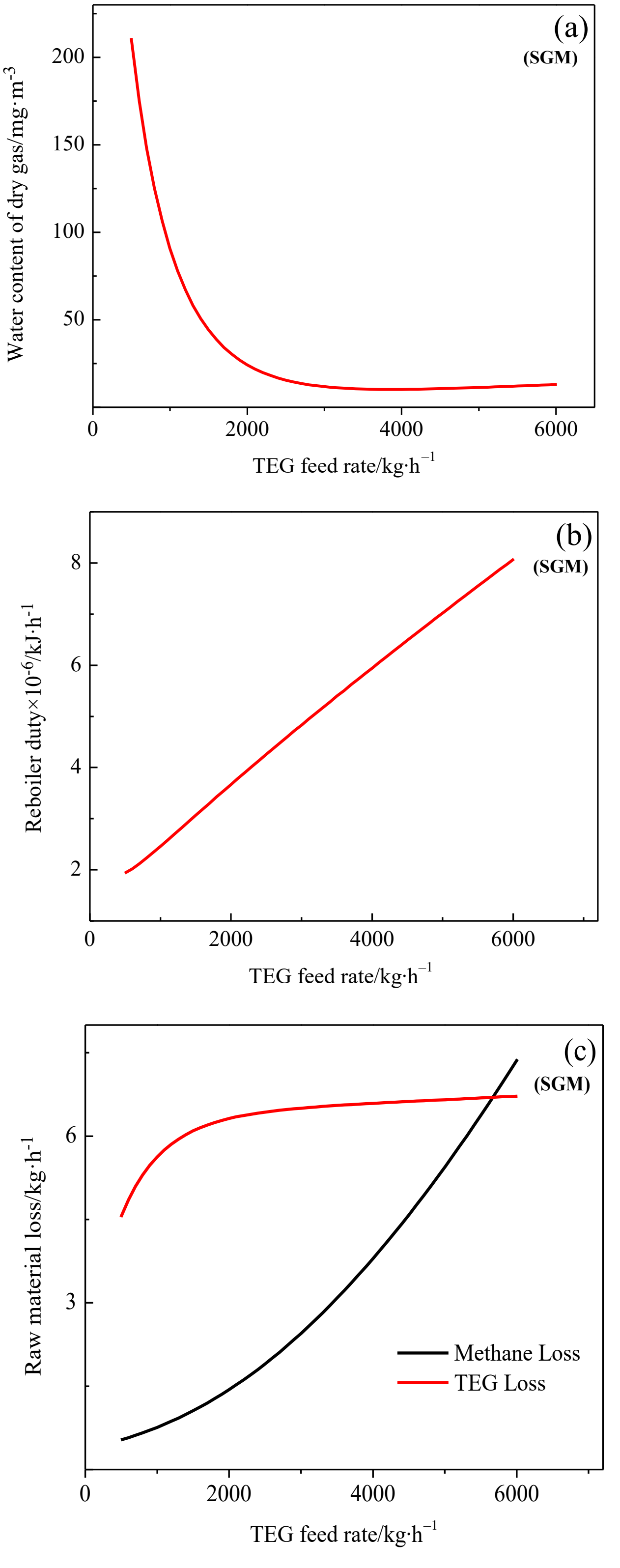

Fig. 6. Effect of TEG feed rate on (a) water content of dry gas; (b) Reboiler duty; (c) TEG and Methane losses for SGM.

around 100 $kg\cdot h^{-1}$ and decreasing gradually afterwards, while TEG losses are becoming less sensitive as the rate is increasing and the change is almost constant after 300 $kg\cdot h^{-1}$ of stripping rate. Moreover, from Fig. 8, increasing the stripping gas rate above 300 $kg\cdot h^{-1}$ will not significantly increase the TEG purity but will increase TEG losses. Therefore, in this case, 300 $kg\cdot h^{-1}$ (378.7 $m^3\cdot h^{-1}$) is found as the optimum stripping rate of dry gas.

