

Two Novel and Simple Correlations to Estimate Equilibrium Water Dew Point for Natural Gas Dehydration Process

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ABSTRACT

Water is probably the most undesirable component found in crude natural gas because its presence can produce hydrate formation, and it can also lead to corrosion or erosion problems in pipes and equipment. Natural gas must be dehydrated before being transported through a long distance to ensure an efficient and trouble-free operation. Thermodynamic modelling of triethyleneglycol (TEG)-water system is still rather inaccurate, especially with regard to systems at high temperature and high TEG concentration. As a consequence, design and operation of absorber towers are affected by the lack of accurate data. Two novel correlations have been developed to estimate the equilibrium water dew point of a natural gas stream by evaluating experimental data and literature. These data were collected and analyzed by means of images scanned with MATLAB software R2012B version. An average percentage error is of 1-2% for linear correlation and it is of 2-3% for non-linear correlation. Results are quite accurate and they are consistent with literature data. Due to the simplicity and precision of the correlations developed in this work, the equations obtained have a great practical value. Consequently, they allow process engineers to perform a quick check of the water dew point at different conditions without using complex expressions or graphics.

Keywords-Correlation, Dew Point, Natural Gas, TEG-water system, Triethylene glycol, Water Dehydration

I. INTRODUCTION

Natural gas is a vital component of the world's supply of energy. It is a fossil fuel which is one of the cleanest, safest, and most useful energy sources. Natural gas burns more cleanly than other hydrocarbon fuels, such as oil and coal, and produces less carbon dioxide per unit of energy released. Natural gas is a hydrocarbon gas mixture which is formed primarily of methane, ethane, propane and butane; but commonly includes some impurities such as water, carbon dioxide, nitrogen, hydrogen sulfide and traces of heavier condensable hydrocarbons.

Water is probably the most undesirable component found in raw natural gas. Its presence could produce important clogging and plugging in pipelines, valves and other devices. Normal gas flow is stopped and obstructed in transport lines due to hydrate formation, Fig.1 (a) and (b) [1].

Furthermore, it could lead to corrosion or erosion problems in pipes and equipment, caused by the dissolution of CO₂ and H₂S in water.

Natural gas treating should be unavoidable to prevent such problems. Therefore, impurities such as H₂S, CO₂ and H₂O should be reduced or removed from natural gas stream in order to use it as a fuel. The removal is made to satisfy and meet certain specifications regulated by governmental or private entities

Natural gas dehydration represents an important operation in the gas industry. A natural gas stream must be dehydrated before being carried to consumption and distribution centers to ensure an efficient and trouble-free operation. Basically, the fundamental objective of the dehydration is to remove water, in vapor phase mainly, from the treating gas which leaves sweetening process. By far, the most common and successful technique for natural gas dehydration is the contact between the gas and a hygroscopic liquid. Glycol solutions are the most common liquid absorbents in gas industry. Glycols are diols whose hydroxyl groups give them a high affinity for water. Particularly ethylene glycol

(EG), diethylene glycol (DEG), triethylene glycol (TEG), and tetraethylene glycol (T4EG) allow reaching different dehydration levels. TEG Absorption process is one of the most acknowledged methods used for natural gas dehydration [2].



Figure 1(a). Adhered Hydrate on internal walls on gas pipelines (Picture from Repsol YPF)

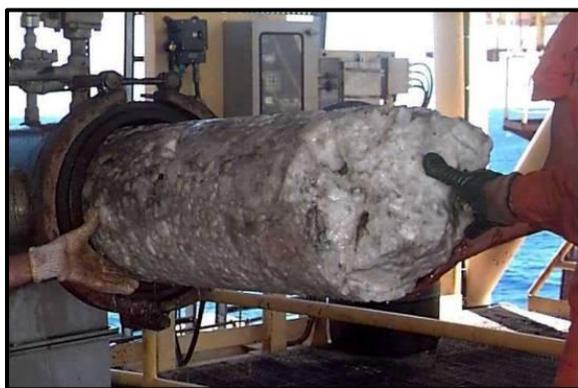


Figure 1(b). A large gas hydrate plug formed in a subsea hydrocarbon pipeline (Picture from Petrobras - Brazil).

