Evaluation of the Diethylene Glycol Regeneration rate in Gas Fields Based on Indirect Measurements

A N Krasnov

1IT-institute, Ufa state petroleum technological university, 1 Kosmonavtov St, Ufa 450064, Russia

E-mail: ufa-znanie@mail.ru

Abstract. Gas dehydration in the field is a mandatory procedure before long-distance transportation. In Russia, gas is dried by absorption using diethylene glycol (DEG). Upon absorbing moisture from the raw gas, DEG is regenerated and recycled to dehydration, the quality of which largely depends on the regeneration rate. This indicator is not measured directly at the dehydration plant, and regeneration is controlled discretely based on the periodic laboratory analysis results. The paper describes a virtual analyzer determining the DEG concentration in a real-time mode based on the temperature and DEG consumption measurement results. The regression mathematical model underlying the virtual analyzer has been built based on experimental data obtained at the Yamburg gas condensate field. As part of the gas treatment plant APCS, a virtual analyzer improves the treatment efficiency and reduces the DEG consumption.

1. Introduction

The gas well product – the so-called raw gas is a mixture of gaseous hydrocarbons of predominantly methane series, droplet moisture, and mechanical impurities. However, the gas supplied to the main gas pipeline for further transportation should meet rather stringent quality requirements, i.e., should be preliminarily prepared according to the regulatory documents in force, specifying the water dew point (DP) (moisture content), hydrocarbon DP, and the content of mechanical impurities. Therefore, dehydration is the main operation in preparing gas for transportation.

For purely gas fields, as a rule, absorption dehydration of natural gas is used [1]. This process is performed in an absorption column where droplet moisture is extracted from the natural gas at the counter-current flow of the gas (bottom-up) and liquid (top-down) phases. Various glycols such as diethylene glycol (DEG) or triethylene glycol (TEG) are used as an absorbent in gas fields. Their almost common use is determined by their recoverability. Herewith, DEG is used predominantly in Russia (the use of TEG is of a single nature), and TEG abroad [2]. Each glycol has its benefits and shortcomings. The choice in favor of DEG in Russian gas fields is determined by the DEG price, which is more than one and a half times cheaper, higher hydrate suppression degree, lower viscosity at dehydration temperatures, and lower solubility in hydrocarbon condensate, due to which it is highly selective in the water-hydrocarbon system [3]. Therefore, it is used despite its lower efficiency in decreasing the DP, its higher process losses with gas during dehydration, and achievable regenerated solution concentration compared to TEG [4]. The availability of own industrial base at Russian chemical plants is also an argument in favor of DEG.
To restore its properties in gas fields, it is regenerated in rectification columns, where a binary liquid phase consisting of DEG and drop moisture is separated. After the restoration of properties, DEG is fed back to the absorption column. Thus, the absorption natural gas dehydration at the gas treatment plant (GTP) is performed in a closed cycle (by the liquid phase) [1].

Since DEG properties cannot be restored endlessly to the initial level due to the irrecoverable losses [5], pure DEG should be periodically added to the circulating solution. It is produced according to the GTP regulations. This approach does not allow considering all the factors affecting the DEG concentration in the work solution, therefore, this value is not always optimal. The paper discusses the possibility of controlling the regeneration rate in a real-time mode.

2. Materials and methods
The most common simplified gas dehydration and DEG regeneration process flow sheet is shown in Fig. 1. The process specifics are performing the absorption at a relatively low temperature and high pressure, and the regeneration, on the contrary, at high temperature and low pressure. In general, each dehydration process line comprises an inlet (primary) KO drum, an absorber, a filter to capture finely dispersed glycol from the dried gas stream (these three vessels can be combined into a single multifunctional apparatus, as shown in Fig. 1), and a DEG circulation system including a regeneration column, a heat exchanger, and an evaporator. The dehydration line also includes pumps and process tanks. Solid particles and droplet moisture are removed, and gas dried in the multifunctional apparatus A-1, where raw gas is fed. DEG regeneration occurs in the R-1 regeneration column (stripper).

