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Improving performance of absorption tower in natural gas dehydration process

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Abstract

Absorption tower is the most important section of a natural gas dehydration plant. In this paper the effect of some influential factors such as temperature and flow rate of TEG entering the tower, number of equilibrium stages and liquid fractional entrainment in gas phase on performance of dehydration absorption tower is investigated. Entrainment is one of the most effective factors on tray tower performance, particularly absorption towers where the liquid concentration is much higher than the vapor in equilibrium with it. The effect of this parameter has not been considered in commonplace simulating softwares. Having extracted an equation for the fractional entrainment factor with the aid of Fair empirical correlation, a simulator is prepared using VC^{++} programming language containing 9000 lines of source code which includes subprograms for simulating absorption, desorption and distillation towers, heat exchangers, condensers and flash drums. Input data corresponded to TEG dehydration unit of Asaloye gas field in Iran. The simulation results show that increasing TEG inlet temperature decreases water absorption efficiency while increasing TEG flow rate and number of stages increases this efficiency as well as absorption of pollutants like benzene and toluene. Finally it was observed that increasing entrainment decreases water absorption efficiency as expected.

Keywords: Dehydration, Absorption Towers, TEG, Entrainment, Simulation

1. Introduction

All gasses have the capacity to hold water in a vapor state. This water vapor must be removed from the gas stream in order to prevent the formation of solid ice-like crystals called hydrates. Hydrates can block pipelines, valves and other process equipment. The dehydration of natural gas must begin at the source of the gas in order to protect the transmission system. Pipeline drips installed near well heads and at strategic locations along gathering and trunk lines will eliminate most of the free water lifted from the wells in the gas stream. Multi stage separators can also be deployed to insure the reduction of free water that may be present (Company of royal Dutch/shell group, 1994, Ikhlaq, M., 1992).

Joule-Thomson Expansion utilizes temperature drop to remove condensed water to yield dehydrated natural gas. The principal is the same as the removal of humidity from

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outside air as a result of air conditioning. In some cases glycol may be injected into the gas stream ahead of the heat exchanger to achieve lower temperatures before expansion into a low temperature separator.

Solid desiccant dehydration, also known as solid bed, employs the principal of adsorption to remove water vapor. Adsorbents used include silica gel (most commonly used), molecular sieve (common in NGV dryers), activated alumina and activated carbon. The wet gas enters into an inlet separator to insure removal of contaminants and free water. The gas stream is then directed into an adsorption tower where the water is adsorbed by the desiccant.

The third method of dehydration which has been dealt in this study is via liquid desiccants. This method removes water from the gas stream by counter current contact in a tray type contactor tower with some adsorbents such as tri-ethylene glycol (TEG). Natural gas enters the unit at the bottom of the adsorber tower and rises through the tower were it is intimately contacted with the TEG solution flowing downward across bubble trays. Through this contact, the gas gives up its water vapor to the TEG. The water laden TEG is circulated in a closed system, where the water is driven off from the TEG. The regenerated TEG is then recirculated to the contacting tower (Company of royal Dutch/shell group, 1994, Ikhlaq, M., 1992). A schematic view of a dehydration process with the aid of TEG is represented in Figure 1.