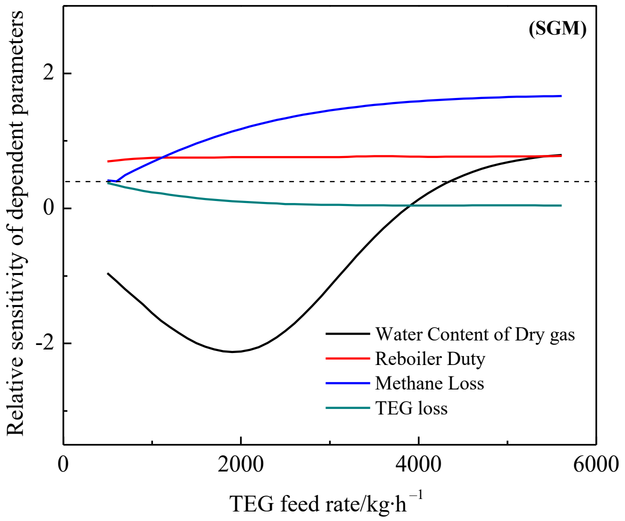

Fig. 7. TEG feed rate *vs.* relative sensitivities of dependent parameters for SGM using.

4.2. Optimum results for the fixed target output specifications of dry gas

After sensitivity analysis and optimization of CDM and SGM, further improvement can be made by making both optimized processes achieve a fixed target output specification of dry gas, *i.e.*, 60 $mg\cdot m^{-3}$ of water content and 16 dew point.

Firstly, CDM is made to achieve the required target water content in dry gas. For CDM, the optimum TEG feed rate after sensitivity analysis gives 58.84 $mg\cdot m^{-3}$ water content value. Furthermore, to change the water content value, one of the independent parameters must be modified. According to Fig. 4, the TEG feed rate is the most sensitive parameter for change in the water content of dry gas. Therefore, we can achieve the target value of the water content of dry gas by only adjusting the TEG feed rate. From Fig. 3(a), by further decreasing the TEG feed rate from 2500 to 2370 $kg\cdot h^{-1}$, we can achieve our target water content value, *i.e.*, 60 $mg\cdot m^{-3}$.

In the case of SGM, after sensitivity analysis, we get 15.48 $mg\cdot m^{-3}$ water content in dry gas. This result is much better than our required target output. Like CDM, the target value of water content of dry gas can be reached in SGM by varying the TEG feed rate, as the water content of dry gas is the most sensitive to change in the TEG feed rate. The TEG purity is kept constant at 99.97% and specifications of absorber and regenerator are fixed. The only variable parameter here is TEG feed rate. From Fig. 6(a), by decreasing the TEG feed rate from 2500 $kg\cdot h^{-1}$ to 1270 $kg\cdot h^{-1}$, 60 $mg\cdot m^{-3}$ of water content in dry gas can be achieved. Resultantly, the stripping gas rate decreased from 300 to 99.06 $kg\cdot h^{-1}$ (127.1 $m^3\cdot h^{-1}$). Table 3 shows the optimum results for the fixed output of dry gas for CDM and SGM.

From Table 3, for the fixed target output of dry gas, SGM gives 46% lower TEG feed rate and 42% lower reboiler duty than CDM. Hence, SGM is technically more feasible than CDM. Next, economic analysis will be performed to investigate both processes from an economic point of view.

4.3. Economic analysis

In economic analysis, CDM and SGM were evaluated at final optimum conditions for a fixed target output of dry gas. Total capital cost (TCC), total equipment cost (TEC), annual operating cost (AOC), annual utility cost (AUC), the annual cost of raw materials (ACR) for operations and annual cost for raw material loss (ACRL) are investigated. Aspen