![Flow Sheet](image.png)

**Figure 1.** Natural Gas Dehydration and DEG Regeneration Flow Sheet.

Depending on the field development phase, which affects the liquid content of the gas produced, various regeneration technologies are used: atmospheric or vacuum distillation, combined distillation using stripping gas, and azeotropic distillation [6]. Each of these technologies has its pros and cons and provides a different regeneration rate: from 95.0-97.6% for atmospheric distillation to 99.4-99.9% for azeotropic one [7]. Herewith, it cannot be said unequivocally that the greater the regeneration rate, the better; this indicator should correspond to the current gas field operation phase. The initial gas field operation phase is characterized by high gas pressure and low moisture content; therefore, the use of a regenerated absorbent with a DEG concentration of 95.0 - 97.6% is sufficient. Accordingly, the atmospheric regeneration scheme can be used [8]. When the field enters the final operation phase, the
reservoir pressure decreases gradually, and the moisture content starts increasing. In this case, to ensure the required water DP of the gas in the absorber, the DEG content in the regenerated absorbent should be reduced to 97.5-99.0 % and, accordingly, the regeneration operating parameters or process flow sheet should be changed. Herewith, the greater the liquid content of raw gas, the more difficult is to ensure the required regeneration rate and the more often is the need to intervene in this process since regeneration depends on not only the plant process mode but also many external factors such as flow rate and gas temperature and pressure [9].

The real-time change of operating parameters is a problem in this case. Regardless of the regeneration technology used, its degree is estimated by laboratory analysis with a certain frequency specified in the GTP process regulations. The interval between analyzes may be several weeks, which does not allow ensuring the regenerated DEG (RDEG) concentration, optimal for the current liquid content of gas. The main cause of this problem is the lack of in-line control over the DEG concentration in the regenerated solution, i.e., in fact, this process quality indicator is not measured.

It is adopted [10] that the processes occurring in the CGTP vessels are quasi-steady. However, the impact of various disturbing factors (changes in the process mode, the moisture content and pressure of the gas, etc.) lead to significant deviations of these processes from the steady-state modes [11].

Possible solutions to this problem are the subject of many studies, in particular, [12–16]. Virtually all these studies specify the need for building adequate dynamic mathematical models (MM) of controlled processes, considering the multiphase nature of interacting flows, spatial distribution, boundary conditions, and nonlinear relationship of physical quantities [11]. Of course, the models proposed differ in the principles of their building and use. E.g., in [15, 16], it is proposed to use these models to arrange multi-mode control and analysis of dynamic situations.

This study is aimed at estimating the possibility of determining the regenerated DEG concentration by some indirect parameters and building a virtual analyzer to control the regeneration in a real-time mode.

3. Theoretical part

3.1. The virtual analyzer concept

The emergence and rather intensive development of virtual analyzers is determined by the fact that any production requires quality control of both the final product and raw materials and intermediates involved in the process. Either laboratory analyzes or online ones can be used for this purpose [17]. Both control techniques have serious limitations in terms of practical use. Thus, the laboratory analysis causes a large time lag from the current process state, i.e., in fact, its data reflect the archival value of a certain quality indicator and therefore, are unsuitable for real-time process control. Online analysis is performed almost in a real-time mode, but such analyzers are, firstly, difficult to operate and require constant calibration, and secondly, very expensive (tens and hundreds of thousands of dollars), which limits their use [18].

Virtual analyzers (VA) are software-algorithmic complexes implementing the functions of in-depth estimating the current process state and its possible evolution [19]. In fact, this is a kind of mathematical model describing the relationship of a not directly measured quality indicator with the current values of the measured process parameters, e.g., temperature, pressure, flow rate, etc. Herewith, VAs do not have own sensors and use the data of measuring instruments that are part of the APCS. Compared to the aforementioned laboratory and online analysis, VAs are not inferior to or even surpass them in almost all significant characteristics – the analysis accuracy, the promptness of obtaining the result, the need for calibration, and cost. Another target VA niche is using it as a redundant control and diagnostic measuring system for real-time monitoring of the instrument conditions and predictive analytics.

