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Predicting the Cricondenbar of Lean Natural Gas

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Abstract

This work focuses on predicting lean sweet natural gas cricondenbar. This is an important parameter used in predicting the phase envelope, which determines whether the transported gas is in a single gas phase or a two phase (gas and liquid) and in compressor horsepower sizing and selection. Equations of state are the best methods for predicting natural gas cricondenbar, but they are usually very tedious and rigorous. For instance the use of an equation of state requires the knowledge of the gas critical properties, Acentric factors, Molecular Weight and Binary interaction parameters some of which are not so easy to get. In this study, a FORTRAN compiler was used to generate natural gas composition data in the range of lean and processed natural gas with a specific gravity of 0.58 to 0.69. From the data generated, a correlation was found to exist between the specific gravity of the gas and the cricondenbar. A relationship between natural gas cricondenbar and apparent molecular weight of natural gas was developed. This model was then tested with the calculated cricondenbar of fourteen (14) different natural gases obtained from the field and literature using the SRK equation of state phase envelope utility tool of ASPEN HYSIS software. The results gave a percentage average relative deviation and average absolute deviation of 1.85 and 5.3 respectively.

Introduction

The presence of liquid hydrocarbons in natural gas transmission lines has become much more prevalent in recent past due to increasing natural gas prices relative to natural gas liquids (Todd et al, 2010). Hydrocarbon liquid condensation can lead to a number of problems in gas distribution and transmission lines. These may include increased pressure drop, increased compression costs, reduced line capacity, frequent pigging operations, flame extinguishing or over-firing in home appliances, physical damage to gas turbines used to generate electricity, corrosion and compressor damage. Condensed hydrocarbon liquids present in pipelines asides operational and safety problems can also result in significant measurement error and volume/energy losses. If such liquids enter the gas sampling points, the sample will not be representative of the flowing gas stream, which can lead to inaccurate energy data (calorific content). Rich gas is partially processed natural gas transported with an appreciable amount of condensable liquid hydrocarbons. In such cases, the capacity of the pipelines is limited by the lowest possible arrival pressure

– the cricodenbar (Ø. Mørch et. al, 2006). To avoid liquid condensation, operating specifications for gas transmission require that the pipelines be operated above the hydrocarbon dew point (HDP) or cricondentherm /cricondenbar hydrocarbon dew point. Hydrocarbon liquids in distribution systems can be carried from main transmission lines or can result from retrograde condensation downstream of the pressure regulating station and the corresponding Joule Thomson (JT) cooling effect. Most pipelines usually have a small amount of hydrocarbon liquids from compressor oils. Additional liquids would be formed by retrograde condensation any time the HCDP is reached through cooling or pressure reduction. The volume of additional liquids depends on the amount and composition of the C_{6+} in the gas stream.

Gas transmission and distribution lines are one of the core assets in the gas utilization value chain. As the gas pressure is reduced, the temperature also will be reduced (the Joule Thomson effect). If there exist an appreciable amount of condensable hydrocarbons in the gas, a pressure reduction is enough to cool the gas to below the corresponding hydrocarbon dew point, thereby causing liquids to condense. Also, existing preheaters, separators or knockout vessels may be overwhelmed as to their capability to handling more than their design capacity for handling excess liquids (Gas quality white paper, 2005). As a result, the operation of these lines must be devoid of such problems as liquid condensation. A major operational consideration for gas pipelines is hydrocarbon liquid condensation from the natural gas. In order to avoid hydrocarbon condensation or ″liquid dropout″ in gas pipelines, various control parameters have been monitored and assigned limits. These parameters include (Jerry, A. et al, 2009):

1. C6+ GPM (gallons of liquid per thousand standard cubic feet of gas),
2. Mole fraction C6+,
3. Hydrocarbon dew point (HDP)
4. Cricondentherm hydrocarbon dew point (CHDP).

Cricondenbar

This is defined as the highest pressure at which a mixture can exist in the two phase regions. It can also be defined as the minimum pressure above which mixtures exist only in the gas phase (J. Herring, 2011). A specification made on hydrocarbon dew point is often related to the cricondenbar (Michalsen, K and Naevdal, H, 2014).

In order for the gas to remain in a single gas phase during transportation, the minimum pressure must be set above the cricondenbar (figure 1) to prevent liquid drop out. This is usually done by appropriate compressor horsepower sizing and selection. Also, during experimental dew point determination, in order for the gas composition to be representative, the gas from the storage cylinder must be flowed into the experimental rig at a pressure above the cricondenbar so as to prevent the condensation of the heavy components in the gas, which could result in erroneous hydrocarbon dew point measurement (D. L. George, 2006.)