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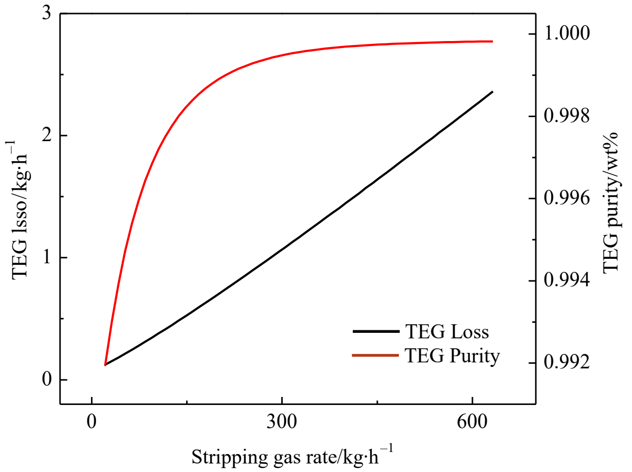

Fig. 8. Effect of Stripping gas rate on TEG purity (wt.%) and TEG loss (kg·h^{-1}).

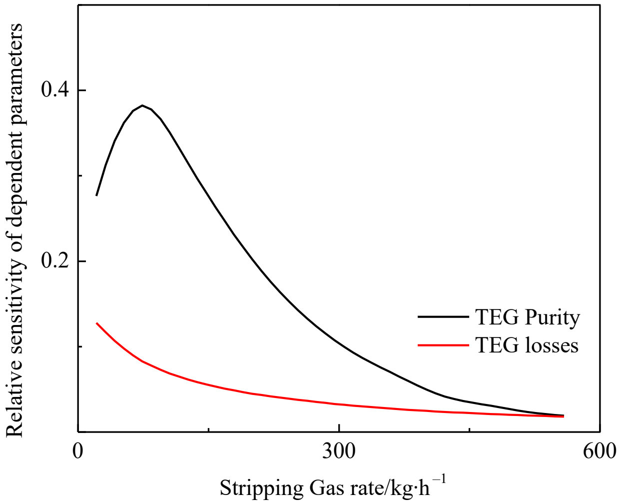

Fig. 9. Stripping gas rate *vs.* relative sensitivities of dependent parameters.

Table 4
Components of cost analysis

Cost item	Basis
TCC	Fixed capital investment (FCI) and working capital (WC)
FCI	TEC, piping cost, civil work, contractor's fee and contingencies
WC	10% of FCI
AOC	AUC, ACR, ACRL, operating labor and maintenance cost (OPMT), operating charges, plant overhead and general and administrative (G and A) expenses

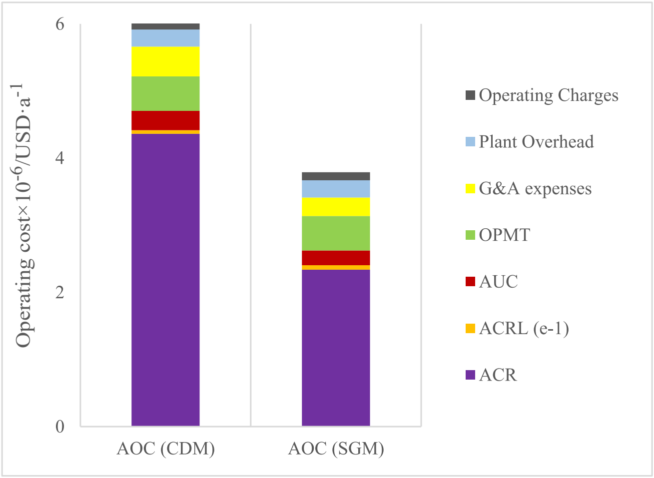

Fig. 10. Graphical breakdown representation of Annual Operating Cost (AOC) of SGM and CDM.

process economic analyzer (APEA) has been used for the economic study. Fixed parameters for economic evaluation are provided in supporting information Table S4. The purchase cost of TEG is 0.21 USD·kg^{-1} [25] while, the cost of natural gas is 6.23 USD·1000 ft^{-3} [26]. The working capital is considered as 5% of fixed capital investment per year. Furthermore, the cost of natural gas is not considered in ACR due to the fixed natural gas feed rate for CDM and SGM. However, the price of natural gas loss has been calculated. Similarly, the price of TEG loss is also calculated for both processes. Components of cost analysis are provided in Table 4.