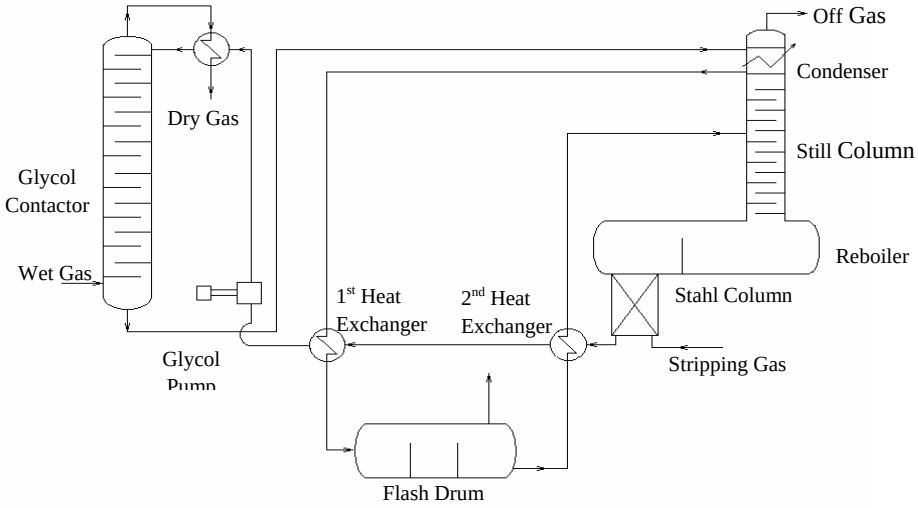

Figure 1. Schematic view of TEG dehydration process

Absorption tower is the most important section of a dehydration unit. Principal role of the regeneration section is TEG consumption optimizing. In this study the effect of temperature and flow rate of TEG entering the tower, number of equilibrium stages and fractional entrainment parameter on absorption tower performance has been investigated. Logically increasing TEG flow rate and number of stages will increase moisture absorption. Since absorption is an exothermic process temperature increase,

decreases dehydration efficiency. The effect of entrainment factor not taken into account in common simulation softwares of chemical processes has been taken into consideration in the model developed as a base for the present simulation.

Liquid entrainment in a plate column is the liquid carried with the vapor from a plate to the plate above. It is detrimental in that the effective plate efficiency is lowered because liquid from a plate of lower volatility is carried to a plate of higher volatility, thereby diluting distillation or absorption effects. Entrainment is also detrimental when nonvolatile impurities are carried upward to contaminate the overhead product from the column.

Many experimental studies of entrainment have been made, but few of them have been made under actual distillation conditions. The studies are often questionable because they are limited to the air water system, and do not use a realistic method for collecting and measuring the amount of entrainment. Tray spacing, liquid height on trays and liquid and vapor velocity between trays are the most important factors which influence entrainment in tray columns. It is clear that the dominant variable affecting entrainment is gas velocity through the two-phase zone on the plate. Entrainment has a minor impact on close separations when the difference between vapor and liquid concentration is small, but this factor can be dominant for systems where the liquid concentration is much higher than the vapor in equilibrium with it (i.e., when a component of the liquid has a very low volatility, as in an absorber, Perry, R.H. and Green, D.W., 1997). The main part of this study is focused on the impact of entrainment factor on tray efficiency of dehydration absorption columns.

2. Model description

Four sets of equations, mass balance, equilibrium relations, sum of mole fractions of each phase and heat balance (the so called MESH equations) are used to describe tray columns treatment. Material balance of component *i* on tray *j*, for liquid phase without sidestream is as follows (Seader, J.D. and Henley, E.J., 1998):

$$L_j x_{i,j} - L_{j+1} x_{i,j+1} - F^l_{i,j} = 0 \qquad (1)$$

Where, L is Liquid molar flow rate, x is Mole fraction in liquid phase, F is feed molar flow rate and the superscript l refers to liquid phase. Considering the impact of entrainment factor in vapor phase the following equation will be obtained:

$$(1 + E^l_j) L_j x_{i,j} - L_{j+1} x_{i,j+1} - E^l_{j-1} L_{j-1} x_{i,j-1} - F^l_{i,j} = 0 \qquad (2)$$

As can be seen, a part of component *i* which enters tray *j* from *j*-1 and also enters tray *j*+1 from *j*, along with vapor in liquid form is taken into account in the above equation. It is obvious that as fractional entrainment increases, calculated values of Equation (2) become more different than that of Equation (1). The same equations could be written for the gas phase. Equilibrium relation for component *i* at tray *j* is given by:

$$K_{i,j} = y_{i,j} / x_{i,j} \qquad (3)$$

Where, K is equilibrium constant. Sum of mole fraction of each phase are written as follows:

$$\sum_{i=1}^{N} y_{i,j} - 1.0 = 0\,,\ \sum_{i=1}^{N} x_{i,j} - 1.0 = 0 \tag{4}$$