Building VAs are the subject of research by many famous companies such as Emerson (Delta V Neuro), Honeywell (Profit Sensor Pro), Yokogawa (RQE, Robust Quality Estimator), and Aspen Technology (Aspen IQ) [20]. A variety of mathematical models are used: regression ones, those based
on the alternating mathematical expectation algorithm, linearized strict models, those based on fuzzy logic, neural networks of various types, etc.

3.2. The physical nature of regeneration
When building a mathematical model of any process, to ensure its adequacy, the physical principles underlying the simulated process and limitations imposed by it should be fully considered.

DEG is regenerated in an evaporation (rectification) column through multiple contacts between the counter current flows of liquid and vapor phases. The interaction of phases during rectification represents the diffusion of a low-boiling component (droplet moisture) from liquid to vapor and a high-boiling component (DEG) in the opposite direction. The mutual diffusion of components is determined by the difference in their concentrations in vapor and liquid flows. Depending on their design, columns differ in the phase separation method, which can be stepwise or continuous. Structurally, this is implemented in the form of tray columns (the component concentration in the phases changes sharply from one tray to another) and packed ones, in which the target component concentration in the interacting phases changes smoothly along the packing bed. In a packed column (with has higher performance characteristics), the liquid phase flows down the packing surface in the form of a film (film flow regime), and the vapor phase rises upward in a continuous flow through the free packing volume [1].

Thus, the main physical DEG regeneration processes are those of heat and mass exchange. Thereat, heat exchange processes are more important since an increase in the DEG concentration (the regeneration rate) occurs due to its heating. Also, at constant pressure, the DEG boiling point unambiguously depends on its concentration.

Mass transfer processes in the column will depend mainly on the velocities of the counterflows, i.e., their flow rates controlled by pressure drop.

3.3. Synthesis of a virtual analyzer of the DEG regeneration
The proposed VA is a part of the existing GTP APCS (Fig. 2) and is used to determine the required process mode parameters (DEG flow rate) based on the evaporator temperature analysis results and the specified rundown quality (the DEG regeneration rate).

![Figure 3. Simplified Model of Gas Treatment Plant and Regeneration Unit.](image-url)
As the source data to build a mathematical model of VA, the results of an experiment performed at gas field No. 9 of the Kharvutinskaya area of the Yamburg field have been used. As an example, a fragment of the experimental data of the temperature and flow rate dependence of the DEG regeneration rate is shown in Table 1.

To calculate the dependence of the pressure drop in the column on the linear flow rate, the Darcy-Weisbach equation has been used; the Darcy factor has been determined by the Poiseuille equation (the case of laminar flow in smooth pipes with rigid walls) [21]. The results are given in Table 2.

| Parameter                  | Value  |
|----------------------------|--------|
| Linear velocity, m/s       | 25 23 21 19 17 15 13 11 9 7 |
| Pressure drop, MPa          | 0.48 0.41 0.345 0.2771 0.222 0.173 0.13 0.093 0.062 0.04 |

| Table 2. Dependence of the DEG Regeneration rate on Temperature and Flow Rate. |
|-------------------------------|---------------------------------|
| Parameter                     | Value                           |
| Temperature, °C               | 87 92 96 98 105 112 120 129 145 164 |
| Flow rate, kg/h               | 40 50 60 70 80 90 100 110 120 130 |
| Regeneration, %               | 98.9 99.02 99.23 99.42 99.61 99.73 99.83 99.91 99.97 99.99 |

4. Results and discussion
To build a mathematical model, the DATA FIT software has been used, which allows performing a regression analysis of the source statistical data.

