CHEMICAL ENGINEERING TRANSACTIONS
VOL. 88, 2021

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš

ISBN 978-88-95608-86-0; **ISSN** 2283-9216

DOI: 10.3303/CET2188154

Process Intensification of Triethylene Glycol Dehydration Units with Respect to Rated Energy Consumption, Emissions and Product Quality

Václav Miklas, Ibrahim Abdulrahman, Vítězslav Máša*

Brno University of Technology, Institute of Process Engineering & NETME Centre, Technicka 2896/2, 616 69, Brno, Czech Republic
masa@fme.vutbr.cz

Natural gas is the most widespread fossil fuel nowadays, used both domestically and in industry. Its processing is highly energy and cost intensive and consists of multiple steps. The gas dehydration is an essential and irreplaceable process because water content minimization is crucial in prevention of hydrate formation, electrochemical corrosion control as well as for subsequent cryogenic processing if present. Despite its importance, the dehydration step is often designed and operated based on rules of thumb and good practice instead of a systematic approach. This makes dehydration an adequate candidate to apply a previously suggested complete and concise Process Intensification (PI) framework developed specifically for oil & gas (O& G) industry. This framework suggests the Rated Energy Consumption (REC) as the key and measurable driver for design and implementation of PI tools. This paper presents a case study on absorption dehydration using triethylene glycol (TEG). The study is based on an existing facility. First, a process model was built and used to evaluate REC of the system with three main contributors: reboiler, stripping gas and circulation pump. For a PI analysis, two key process parameters affecting the REC were identified, i.e. TEG circulation rate and stripping gas consumption. Using response optimization, it was shown that the original design point is sub-optimal with respect to REC and indirect CO_2 emissions, which could be reduced by 23 and 19 % respectively, while maintaining the product water content. The outcome of this work represents an important foundation for future PI within a more complex dehydration process considering also cooling and condensation upstream of the TEG unit and adsorption as a subsequent step.

1. Introduction

Implementation of Process Intensification (PI) in O&G represents the most promising way to achieve sustainable development of this industry in an environmentally friendly manner (Abdulrahman et al., 2021). Most PI publications have been subjected to the chemical and energy sectors, while the research interest in the implementation of the PI technologies in O&G has shown an increasing trend only after the Kyoto Protocol, 1997. In the previous work (Abdulrahman et al., 2021), presented a complete and concise PI framework for O&G, which depends mainly on rated energy consumption (REC) as a key driver for PI implementation. Previous research also showed that there is a positive correlation between the REC of a process and the PI tool occurrence. In this paper, the concept of REC is applied to one of the key parts of gas processing facilities, a natural gas dehydration unit using triethylene glycol (TEG), to reduce its operating expenses (OPEX) and minimize its environmental impact. TEG units are a suitable subject to PI for multiple reasons: a) they are present in virtually all gas processing facilities, b) they emit a significant amount of greenhouse gases (CO_2 and hydrocarbons), c) their REC contribution within a gas processing facility is relatively high, d) the process layout is relatively consistent among different TEG dehydration units which makes results applicable to a large number of facilities e) the amount of publications about the process is relatively small – a broad Scopus search "TITLE-ABS-KEY (teg AND dehydration)" returns only 256 results.
Running a more specified search on Scopus about PI and TEG units will return only with 2 document ("TITLE-ABS-KEY (teg AND dehydration AND process AND intensification"). Duyen et al. (2016) investigated the

Paper Received: 9 June 2021; Revised: 3 July 2021; Accepted: 6 October 2021
Please cite this article as: Miklas V., Abdulrahman I., Máša V., 2021, Process Intensification of Triethylene Glycol Dehydration Units with Respect to Rated Energy Consumption, Emissions and Product Quality, Chemical Engineering Transactions, 88, 925-930 DOI:10.3303/CET2188154