A TEG dehydration process could be divided into two main parts, 'gas dehydration' and 'solvent regeneration'. In the dehydration stage, water is removed from the gas; while in the regeneration stage, water is removed from the solvent. After this process, the fresh glycol solution is apt again to be used in the contactor tower [4, 5]. The regeneration stage is a normal operation in the gas industries. It allows reducing undesirable solvent waste which implies mainly important economic saves.

A typical dehydration process diagram is shown in Fig. 2 [4, 5]. A lean TEG solution is fed at the top side of the contactor, while natural gas is introduced at the bottom. It leads to a countercurrent contact between the gas stream and the lean TEG solution. The contactor is an absorption column which allows mass transfer at high pressure and low temperature. Consequently, the bottom stream, which leaves the contactor unit, is a rich TEG solution with

high concentration of water and some hydrocarbons. It is depressurized by means of a pressure reducing valve. This stream enters into the regeneration stage where it is forced to pass by a flash separator in order to strip gaseous hydrocarbon and condensates which are carried by the glycol.

The rich glycol is heated in the rich-lean heat exchanger. Then it is filtered before being fed to the regenerator step. The regenerator sector includes a reboiler, a distillation column (STILL), and a surge drum. In the regenerator column, the glycol itself is stripped from the absorbed water. The process occurs almost at near atmospheric pressure by the application of external heat. The low water concentration stream that leaves the surge drum is the regenerated lean glycol. Then, it is partly cooled in the lean-rich exchanger. Finally, the solution is pumped through the glycol cooler before being recycled to the contactor.

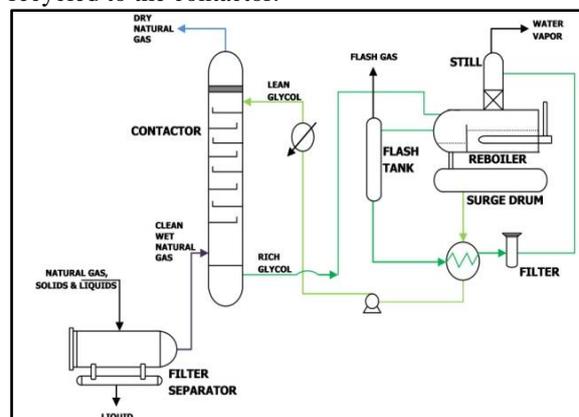


Figure 2. Diagram of a Typical Process Natural Gas Dehydration with TEG.

Evaluation of a TEG dehydration system consists of establishing the minimum TEG concentration required to reach water dew point specification in the final gas stream [6]. In order to have a precise design of a dehydration unit, data from liquid-vapor equilibrium (LVE) for TEG-water system must be accurate, particularly in the diluted water region. For this purpose, sophisticated graphs, charts and correlations are found in literature. They show these equilibrium data as water dew point of a natural gas stream in equilibrium with a TEG solution at diverse contactor temperatures and TEG concentrations (Worley, Rosman and Parrish) [7]. So, a required TEG concentration can be estimated for a particular application, or the dew point depression for a given theoretical TEG concentration at a given contactor temperature.

A better alternative for the complex graphs and correlations is the application of the correlations presented by Bahadori and Vuthaluru. The new correlation reported has been developed for the simple estimation of water dew point in a stream of

natural gas in equilibrium with a solution of TEG at different TEG concentrations and temperatures [8].

In spite of this, thermodynamic modeling of TEG-water system is still rather inaccurate, especially with regard to systems at high temperature and high TEG concentration [3]. As a consequence, the design and operation stages of absorber towers are affected by the lack of accurate data. A better alternative to these complex tools is the application of simpler correlations. Consequently, two novel correlations have been developed to estimate the equilibrium water dew point of a natural gas stream by evaluating experimental data and literature.

II. METHODS

Mathematical models for prediction of water dew point of a natural gas stream could be estimated as a linear function and a non-linear function of contactor temperature for different TEG concentration.

Correlations have been developed by evaluating experimental data and literature. The required literature data to develop the correlation is presented in Figure 20.54 in GPSA (Gas Processors and Suppliers Association Engineering Data Book, 2004). This figure is based on Parrish, et al. (1986) [7] equilibrium data, which covers VLE data for TEG-water system for contactor temperatures between 80 F and 130 F and TEG concentrations ranging from 95wt% to 99.99wt%. These data were collected and analyzed by means of an image scanning technique with MATLAB software R2012B version. MATLAB and Image Processing Toolbox provide a wide set of tools that allow users to easily handle, process and analyze data from various format image.