The regression equation obtained in simulation and data processing has the form:

\[ Y = a + b \times x_1 + c \times x_1^2 + d \times x_1^3 + e \times x_1^4 + f \times x_1^5 + \frac{g}{x_2}, \]

where \( x_1 \) is the flow rate; \( x_2 \) is the temperature value; \( a, b, c, d, e, f, \) and \( g \) are constant coefficients.

The diagram of the temperature and flow rate dependence of the DEG regeneration rate is shown in Fig. 3. The regression model obtained is given in the upper left corner. Along with this diagram, the program generates a table with the obtained equation errors (Fig. 4).
Figure 3. Dependence of the DEG Regeneration Rate on the Gas Temperature and Flow rate.

| X1 Value | X2 Value | Y Value | Calc Y | Residual | % Error | Abs Residual | Min Residual | Max Residual |
|----------|----------|---------|--------|----------|---------|-------------|--------------|--------------|
| 1        | 62       | 67      | 98.99890484 | -0.000484 | 0.000489 | 0.0004837217 | -0.0028852464 | 0.0028151029 |
| 2        | 60       | 92      | 99.0299617981 | 0.0021488 | 0.002337 | 0.0026187594 |               |              |
| 3        | 66       | 96      | 99.2199323283 | -0.002328 | 0.002346 | 0.0023278968 |               |              |
| 4        | 70       | 98      | 99.4299421339 | -0.001339 | 0.001347 | 0.0013390332 |               |              |
| 5        | 80       | 105     | 99.6199665184 | 0.0048161 | 0.004835 | 0.0048161021 |               |              |
| 6        | 90       | 112     | 99.7399732685 | -0.002895 | 0.002893 | 0.0028852454 |               |              |
| 7        | 100      | 120     | 99.8399830762 | -0.000762 | 0.000763 | 0.0007617864 |               |              |
| 8        | 110      | 129     | 99.9199908544 | 0.0013562 | 0.0013674 | 0.0013562251 |               |              |
| 9        | 120      | 145     | 99.9799570373 | -0.000373 | 0.000373 | 0.0003732993 |               |              |

Figure 4. The Regression Model Errors.

To assess the model adequacy according to Fisher’s test, calculate the experiment adequacy variances and errors should be calculated:

The experiment adequacy variance

$$S_{ad}^2 = \frac{1}{N - k - 1} \sum_{i=1}^{N} (Y_i - \bar{Y}_i)^2,$$

(2)

where $N$ is the number of experiments; $k$ is the number of variable experimental factors; $Y_i$ is the measured DEG regeneration rate; $\bar{Y}_i$ is the DEG regeneration rate calculated according to the model (1).

The experiment error variance:

$$S_y^2 = \frac{1}{N(m-1)} \sum_{i=1}^{N} \sum_{t=1}^{m} (Y_{it} - \bar{Y}_{it})^2,$$

(3)

where $m$ is the number of experiment repetitions; $Y_{it}$ is the DEG regeneration rate measured at the $t$ experiment repetition.

The variance values:

$$S_{ad}^2 = 0.0192; \quad S_y^2 = 0.00784.$$

The F-test value:

$$F = \frac{S_{ad}^2}{S_y^2} = \frac{0.0192}{0.00784} = 2.45.$$
The tabular F-test value at a 5\% significance level is $F_2 = 2.52$, which allows concluding on the resulting model adequacy.

Fig. 5 shows a software screenshot with the DEG regeneration rate estimation results.

**Figure 5.** Software Screenshot with the DEG Regeneration Rate Estimation Results.

5. **Conclusions**
When prepared for long-distance transportation, the gas dehydration quality depends on many factors, including the concentration of diethylene glycol used for drying. This absorbent is recoverable, i.e., DEG is dehydrated and regenerated in a closed cycle by the liquid phase. The required concentration is achieved by either adjusting the regeneration mode parameters or, when the mode capabilities are exhausted, adding fresh DEG. Thereat, the DEG concentration is, in fact, a parameter not measured online. As a result, the GTP has no real-time control of the regeneration rate.