feasibility of sweeping gas membrane distillation on concentrating triethylene glycol from waste streams, where a hydrophobic hollow fiber membrane operation was operated. The other paper has presented the inline separation technology, so called Compact Mass transfer and Inline Separation Technology (cMIST™) as a replacement for the TEG unit (Ramkumar et al., 2017). Further searching returns some other papers where TEG has been compared with other developed dehydration technologies such as supersonic separation (Machado et al., 2012), or ionic liquids usage method (Han et al., 2018), while some attempts was done to optimize the TEG unit performance via some rigorous models to optimize stripping gas rate in natural gas dehydration units (Ghiasi et al., 2015), and some novel absorption process where a mixture of TEG and lean oil was used (Díaz Rincón et al., 2016).
Based on the literature review, however, there is no published work using simulation software for PI purposes of a TEG dehydration unit. This work takes a holistic approach, including a creation of a complex process model, its validation, and use to generate a response surface, which is beneficial for multi-criteria optimization with REC and indirect CO_2 emissions as objective functions. There is only one existing article combining process simulation with response surface methodology for an existing TEG dehydration unit (Kamin et al., 2017), however not in the context of PI. An obvious research gap shows that there is no similar application of PI methodology on TEG dehydration unit, using cost-effective parameter manipulation to maximize the synergy of partial effects according to the PI criteria described by Abdulrahman et al. (2021).
The PI within this paper has been approached as a “chemical engineering development that leads to a substantially smaller, cleaner, safer, and more energy-efficient technology” (Stankiewicz et al., 2000), where one of the fundamental concepts is synergetic integration of a process. The methodology is demonstrated on an industrial case study representative of numerous other dehydration units.

2. Process description

The case study is based on existing facility in the Middle East. The process layout is presented in Figure 1.

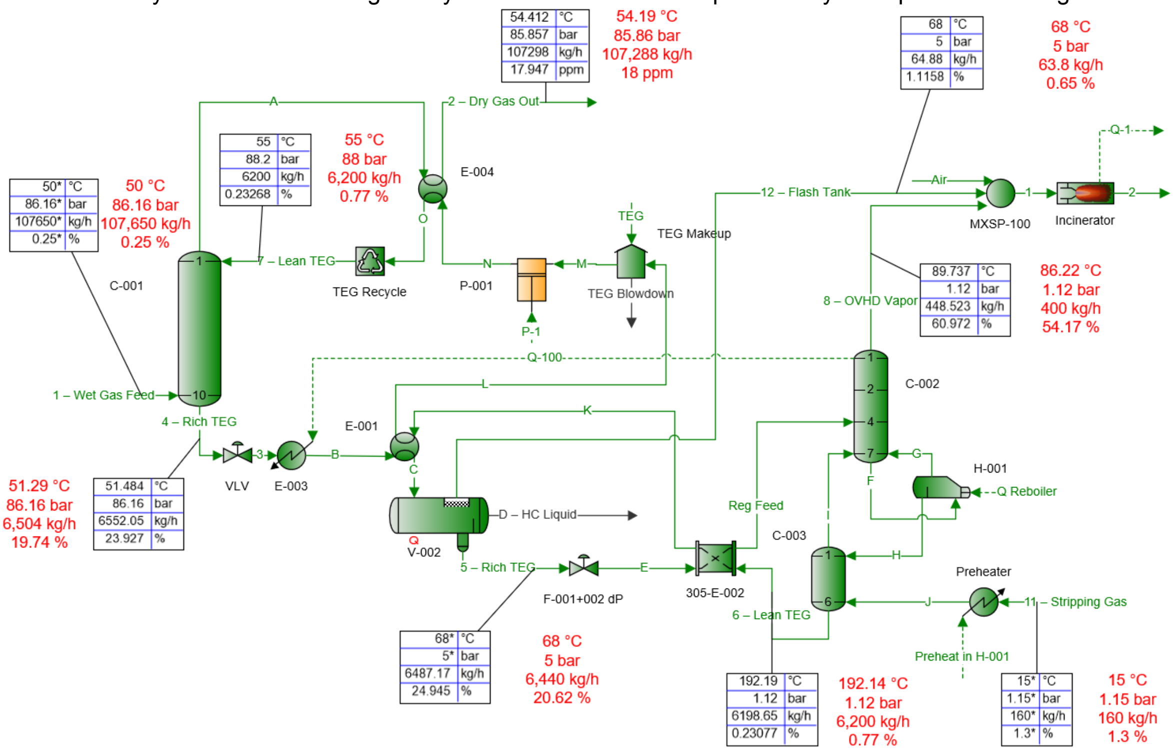

Figure 1: TEG dehydration process layout used for a ProMax model in the case study; model results are in black tables, design documentation data in red.