Energy balance equation is as follows:

$$L_{j+1}H_{L_{j+1}} + V_{j-1}H_{V_{j-1}} + F_j H_{F_j} - L_j H_{L_j} - V_j H_{V_j} - Q_j = 0 \tag{5}$$

Saturation pressure of TEG is evaluated by the following equation:

$$p_i^{sat} = P_{ci}\, exp\left[\frac{(4.92\omega_i + 5.81)Ln(T_{ri}) - 0.0838(4.92\omega_i + 2.06)}{\left(\frac{36}{T_{ri}} - 35 - T_{ri}^6 + 42Ln(T_{ri})\right)}\right] \tag{6}$$

Where, ω is acentric factor and subscripts *c* and *r* refer to critical and reduced properties ($T_{ri} = T/T_{ci}$), respectively. Saturation pressure of components other than TEG is evaluated by:

$$p_i^{sat} = a_i + \frac{b_i}{(T + c_i)} + d_i LnT + e_i T^{f_i} \tag{7}$$

Where *a*, *b*, *c*, *d*, *e* and *f* are constants which are available in literatures for each component (Prausnitz, J.M., 1999) Real enthalpy of components is calculated by combination of ideal gas enthalpy and residual enthalpy of gases and liquids. Ideal gas enthalpy is evaluated by:

$$H_i^{ig} = a' + b'T + c'T^2 + d'T^3 + e'T^4 + f'T^5 \tag{8}$$

a', b', c', d', e' and f' could be found in literature (Prausnitz, J.M., 1999). General form of gas and liquid residual enthalpy are as follows:

$$\frac{H - H^{ig}}{RT} = \frac{1}{RT}\int_0^P \left[\forall - T\left(\frac{\partial \forall}{\partial T}\right)_p\right] dP \tag{9}$$

$$\left(\frac{\partial Lnf_i^l}{\partial T}\right)_{P,x} = -\frac{\overline{H}_i - H_i^+}{RT^2} \tag{10}$$

Where $\overline{H}_i$ and H_i^+ are fractional molar enthalpy of component *i* in liquid phase and ideal gas state, respectively. With regards to the type of applied equilibrium relations, liquid and gas residual enthalpy could be extracted by equations of state and activity model relations. Peng Robinson (PR) equation is the most common equation of state applied for hydrocarbons. In the present work standard PR, HYSYS extracted PR (HYSYS-PR) and PR Stryjek-Vera (PRSV) equations are used. Wilson activity model is utilized for prediction of liquid phase treatment. Evaluating fugacity coefficient of gas phase (φ_i^v) from PR equation of state and activity coefficient (γ_i) from Wilson activity model, the following equilibrium relation could be applied:

$$y_i \varphi_i^v P = x_i \gamma_i p_i^{sat} \varphi_i^{sat} \tag{11}$$

2.1 Relevant relations of entrainment factor

Applying Fair diagram is the most usual method for extraction of entrainment factor. In this diagram with the aid of flooding percentage and $(L/V)(\rho_V/\rho_L)^{0.5}$, fractional entrainment will be evaluated. In order to use entrainment factor in material balance relations, an equation should be determined for it using Fair diagram [3]. For this, the relevant diagram is scanned and its lines coordinate is extracted using a diagram processing software (Grafula). Then some equations have been fitted for extracted points. The most accurate equation which has been obtained for flooding percentage, *z*, is given by:

$$z = \frac{a + c\alpha + e\beta + g\alpha^2 + i\beta^2 + k\alpha\beta}{1 + b\alpha + d\beta + f\alpha^2 + h\beta^2 + j\alpha\beta} \quad (12)$$

Where, *y* is fractional entrainment of liquid in vapor phase, $\alpha = Ln(x)$, $\beta = Ln(y)$ and $x = (L/V)(\rho_V/\rho_L)^{0.5}$. Parameters in Equation (12) are as follows:

a = 0.28362298 *b* = 0.40892497 *c* = 0.09919173 *d* = 0.28949153
e = 0.04985902 *f* = 0.04823497 *g* = 0.01522077 *h* = 0.02127136
i= 0.00185708 *j* = 0.06888185 *k* = 0.01413295

y in Equation (12) is a dependent variable which should be extracted. Using numerical root defining method the best real root is as follows:

$$y = exp\left[\frac{\left(z(1 + b\alpha + d\beta + f\alpha^2 + h\beta^2 + j\alpha\beta\right) - \left(a + c\alpha + g\alpha^2 + i\beta^2 + k\alpha\beta\right)}{e}\right] \quad (13)$$

Variables and parameters of this equation are similar to Equation (12). Evaluation of gas in liquid fractional entrainment is more difficult than that of liquid in gas phase and no diagram or equation is presented for estimation of this parameter until now.