After economic evaluation, the following results have been found. TCC for CDM (TCC_{CDM}) is 5.62 million USD, while the TCC of SGM (TCC_{SGM}) is 5.58 million USD. The decrease in TCC_{SGM} is due to decrease in TEG feed rate, which resultantly decreases TEC of the process, as the change in the feed rate will consequently change the equipment specifications. TEC for CDM is 0.42 million USD while TEC for SGM is 0.412 million USD. Detailed TEC for both processes is shown in supporting information Table S5.

Table 3
Optimum results for fixed output of dry gas

Equipment or stream	Operating parameters	Optimum value (CDM)	Optimum value (SGM)
TEG Feed	Flow rate/kg·h^{-1}	2370	1270
	Purity/wt%	98.95	99.97
Absorber	Number of stages	5	5
	Diameter/m	1.676	1.676
	Tray section height/m	3.048	3.048
Water Content of Dry Gas (fixed)	Purity/mg·m^{-3}	60	60
Regenerator	Number of Stages	3	3
	Diameter/m	0.4572	0.4572
	Packing height/m	1.372	1.372
Rich TEG to the regenerator	Temperature/°C	180	180
Reboiler	Heat duty/kJ·h^{-1}	3.943×10^5	2.298×10^5
Stripping gas	Flow rate/kg·h^{-1}(m^3·h^{-1})	N/A①	99.06 (127.1)
	Temperature/°C	N/A	25
	Pressure/MPa	N/A	0.101325 bar

① Stripping gas specifications are not available for CDM as no stripping gas is used in the process.

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Fig. 11. The percentage decrease in AUC, AOC, reboiler duty and TEG rate of SGM, compared to CDM.

Next, the AOC of both processes is calculated. AOC for CDM (AOC_{CDM}) is 5.984 million USD per year. while AOC for SGM (AOC_{SGM}) is 3.730 million USD per year. The decrease in AOC_{SGM} is due to decrease in TEG feed rate, which consequently decreases AUC and ACR. The ACR for CDM (ACR_{CDM}) is 4.362 million USD per year. and ACR for SGM (ACR_{SGM}) is 2.337 million USD per year. Furthermore, AUC for CDM (AUC_{CDM}) is 0.288 million USD per year, while AUC for SGM (AUC_{SGM}) is 0.221 million USD per year. In case of ACRL, ACRL for CDM ($ACRL_{CDM}$) is 5372 USD per year, while ACRL for SGM ($ACRL_{SGM}$) is 6249 USD per year. The reason for marginally higher $ACRL_{SGM}$ is the higher TEG and methane losses. Higher methane loss is due to splitting a part of dry gas, which is being used for stripping in SGM. However, the effect of these losses is almost negligible. As using the stripping gas, significantly decreased TEG feed rate (shown in Table 3) which resultantly decrease ACR_{SGM}. Consequently, there is a significant decrease in the AOC of the process. The graphical breakdown of AOC for both CDM and SGM is shown in Fig. 10.

4.4. Comparison of both processes

Finally, a comparison is held between optimized CDM and SGM for the specified target output of dry gas. From Table 3, comparing to CDM, with SGM the required target of dry gas can be achieved using 46% and 42% lower TEG feed rate and reboiler duty, respectively. Moreover, economic analysis reveals that utilizing stripping gas can decrease TEG feed rate, resultantly giving 38% lower AOC of the process. AOC_{SGM} is 2.254 million USD per year less than AOC_{CDM}. Furthermore, SGM has 22% lower AUC and 46% lower ACR than CDM. However, there is no significant difference between TCC_{CDM} and TCC_{SGM}. Although a part of dry gas is being utilized for the stripping process in SGM which increases the cost of methane loss, this part is only 0.05 vol% of overall dry gas. Moreover, the cost of this loss is minimal comparing to the reduction in ACR (due to decrease in TEG feed rate for SGM). Therefore, from Table 3 and Fig. 10, for the required target outlet of dry gas, SGM for dehydration of natural gas is technically and economically more feasible than CDM. Fig. 11 depicts this comparison in graphical form.