The most important process parameters are presented in Table 1. They also represent specifications that were, among detailed information from the design documentation of the facility, used for the creation of a process model using commercial simulation software ProMax (Bryan Research & Engineering LLC, 2020). There was an exceptionally close agreement between the model and the design data (see the differences between red and black values in Figure 1).

Table 1: Overview of key process parameters; variables directly controlled by an operator with an asterisk.

Process Streams	Parameter	Value	Unit
1 – Wet Gas Feed	Temperature	50	°C
	Pressure	86.2	bar(a)
	Flowrate	125,220	Nm3/h
	Water content	0.25	mol.%
2 – Dry Gas Out	Design water content	18	ppm
7 – Lean TEG	Temperature	55	°C
	Circulation rate	6,200*	kg/h
11 – Stripping Gas	Temperature	15	°C
	Flowrate	160*	kg/h
Equipment			
Reboiler (H-001)	Operating temperature	204*	°C
	Operating pressure	1.12*	bar(a)
Flash Tank (V-002)	Operating temperature	68*	°C
	Operating pressure	5*	bar(a)

3. Methodology

The goal of the presented methodology is to manipulate parameters that are adjustable in real operation in a way that will reduce rated energy consumption (REC) and Greenhouse Gas emissions of the process. The cost of implementing the results of this study is lowest comparing to other PI methods that could be applied to optimize the TEG units due to minimum capital expenses. There are six main operational parameters that can be controlled by operator (note asterisks in Table 1); however, all of them are subject to the following process constraints:

a) circulation rate – the circulation pump, piping, and columns are unlikely to hydraulically handle more than a 30% deviation from the design point,
b) stripping gas consumption – similar concerns as for the circulation rate from the hydraulic point of view,
c) reboiler temperature – the reboiler is typically operated just below the TEG degradation point (206 °C) as lower temperatures would reduce the regeneration efficiency,
d) regeneration section pressure – lower pressures favor stripping, however, there is an incinerator downstream of the regeneration section, thus the pressure needs to be maintained slightly above the atmospheric pressure: 1.01325 bar(a),
e) flash tank temperature and pressure – not appreciably affect the water balance and overall efficiency.

For the abovementioned reasons, the circulation rate and stripping gas consumption were identified as the two variables to be used for the process intensification purposes as the others have no degree of freedom or a limited effect on the process performance. The investigated domain was therefore bounded as follows:

Table 2: The two manipulated variables in the case study and their ranges.

Parameter	Lower bound (-30 %)	Original value	Upper bound (+30 %)	Step
Circulation rate [kg/h]	4,340	6,200	8,060	310
Stripping gas consumption [kg/h]	112	160	208	8

Although the response surface methodology is mainly used in statistics, a surrogate (meta) model is also advantageous for deterministic models in cases when one call of the objective function (i.e., execution of the process simulator) is time or computationally intensive. The meta model is created based on a limited number of data points and provides a continuous description of the investigated domain. In this case, 169 data points were used to generate response surfaces for the following parameters to be optimized or targeted:

- total REC of the process,
- indirect CO_2 emissions from incinerating flash gas and water vapor,
- dry gas water content.