Taking entrainment factor into account, a simulation program has been developed for the dehydration of natural gas. This simulator is prepared using VC^{++} programming language in 9000 lines of source code and includes subprograms for simulating absorption, desorption and distillation columns, heat exchangers, condensers and flash drums. Input data correspond to TEG dehydration unit of Asaloye gas field in Iran (Table 1).

Table 1- Simulator input data from Asaloye gas field in Iran

Wet Gas	
Components mole fraction	
Water	0.001420
CO_2	0.013200
H_2S	0.000001
N_2	0.035200
CH_4	0.853000
C_2H_6	0.055400
C_3H_8	0.023500
i-C_4H_{10}	0.004600
n-C_4H_{10}	0.006690
i-C_5H_{12}	0.001890
n-C_5H_{12}	0.001762
C_6+	0.003920
Benzene	0.000045
Toluene	0.000030
Flow rate (*kmol/hr*)	2403.00
Pressure (*bar*)	73.20
Temperature (°*C*)	40.00
Lean TEG	
Components mole fraction	
TEG	1.00
Flow rate (*kmol/hr*)	104.46
Pressure (*bar*)	71.20
Temperature (°*C*)	45.00

3. Results and discussion

3.1 TEG flow rate

Absorption of toluene and benzene which cause environmental pollution is investigated besides water in this section. Absorbed toluene and benzene in absorption column are exhausted to the environment in regeneration section. Since disposal of such pollutants should be kept at a specified level, TEG flow rate is regulated in an optimum value at which not only dehydration efficiency becomes maximum (economical aspects) but also air pollution criteria are considered (environmental aspects). Water, toluene and benzene absorption rate variations as a function of TEG flow rate is depicted in Figure 2.

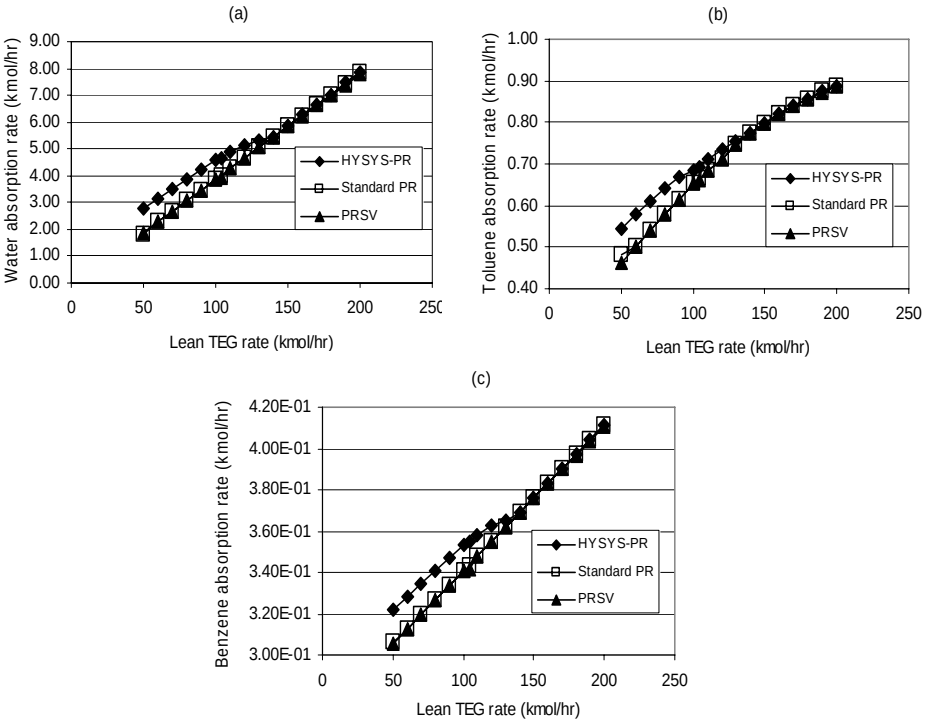

Figure 2. Variation of (a) water (b) toluene and (c) benzene absorption rate with lean TEG flow rate