2.1 METHODOLOGY FOR THE DEVELOPMENT OF A LINEAR CORRELATION

Water dew point (T_d) of a natural gas stream in equilibrium with a TEG solution is correlated as a linear function of contactor temperature (T_c) for different TEG concentration in weight percent (W). Coefficients for this equation are correlated as a new function of their corresponding TEG concentrations.

The methodology that has been applied to set correlation's coefficients is summarized in the following steps:

1. The linear function $T_d = a_i + b_i T_c$ correlate the water dew point T_d of a natural gas stream in equilibrium with a solution of TEG as function of temperature of the contactor T_c , for a given concentration of TEG W_i . As a result, values of a_i and b_i are obtained which are associated to the W_i concentration.
2. Repeat step 1 for different concentrations of TEG.

3. Correlate the coefficients a_i and b_i , which were found in the previous steps, with the concentration of TEG W_i . Indeed, functions $fa(W)$ and $fb(W)$ were determined such that provides the best fit to the values a_i and b_i respectively. To obtain the appropriate structure of each of the above functions, a bank of adjustment functions was used, whose parameters were adjusted by regression. The best fit functions were selected to be part of the correlation. Fig. 3(a) and Fig. 3(b) show adjustment achieved.

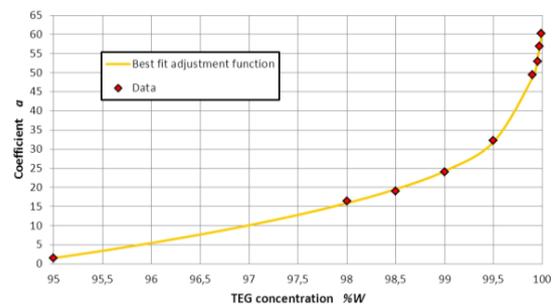


Figure 3(a). Functions $fa(W)$ that provides the best fit to the coefficients values a_i

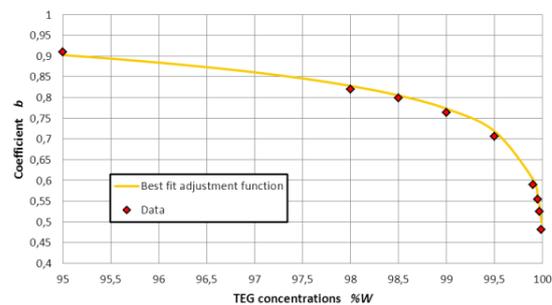


Figure 3(b). Functions $fb(W)$ that provides the best fit to the coefficients values b_i

Thus, the first proposal correlation is obtained, which is listed below:

$$T_d = a + bT_c \quad (1)$$

$$a = A_1 + \frac{B_1 W^2}{W^2 - C_1^2} + \frac{D_1 W^2}{W^2 - E_1^2} + \frac{F_1 W^2}{W^2 - G_1^2} \quad (2)$$

$$b = A_2 \exp \left(G_2 \left(\frac{1}{C_2} \ln \left(\frac{W - E_2}{B_2} \right) \right)^{D_2} \right) + F_2 \quad (3)$$

W dependence is shown in equations (2) and (3) whose coefficients are reported in Table 1.

Table 1. Coefficients used in Equations (2) and (3)

Coeff.	95%<TEG<99.99%	Coeff.	95%<TEG<99.99%
A_1	-4.368339E+01	A_2	2.109645E+00
B_1	-1.662446E+01	B_2	4.398181E+01
C_1	1.115752E+02	C_2	-1.291611E+01
D_1	-1.001244E-01	D_2	-1.057123E-01
E_1	-1.101131E+03	E_2	5.603903E+01
F_1	-1.587084E-01	F_2	-2.988238E-02
G_1	1.002125E+02	G_2	-5.000000E-01

Table 2 shows the average absolute percentage error (AAPE) from the literature reported data is 1.40% [7 – 9]. There is also an average absolute error of 0.35% compared with data source [7] which were used into the adjust step, with a maximum error of 1.00% and a minimum of 0.01%. This demonstrates an excellent accuracy and performance of the proposed correlation.