The total REC consists of three main contributors denoted respectively by A, B and C, the reboiler duty ($\dot{Q}_{reboiler}$), the total heating value of stripping gas (i.e., mass flow rate $\dot{m}_{stripping\ gas}$ multiplied by the specific lower heating value $LHV_{stripping\ gas}$), and the power of the circulation pump (P_{pump}):

$$REC_{total} = REC_A + REC_B + REC_C = \dot{Q}_{reboiler} + \dot{m}_{stripping\ gas} \cdot LHV_{stripping\ gas} + P_{pump} \quad (1)$$

In this paper, CO_2 emissions from burning fuel to generate process heat are considered as direct emissions and are not included. The indirect emissions include those produced from flash gas and water vapor, since they can be considered purposeless in the current configuration. These streams could be used in a beneficial manner, rather than burning in a flare or incinerator without heat utilization, which is the case in this facility.
Regression features in the Minitab data analysis tool (Minitab LLC 2020) were used to generate the meta models in the following form:

$$\ln(\text{response}) = C_0 + C_1 \cdot \dot{m}_{cir} + C_2 \cdot \dot{m}_{strip} + C_3 \cdot \dot{m}_{cir}^2 + C_4 \cdot \dot{m}_{strip}^2 + C_5 \cdot \dot{m}_{cir} \cdot \dot{m}_{strip} + C_6 \cdot \dot{m}_{cir}^3 + C_7 \cdot \dot{m}_{strip}^3 + \\ + C_8 \cdot \dot{m}_{cir}^2 \cdot \dot{m}_{strip} + C_9 \cdot \dot{m}_{cir} \cdot \dot{m}_{strip}^2, \text{ where:} \quad (2)$$

response represents REC, CO_2 emissions or dry gas content, each of which an individual response surface was generated for, C_0 ... C_9 are the regression coefficients [–], $\dot{m}_{cir}$ is the circulation rate [kg/h], $\dot{m}_{strip}$ is the stripping gas consumption [kg/h]. Using this methodology, the goal to evaluate the REC and CO_2 emissions for a wide range of manipulated variables' values is achievable. This ultimately allows for minimization of these two key PI metrics. Although the approach is applied to the TEG dehydration unit, the same methodology is appropriate for a large number of other processes not limited to the oil & gas industry.

4. Results and discussion

The base case results are an important benchmark for the subsequent optimization. They are shown in Table 3 and provide multiple interesting insights. Evaluating these results shows that the contributor C (circulation pump) is almost negligible, while a counter-intuitive fact is that more than 80 % of the rated energy consumption (REC) is represented by the chemical energy (heating value) wasted in the process (REC B). This is an important indication that a reduction of the stripping gas consumption might be beneficial from the REC standpoint.
Indirect CO_2 emissions are rather high. However, an even more alarming fact is that they are several times higher than the direct emissions (which are below 1,000 t/y). Although it is impossible to reduce the indirect CO_2 emissions in a TEG dehydration to zero, minimizing this value is still a valid and important goal.

Table 3: The simulation results for the base case (the circulation rate of 6,200 kg/h, the stripping gas consumption of 160 kg/h); REC = rated energy consumption, A = reboiler, B stripping gas, C = circulation pump.

Dry gas H_2O content	18.0	ppm
REC A	391.0	kW
REC B	1,981.3	kW
REC C	19.3	kW
REC Total	2,391.5	kW
CO_2 emissions	5,894.3	t/y

Although the model-based approach has a number of advantages such as possibility to quantify otherwise unavailable variables (e.g., CO_2 emissions of a single unit within an integrated flare system) or evaluate variable combinations which would yield an insufficient dry gas quality, it is important to recognize its limitations:

- Any variation in process parameters limits the validity of steady-state process simulation. The most probable deviations are: a) feed flowrate, temperature, pressure or composition changes, b) seasonal effects causing the lean TEG temperature fluctuations.
- Process upsets that a process simulator is unable to predict (equipment failure, column foaming, heat exchanger fouling).
- Technical limitations of individual equipment that are not included in the simulation (control system, sizing of pumps, piping, valves, flash tank).

Most of the subsequently generated surrogate models are almost linear (i.e., the response surface is close to a plane), with the exception of the dry gas water content. Non-linear response surfaces are generally more subjected to undesirable effects such as oscillation between the basic data points; however, Figure 2a demonstrates that the function is well-behaved. The figure also shows that the water content is rather insensitive to stripping gas flowrate, especially for relatively high water concentrations (over 20 ppm). On the other hand, the REC (Figure 2b) is a strong function of the stripping gas flow rate.