According to this figure, increasing TEG flow rate increases water absorption rate (dehydration efficiency) as well as that of toluene and benzene. As can be seen, standard PR results coincide with PRSV at all TEG flow rates while HYSYS-PR results show some deviation at lower flow rates.

3.2 TEG temperature

Water absorption rate as a function of lean TEG temperature is represented in Figure 3. Since absorption is an exothermic process, increasing input TEG temperature decreases water absorption rate. In real dehydration plants temperature of TEG entering the absorption tower is kept at 5-6 °*C* more than entering gas temperature (Manning, W.P. and Wood, H.S., 1993). Figure 3 shows that, HYSYS-PR, standard PR and PRSV results are almost the same at different lean TEG temperatures.

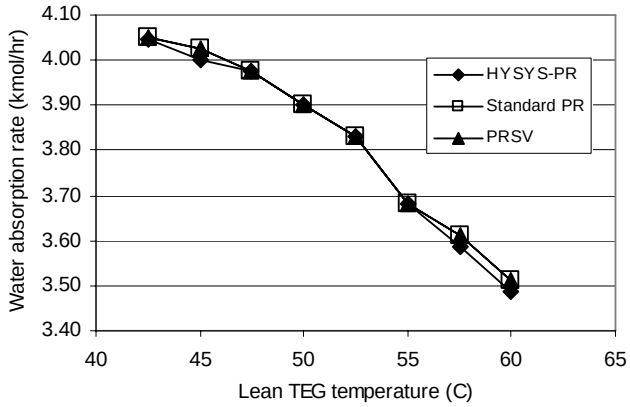

Figure 3. Water absorption rate as a function of lean TEG temperature

3.3 Number of stages

The effect of number of stages on water absorption rate is shown in Figure 4. As can be seen, using HYSYS-PR equation of state, the simulator gives different results from that of standard PR and PRSV. Increasing number of equilibrium stages increases water absorption rate as well as manufacture and maintenance costs. Therefore an optimum number of stages should be specified based on required amount of water absorption and economic aspects.

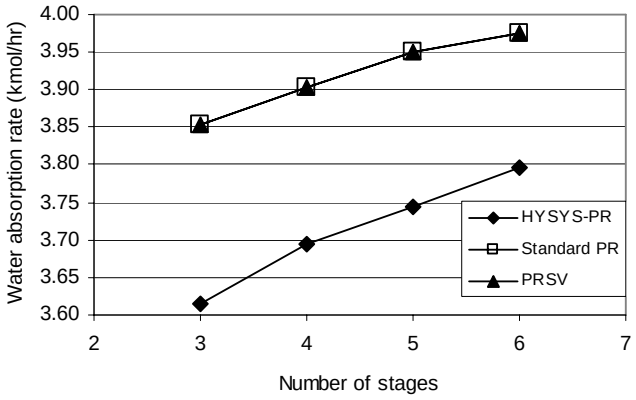

Figure 4. Water absorption rate as a function of number of stages

3.4 Fractional entrainment factor

The effect of flooding percentage on water concentration in leaving dry gas and on TEG flow rate in the liquid leaving the column are illustrated in Figures (5) and (6), respectively. Flooding percentage is utilized in these figures due to its effect on entrainment factor based on Fair empirical correlation and Equation 13.