The experiments performed at the GTP allowed establishing a specific relationship between the DEG concentration and flow rate and the evaporator temperature and building a regression mathematical model, which formed the basis of the virtual analyzer. Checking the model according to Fisher's test confirmed its adequacy.

Inclusion of this VA into the structure of the existing at the GTP ACPS allows real-time monitoring of the regenerated DEG quality indicator, which is not directly measured, by the readings of standard instruments measuring the process parameters and, as a result, improving the gas dehydration efficiency.

6. **References**
[1] Abramkin S E, Dushin S E and Serditov Yu N 2018 Research of physical processes in the rectification column while regenerating diethylene glycol *Izvestiya SFedU Engineering Sciences* pp 69-78 DOI 10.23683/2311-3103-2018-5-69-78
[2] Panshin G A 2017 Comparative analysis of gas treatment *Young scientist* **50**(184) pp 69-70
[3] Istomin V A and Elistratov M V 2000 Analysis of the drying capacity of glycols *Gas industry* **3** pp 59-60
[4] Kazak D V, Solomatin V P and Gladkikh M A 2018 Comparative characteristics of glycols used in gas absorption dryers *Conf. of the Problems of Geology and Subsoil Development* pp
Cole A L and Riesenfeld F S 2006 Gas cleaning (Moscow: Nedra Press publishing) p 535

Arthur J K, William R P and McCartney G D 2012 *Fundamentals of Natural Gas Processing* (CRC Press publishing) p 574

Zhdanova N V and Khalif A L 1984 *Drying of Hydrocarbon Gases* (Moscow Khimiya Publishing House) p 192

Ali A A, Rogalev M S and Magaril R Z 2013 Possibility and assessment of increasing the efficiency of natural gas absorption dehydration with glycol *Proceedings of universities. Oil and Gas* 3 pp 74–6

Abramkin S E and Dushin S E 2016 Modeling and control of technological processes of natural gas dewatering *Izvestiya SFedU. Engineering Sciences* p 159-170

Akramov B Sh, Hayitov O G, Umedov Sh Kh and Nuriddinov Zh F 2014 A systematic approach to analyzing the operation of a complex gas treatment unit *Rusnauka*

Abramkin S E and Dushin S E 2015 Modeling of controlled processes of natural gas absorption drying (SPb Publishing house of SPbGETU «LETI») p 160

Ahsan A 2011 Evaporation, Condensation and Heat transfer *InTech*

Iguchi M and Olusegun J 2010 Modeling Multiphase Materials Processes: Gas-Liquid Systems (Springer)

Dushin S E and Abramkin S E 2015 Mathematical modeling of controlled technological processes of natural gas dehydration Information and control systems 4 (77) pp 41-9

Abramkin S E and Dushin S E 2019 Modeling of technological processes in gas production complexes *Proceedings of 2019 3rd International Conference on Control in Technical Systems* pp 114-17

Abramkin S E and Dushin S E 2017 Prospects for the development of control systems for gas producing complexes *Proceedings of 2017 IEEE 2nd International Conference on Control in Technical Systems* pp 150-3

Bakhtadze N N 2004 Virtual analyzers: Identification Approach Automation and remote control 65(11) pp 1691-1709

Gurieva E M Koltsov A G 2016 Application of virtual analyzers for determining the quality of petroleum products *Dynamics of systems, mechanisms and machines* 1 pp 296-301

Musaev A A 2003 Virtual analyzers: the concept of construction and application in the control of continuous technological processes *Automation in industry* 8 pp 28-33

Khatimov M R, Bogachev A V, Nizameev B M and Ryzhov D A 2015 Key Solutions and Benefits of Yokogawa Advanced Process Control Systems *Exposition Oil and Gas* 5 pp 92-5

Levich V G 2004 *Physico-chemical hydrodynamics* (Moscow State publishing house of physical and mathematical literature) p 699