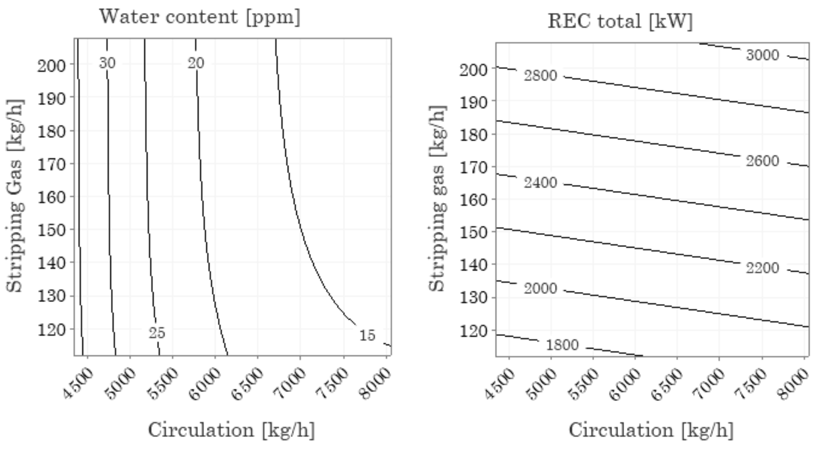

Figure 2: Contour plot of a) the dry gas water content, b) the total REC.

These two effects are combined in an overlaid contour plot which highlights an area where all three key parameters – the water content, REC, and indirect CO_2 – are lower than the baseline presented in Table 3. In other words, the white area represents the possible operating points at which the process can remove more water while consuming less energy and emitting less CO_2. The central point, where all three curves intersect, represents the base case.

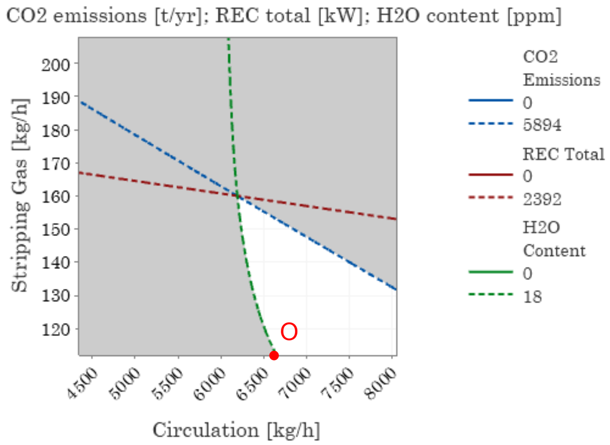

Figure 3: Overlaid contour plot; the overlap where all three criteria (indirect CO_2 emissions, total REC, dry gas H_2O) are lower than the baseline are represented by the white area.

The response optimizer built in Minitab was used to target exactly 18 ppm of water in the product while minimizing the REC to obtain a direct comparison, and not to overtreat the product unnecessarily. The optimum is indicated as point O within the searched domain in Figure 3.

Table 4: Overview of an improved operating point with respect to the REC and CO_2 emissions.

	Base case	Improved (metamodel)	Improved (process simulation)	Difference improved vs. base
Circulation rate [kg/h]	6,200	6,632		+7.0 %
Stripping gas [kg/h]	160	113		-29.4 %
REC [kW]	2,391.5	1,837.2	1,837.1	-23.2 %
Indirect CO_2 emissions [t/yr]	5,894.3	4,976.4	4,976.9	-15.6 %
Water content [ppm]	18	18	18	—

Table 4 summarizes information about the found optimum on the surrogate model and compares it to the base case as well as to the results from the process simulator to verify the meta-model validity – “Improved (process simulation)”. The new operating point at a slightly increased circulation rate (by 7 %) has the potential to reduce

the total REC by 23 %, and the indirect CO_2 emissions by approximately 16 %. At the same time, the key performance indicator of dry gas water concentration would remain the same (18 ppm). All the columns are safely below their respective flooding point for both the base case and improved operating point.
Since the REC minimum is located in the bottom left corner of the domain (minimum circulation, minimum stripping gas; see Figure 2b), the optimization algorithm will drive the objective function toward the bottom of the domain. Any target concentration higher than 18 ppm follows the same optimization trend, with the stripping gas consumption as one of the manipulated variables being at the lower bound of the investigated range. This leads to a conclusion that expanding the range below 113 kg/h could lead to even lower values of the CO_2 emissions and REC. However, this possibility needs to be further investigated since too low vapor load in columns C-002 and C-003 could be problematic.