Table 2. Linear Estimation, as a linear function of the temperature of the contactor, in comparison with the literature reported data (Bahadori y Vuthaluru; Parrish et al., 1986; Herskowitz and Gottlieb, 1984) [7 – 9]

TEG Concn. Weight Percent	T_c (K)	Reported Data	Linear Correlation T_d (K)	Absolute Error Percent
95	303.15	278.15	274.43	1.34
97	318.15	284.65	282.80	0.65
98	333.15	290.65	290.21	0.15
99	283.15	243.15	241.32	0.75
99.9	303.15	232.65	228.20	1.91
99.97	283.15	210.00	204.72	2.52
99.99	303.15	211.70	206.51	2.45

Average absolute percentage error (AAPE) **1.40**

2.2 METHODOLOGY FOR THE DEVELOPMENT OF A NON-LINEAR CORRELATION

It should be possible to develop a correlation with less regression coefficients. Water dew point (T_d) of a natural gas stream in equilibrium with a TEG solution is correlated as a non-linear function of contactor temperature (T_c) for different TEG

concentration in weight percent (W). This new correlation is as follows:

$$T_d = A_3 + B_3 \ln(F_3 W + G_3) + C_3 \ln(H_3 T_c + I_3) + D_3 \ln(F_3 W + G_3)^2 + E_3 \ln(H_3 T_c + I_3)^2 \quad (4)$$

The methodology that has been applied to set correlation's coefficients is the one followed for the linear correlation. The required literature data to develop this correlation is also presented in Figure 20.54 in GPSA [7]. Table 3 shows the coefficients for the correlation obtained from the non-linear regression.

Table 3. Coefficients for the new correlation

Coefficients	95% <TEG< 99.99%
A_3	6.107109E+01
B_3	1.346193E+01
C_3	1.101468E+01
D_3	3.014112E+00
E_3	7.489034E-01
F_3	4.499560E+00
G_3	-1.073135E+03
H_3	-5.953315E+00
I_3	5.952720E+02

Table 4 shows a contrast between the results reported by the non-linear correlation with the literature reported data [7 - 9]; the average absolute percentage error (AAPE) is of 2.41%. There is also an average absolute error of 0.46% compared to data source [7] which were used into the adjust step, with a maximum error of 1.43% and a minimum of 0.01%. This demonstrates an excellent accuracy and performance of the proposed correlation.

For a second time, it is demonstrated that the results reached by using this method have an excellent accuracy and performance. Although absolute error of this correlation is 70% greater than the deflection of the first linear correlation, the number of implemented coefficients is reduced to half.

Table 4. Non-Linear Estimation, as a non-linear function of the temperature of the contactor, in comparison with the literature reported data (Parrish et al., 1986; Herskowitz and Gottlieb, 1984) [7 – 9]

TEG Concn. Weight Percent	T_c (K)	Reported Data	Non-Linear Correlation T_c (K)	Absolute Error Percent
95	303.15	278.15	280.41	0.81
97	318.15	284.65	282.44	0.78
98	333.15	290.65	284.86	1.99
99	283.15	243.15	239.11	1.66
99.9	303.15	232.65	227.86	2.06
99.97	283.15	210.00	197.17	6.11
99.99	303.15	211.70	204.37	3.46

Average absolute percentage error (AAPE) **2.41**

2.3 ASSOCIATED ERRORS

When wet gas is in contact with the rich TEG solution in the absorption column at a constant pressure and temperature, equilibrium is attained in time. Since the gas and TEG are not in contact for a long enough time to reach the state of equilibrium, the actual water dew point is always higher than the equilibrium dew point ($T_{d,eq}$). Consequently, the actual dew point of an output gas stream ($T_{d,act}$) depends on the TEG circulation rate and the number of equilibrium stages. A well-designed and properly operated unit will have an actual water dew point of 6 to 11°C higher than the equilibrium dew point [10].

$$T_{d,act} = T_{d,eq} + (6 \text{ to } 11)^\circ C \quad (5)$$

There is no practical requirement to include temperatures higher than 130 F in the analysis of this study. For higher inlet gas temperatures a cooler is used to limit the TEG loss with dehydrated gas. Both linear and non-linear correlations should be used up to 10.300 kPa (abs) with little error. This is because equilibrium dew points are relatively insensitive to pressure [7, 8].

III. EXAMPLE

A simple example is presented to illustrate the associated simplicity with the use of the proposed correlation for the simple estimation of natural gas water dew point at different temperatures and concentrations of TEG.