5. Conclusions

The technical and economic analysis of the CDM and SGM has been performed in with Aspen HYSYS simulation software and Aspen Process Economic Analyzer software, respectively. Sensitivity analysis is performed to optimize the operating parameters of both processes. The analysis has shown that the water content of dry gas is the most sensitive parameter to the TEG feed rate. Moreover, the decrease in TEG feed rate for CDM and SGM gives lower reboiler duty and lower raw material losses.

Furthermore, for the fixed target output specifications of dry gas (60 $mg\cdot m^{-3}$ and 16), the SGM is found economically and technically more feasible, as it gives lower TEG feed rate, energy consumption, operating cost, capital cost, equipment cost and utilities cost. Although, raw material loss increases, which increased the ACRL of the process. However, this increase is almost negligible as compared to the decrease in ACR_{SGM}, caused by the decrease in TEG feed rate. Therefore, SGM has 46% lower TEG feed rate, 42% lower reboiler duty and 38% lower AOC compared to CDM. In conclusion, SGM is the energy-efficient, cost-efficient and technically improved process for the natural gas dehydration compared to CDM.

Nomenclature

AARD	Absolute average relative deviation
ACR	Annual cost of raw materials used in the operation
ACR_{CDM}	Annual cost of raw materials for conventional dehydration method
ACRL	Annual cost for raw material loss
$ACRL_{CDM}$	Annual cost for raw material loss of conventional dehydration method
$ACRL_{SGM}$	Annual cost for raw material loss of stripping gas method
ACR_{SGM}	Annual cost of raw materials for stripping gas method
AOC	Annual operating cost
AOC_{CDM}	Annual operating cost of conventional dehydration method
AOC_{SGM}	Annual operating cost of stripping gas method
AUC	Annual utility cost
AUC_{CDM}	Annual utility cost conventional dehydration method
AUC_{SGM}	Annual utility cost stripping gas method
FCI	Fixed capital investment
OPMT	Operating labor and maintenance cost
$\bar{S}_{\alpha}^{F}$	Relative sensitivity of dependent parameter 'F' with independent parameter 'α'
TCC	Total capital cost
TCC_{CDM}	Total capital cost of conventional dehydration method
TCC_{SGM}	Total capital cost of stripping gas method
TEC	Total equipment cost
Z	Critical compressibility factor

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Supplementary Material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cjche.2020.03.013.

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References

[1] M. Neagu, D.L. Cursaru, Technical and economic evaluations of the triethylene glycol regeneration processes in natural gas dehydration plants, *J. Nat. Gas Sci. Eng.* 37 (2017) 327–340.

[2] BP Energy Outlook, https://www.bp.com/en/global/corporate/energy-economics/energy-outlook/demand-by-fuel/oil.html 2018, Accessed date: 1 January 2019.

[3] K. Hayhoe, H.S. Kheshgi, A.K. Jain, D.J. Wuebbles, Substitution of natural gas for coal: climatic effects of utility sector emissions, *Clim. Chang.* 54 (2002) 107–139.

[4] N. Kasiri, S. Hormozdi, Improving performance of absorption tower in natural gas dehydration process, *Eur. Symp. Comput. Aided Process Eng.* 15 (2005) 1–11.

[5] F. Liang, M. Ryvak, S. Sayeed, N. Zhao, The role of natural gas as a primary fuel in the near future, including comparisons of acquisition, transmission and waste handling costs of as with competitive alternatives, *Chem. Cent. J.* 6 (2012) S4.

[6] Z.Y. Kong, A. Mahmoud, S. Liu, J. Sunarso, Revamping existing glycol technologies in natural gas dehydration to improve the purity and absorption efficiency: available methods and recent developments, *J. Nat. Gas Sci. Eng.* 56 (2018) 486–503.

[7] M.R. Rahimpour, S.M. Jokar, P. Feyzi, R. Asghari, Investigating the performance of dehydration unit with Coldfinger technology in gas processing plant, *J. Nat. Gas Sci. Eng.* 12 (2013) 1–12.

[8] A.L. Kohl, R.B. Nielsen, Gas Purification, Gulf Publishing Company, Houston, 1997.

[9] M. Netusil, P. Ditl, Comparison of three methods for natural gas dehydration, *J. Nat. Gas Chem.* 20 (2011) 471–476.