5. Conclusions

TEG dehydration units are a crucial part of natural gas processing. Unfortunately, they have not been approached in accordance with PI perspectives, while meeting a product specification prevails over emissions and rated energy consumption considerations.
The principles of PI were applied to a case study dealing with an existing TEG unit. A combination of a rigorous model built in ProMax and a surrogate model generated by Minitab was used for this purpose. The PI of the studied unit has been approached and evaluated in accordance with the REC, and it was found that the design operating point can be improved in terms of energy consumption and indirect CO_2 emissions while varying the circulation and stripping gas rates by no more than 30 % compared to the base case.
Whereas a wide range of circulation and stripping gas rates would result in a lower REC, indirect CO_2 emissions, and dry gas water content, the optimization was constrained to the product water concentrations of 18 ppm analogously to the current operation. This allows to perform a direct comparison between the design point and an optimized operation. The improved operating point would save around 23 % of the REC (~550 kW) and 16 % of the indirect CO_2 emissions (~920 t/y) while keeping the same product water content. This individual case study reveals a huge potential improvement in cleaner, more sustainable and energy-efficient operation of TEG units, a number of which are operated in a similar, sub-optimal manner.
The work presents a complex PI assessment applicable to a wide variety of processes. This general methodology, involving process simulation and the use of response surfaces, allows engineers or researchers to find an optimum with respect to the criteria they define. Future work will focus on a comprehensive evaluation of dehydration including some typical upstream (cooling and condensation) and downstream (molecular sieves) unit operations.

Acknowledgement

This research has been supported by the project No. CZ.02.1.01/0.0/0.0/16_026/0008413 “Strategic partnership for environmental technologies and energy production”, which has been co-funded by the Czech Ministry of Education, Youth and Sports within the EU Operational Programme Research, Development and Education.

References

Abdulrahman, I., Máša V., Teng S.Y., 2021, Process Intensification in the Oil and Gas Industry: A Technological Framework, Chemical Engineering and Processing - Process Intensification, 159.
Díaz Rincón M., Jiménez-Junca C., Roa Duarte C., 2016, A novel absorption process for small-scale natural gas dew point control and dehydration, Journal of Natural Gas Science and Engineering 29, 264–274.
Duyen P.M., Jacob P., Rattanaoudom R., Visvanathan, C., 2016, Feasibility of sweeping gas membrane distillation on concentrating triethylene glycol from waste streams, Chemical Engineering and Processing: Process Intensification 110, 225–234.
Ghiasi M.M., Bahadori A., Zendehboudi S., Chatzis I., 2015, Rigorous models to optimise stripping gas rate in natural gas dehydration units, Fuel 140, 421–428.
Han J., Dai C., Lei Z., Chen B., 2018, Gas drying with ionic liquids, AIChE Journal 64, 606–619.
Kamin Z., Bono A., Leong L.Y., 2017, Simulation and Optimization of the Utilization of Triethylene Glycol in a Natural Gas Dehydration Process, Chemical Product and Process Modeling, 12 (4).
Machado P.B., Monteiro J.G.M., Medeiros J.L., Epsom H.D., Araujo O.Q.F., 2012, Supersonic separation in onshore natural gas dew point plant, Journal of Natural Gas Science and Engineering 6, 43–49.
Ramkumar S., Grave E.J., Larnholm P.-R., Thierens D., 2017, CMISTTM: Novel, compact dehydration system for reducing size & weight, in: Proceedings of the Annual Offshore Technology Conference, 4121–4134.
Stankiewicz A.I., Moulijn J.A., 2000, Process intensification: Transforming chemical engineering, Chemical Engineering Progress 96.