0.85 Million Sm³/day of a natural gas stream enters to a TEG contactor at 38 °C and 4100 kPa (abs). The target H₂O dew point is 4 °C (269.15 K).

Calculate the lean TEG concentration in mass percent at this given temperature (38 °C). Assume a 6 °C approach to equilibrium:

To find the solution, value of W must be iterated until find the one which causes the actual dew point equal to 269.15 K; $T_{d,act} = T_d + 6$ K. The following calculations are performed using the two proposed correlations in this work.

3.1 LINEAR CORRELATION

A- Assume TEG concentration $W = 98\%$

Applying equations (2) and (3), we obtain: $a=15.9124886$ y $b=0.82334051$

Equilibrium water dew point of gas stream was calculated by equation (1) is $T_{d,eq}=272.09$ K. Actual water dew point is $T_{d,act}= 272.09 + 6 = 278.09$ K.

B- Assume TEG concentration $W = 98.9\%$

Applying equations (2) and (3), we obtain: $a=23.2088603$ y $b=0.77423461$

Equilibrium water dew point of gas stream was calculated by equation (1) is $T_{d,eq}=264.11$ K. Actual water dew point is $T_{d,act}= 264.11 + 6 = 270.11$ K.

C- Assume TEG concentration $W = 98.97\%$

Applying equations (2) and (3), we obtain: $a=23.9550366$ y $b=0.76887996$

Equilibrium water dew point of gas stream was calculated by equation (1) is $T_{d,eq}=263.19$ K. Actual water dew point is $T_{d,act}= 263.19 + 6 = 269.19$ K.

3.2 NON-LINEAR CORRELATION

a- Assume TEG concentration $W = 98\%$

Equilibrium water dew point of gas stream was calculated by equation (4) is $T_{d,eq}=271.85$ K. Actual water dew point is $T_{d,act} = 271.85 + 6 = 277.85$ K.

B- Assume TEG concentration $W = 98.9\%$

Equilibrium water dew point of gas stream was calculated by equation (4) is $T_{d,eq}=263.26$ K. Actual water dew point is $T_{d,act} = 263.26 + 6 = 269.26$ K.

C- Assume TEG concentration $W = 98.91\%$

Equilibrium water dew point of gas stream was calculated by equation (4) is $T_{d,eq}=263.14$ K. Actual water dew point is $T_{d,act} = 263.14 + 6 = 269.14$ K.

IV. RESULTS AND DISCUSSIONS

The linear correlation result $T_{d,act}=269.19$ K has good concordance with expected water dew point ($T_d=269.15$ K). So required glycol purity to meets targeted water dew point is $W=98.97\%$. The obtained

non-linear correlation result $T_{d,act}= 269.14$ K has good concordance with the expected water dew point ($T_d=269.15$ K). So required glycol concentration to reach the required water dew point is $W =98.91$ %.

It is noted that using the correlation developed by Bahadori and Vuthaluru [8] to solve the proposed example, they obtained a TEG concentration equal to $W =99.02$ %. This shows an excellent performance of proposed correlation.

V. CONCLUSIONS

Two novel correlations have been developed to estimate the equilibrium water dew point of a natural gas stream. These equations are much simpler than currently available models involving a large number of parameters, requiring more complicated and longer computations. They tend to replace cumbersome, complex tables and graphs which are generally used in the design and operation of gas dehydration systems. Therefore, results show an excellent performance of proposed correlations. Results are quite accurate and they are consistent with experimental and literature data. Due to the simplicity and precision of the correlations developed in this work, the equations obtained have a great practical value. Due to the simplicity and precision of the correlations developed in this work, the equations have a great practical value. Indeed, they are basic algebraic equations that can be easily implemented in a spreadsheet. Consequently, they allow process engineers to perform a quick check of the water dew point at different conditions without using complex expressions or graphics. Additionally, these correlations are also useful in the design of the absorber in the dehydration process.

NOMENCLATURE

A_i	Coefficient
B_i	Coefficient
C_i	Coefficient
D_i	Coefficient
E_i	Coefficient
F_i	Coefficient
G_i	Coefficient
H_i	Coefficient
I_i	Coefficient
T_d	Water Dew Point, K
$T_{d,eq}$	Equilibrium Water Dew Point, K
$T_{d,act}$	Actual Water Dew Point, K
T_c	Contacting Temperature, K
W	TEG concentration in water solution, (weight percent)

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