[10] M.A. Isa, U. Eldemerdash, K. Nasrifar, Evaluation of potassium formate as a potential modifier of TEG for high performance natural gas dehydration process, *Chem. Eng. Res. Des.* 91 (2013) 1731–1738.

[11] H.A. El-Mawgoud, T.M. Elshiekh, S.A. Khalil, Process simulation for revamping of a dehydration gas plant, *Egypt. J. Pet.* 24 (2015) 475–482.

[12] T.K. Ibrahim, R.K. Abdulrahman, F.H. Khalaf, I.M. Kamal, The impact of stripping gas flow rate on triethylene glycol losses from glycol regeneration unit: simulation study, *J. Chem. Eng. Process Technol.* 8 (2017) 0–6.

[13] S. Baktash, R. Khorramirad, M. Abbasi, K. Paymooni, M.R. Rahimpour, Improvement of TEG Regeneration in Natural Gas Dehydration Using a Hydrocarbon Solvent, in: CHISA 2010 ECCE7, Prague, 2010.

[14] K. Paymooni, M.R. Rahimpour, S. Raeissi, M. Abbasi, M.S. Baktash, Enhancement in triethylene glycol (TEG) purity via hydrocarbon solvent injection to a TEG + water system in a batch distillation column, *Energy Fuel* 25 (2011) 5126–5137.

[15] K. Mohamadbeigy, Studying the effectivness parameters on gas dehydration plant, *Pet. Coal.* 50 (2008) 47–51.

[16] N.C.G. Jacob, Optimization of triethylene glycol (Teg) dehydration in a natural gas processing plant, *Int. J. Res. Eng. Technol.* 3 (2014) 346–350.

[17] A. Nemati Rouzbahani, M. Bahmani, J. Shariati, T. Tohidian, M.R. Rahimpour, Simulation, optimization, and sensitivity analysis of a natural gas dehydration unit, *J. Nat. Gas Sci. Eng.* 21 (2014) 159–169.

[18] M.M. Ghiasi, A. Bahadori, S. Zendehboudi, I. Chatzis, Rigorous models to optimise stripping gas rate in natural gas dehydration units, *Fuel.* 140 (2015) 421–428.

[19] M.R. Rahimpour, M. Saidi, M. Seifi, Improvement of natural gas dehydration performance by optimization of operating conditions: a case study in Sarkhun gas processing plant, *J. Nat. Gas Sci. Eng.* 15 (2013) 118–126.

[20] J. Carroll, Dehydration of natural gas, *Nat. Gas Hydrates.* 3 (2014) 175–195.

[21] C.H. Twu, W.D. Sim, V. Tassone, A versatile liquid activity model for SRK, PR and a new cubic equation-of-state TST, *Fluid Phase Equilib.* 194–197 (2002) 385–399.

[22] S. Watanasiri, Dehydration with Aspen HYSYS ® : Validation of the CPA Property Package, http://www.aspentech.com/en/resources/white-papers/clehydration-with-aspen-hysys-validation-of-the-cpa-property-packages.

[23] C.H. Twu, V. Tassone, W.D. Sim, S. Watanasiri, Advanced equation of state method for modeling TEG-water for glycol gas dehydration, *Fluid Phase Equilib.* 228–229 (2005) 213–221.

[24] E.D. Smith, F. Szidarovszky, W.J. Karnavas, A.T. Bahill, Sensitivity analysis, a powerful system validation technique, 2, *Open. Cybern. Syst. J.* (2008) 39–56.

[25] Price of TEG provided by Shandong Baovi Energy Technology Co., Ltd., China, https://www.alibaba.com/product-detail/Maximum-discount-Polyester-and-industrial-grade_60815904405.html?spm=a2700.7724838.2017115.9.4b16338beVUZc6&s=p 2019, Accessed date: 1 January 2019.

[26] Average price of natural gas provided by The Public Policy Institute of New York State, http://www.ppinys.org/reports/jtf2004/naturalgas.html 2018, Accessed date: 1 January 2019.

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