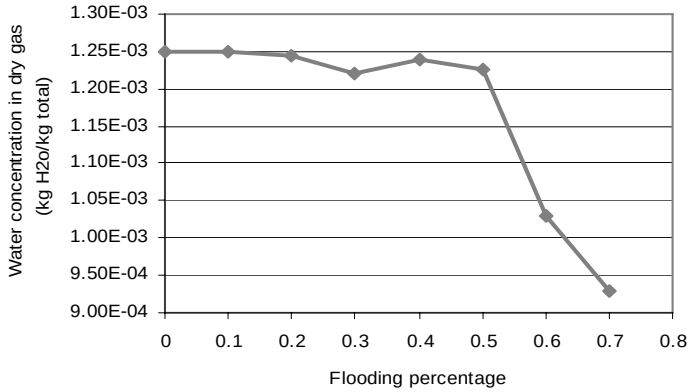

Figure 5. Variation of water concentration in dry gas with flooding percentage

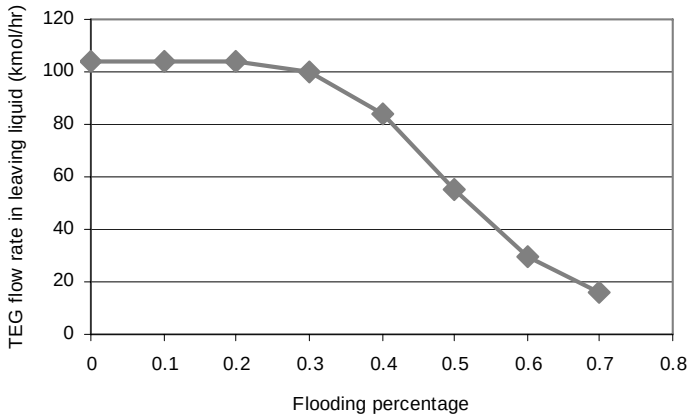

Figure 6. Variation of TEG flow rate in the liquid leaving column with flooding percentage

Figure (5) shows that, increasing flooding percentage decreases water concentration in leaving dry gas and consequently performance of absorption tower improves. But as can be seen in Figure (6), increasing flooding percentage, decreases TEG flow rate which means that TEG concentration in gas phase has been increased because of entrainment phenomena. Eventually it can be concluded that water concentration decrease is due to leaving gas flow rate increase, but not column performance improvement.

4. Conclusion

In the present work the effect of some process parameters on dehydration performance of an absorption tower were investigated. Entrainment of liquid in gas phase was one of these parameters. This parameter was not found in any of the accessible simulation softwares. Hence for studying the effect of this parameter a simulator was developed.

First of all, subprograms related to thermodynamics equations were written. Then the routines related to mass and energy balances and equilibrium relations were provided. Finally, using these subprograms and existing models, programming was accomplished for absorption column of dehydration plant and a simulator was developed. TEG dehydration unit of Asaloye gas field in Iran was simulated using the present simulator. The results showed that increasing flow rate and number of stages increases dehydration efficiency which is in contrast with the behavior of process as temperature and fractional entrainment increased. It has also been found that using HYSYS-PR equation of state gives almost different results from that of standard PR and PRSV.

5. Notation

L	Liquid molar flow rate (*kmol/hr*)
x	Mole fraction in liquid phase
V	Vapor molar flow rate (*kmol/hr*)
F	Feed molar flow rate (*kmol/hr*)
E	Fractional entrainment
K	Equilibrium constant
H	Liquid/vapor molar enthalpy (*J/kmol*)
Q	Molar heat rate (*J/hr*)
P	Pressure (*bar*)
T	Temperature (*°C*)
H^+	Pure component enthalpy in ideal gas state (*J/kmol*)
$\overline{H}$	Fractional molar enthalpy in liquid phase (*J/kmol*)
ρ	Density (kg/m^3)
z	Flooding percentage
y	Mole fraction in gas phase, Fractional entrainment of liquid in gas phase
R	Universal gas constant (*J/kmol °C*)
$\forall$	Volume (m^3)
ω	Acentric factor
f	Fugacity (*bar*)
φ	Fugacity coefficient
γ	Activity coefficient

Subscript

i	Component *i*
j	Tray *j*
V	Gas phase
L	Liquid phase
c	Critical
r	Reduced

Superscript

l	Liquid phase
v	Vapor
ig	Ideal gas
sat	Saturation

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