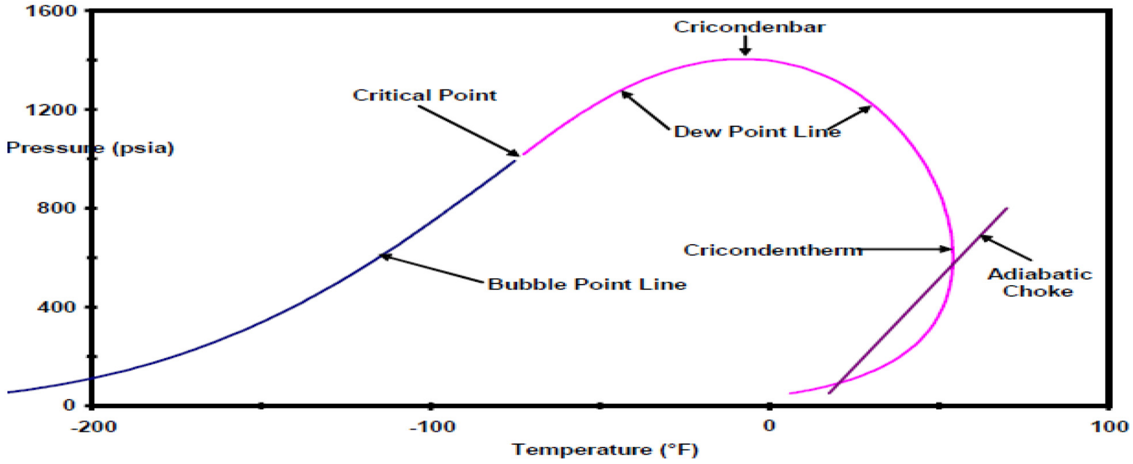


Figure 1—Phase Envelope for a Lean Natural Gas
Source: Todd et al, 2009

Literature Review

Etter (1961) developed empirical correlations for calculating critical, cricondentherm and cricondenbar pressure and temperature value of phase envelope for multicomponent mixtures of normal paraffins. They generated a set of equations to calculate the pressure and temperature value of the critical, cricondentherm and cricondenbar obtained from plotting the critical pressure and the average molecular weight and also from a plot of the temperature with the average molecular weight for binary mixtures. These empirical calculations were specific to individual paraffin which required constants which are not easily obtainable. Although it was shown that this method gave reasonable result with the normal paraffin investigated, the procedures were quite rigorous. The correlation for predicting natural gas cricondenbar (equation 1) is given below.

$$\left(P_{CD}\right)_{Mix} = \sum x_i P_{Ci} + \sum \Phi\left(P_{cidi}\right) \tag{1}$$

Grieves et al (1963) developed a correlation using graphical interpretation for calculating the cricondentherm and cricondenbar temperature. His work was more general for reservoir fluid with maximum and minimum error percentage of 2.41 and 0.26 respectively for cricondentherm and 0.84-9.52 for the cricondenbar pressure when compared with experimental data. To calculate the temperature for the cricondentherm and cricondenbar the input parameters needed were the critical temperatures of the pure components, normal boiling points and approximate vapor pressures. Also the cricondenbar pressure was extrapolated from the plot of $P_{p/}Pc$ versus T^{i}_{b}/T_{b}. These correlations, equations 2 to 5 require input parameters which are not readily available and hence make the process rigorous.

$$T_t / T^I - 1 = \left[\frac{T_b^{\,1}}{T_b} - 1\right] e^{5.4x\ell - 3.39} + 0.01; 0 < x\ell \le 0.55 \tag{2}$$

$$T_t / T_c^{\,I} - 1 = \left[\frac{T_b^{\,1}}{T_b} - 1\right] e^{6.38x\ell - 4.38} - 0.418x\ell + 0.256; 0.55 < x\ell \le 0.925 \tag{3}$$

$$T_P / T_c^{\,I} - 1 = \left[\frac{T_b^{\,1}}{T_b} - 1\right] e^{4.33x\ell - 3.62} + 0.008; 0 < x\ell < 0.7 \tag{4}$$

$$T_P / T_c^{\,I} - 1 = \left[\frac{T_b^{\,1}}{T_b} - 1\right] e^{6.33x\ell - 5.14} - 0.165x\ell + 0.116; 0.7 < x\ell \le 0.925 \tag{5}$$

Firoozabadi (2006) proposed that the composition changes which occur are often limited in some applications and that there is a need to calculate the critical point as many as 108 times. A major motivation of their work was that current methods lack robustness and efficiency for the calculation of the critical point for multicomponent mixtures. Most of the current methods were based on reducing the pressure in stages and carrying out phase split calculations. These methods mostly require rigorous calculations with numerous iterations, which is time consuming and also the predictions are not very accurate due to errors associated with equilibrium calculations.

R. Taraf, R. Behbahani and Mahmood Moshfeghian (2008): Presented a numerical algorithm for calculating the cricondenbar and cricondentherm coordinates of natural gas mixtures of known composition based on the Michelsen method. The equilibrium mole fractions at these points were calculated. In the algorithm presented, the property of the distance from the free energy surfaces to a tangent plane in equilibrium condition was added to saturation calculation as an additional criterion. An equation of state (EoS) was used to calculate all required properties. The algorithm was tested with Soave-Redlich-Kwong

(SRK), Peng-Robinson (PR), and modified Nasrifar-Moshfeghian (MNM) equations of state. For different EoSs, the impact of the binary interaction coefficient *(k*ij) was studied. The impact of initial guesses for temperature and pressure was also studied. The convergence speed and the accuracy of the results of the algorithm when compared with experimental data and the results from other methods and simulation software such as Hysys, Aspen Plus, and EzThermo were satisfactory.

Yunusa A. Abass (2009): Presented an Artificial Neural Network model for the prediction of critical point, cricondentherm and cricondenbar. He presented an expert system which is capable of understanding the complexities of the relationship between the composition and the corresponding values of the key points on the phase envelope. The expert system was able to predict the most relevant input among the compositional data of the reservoir fluid. A four stage neural network was proposed and it was found that, when compared with other constituents that make up the hydrocarbon mixture, the most relevant and consistent of all the input compositional data used in the neural network prediction of the phase envelope, was the C7+ for all the stages examined.

Conventional Methods for Cricodenbar Estmation

The common methods used to determine natural gas cricondenbar are

1. Direct measurement using a chilled mirror procedure
2. Indirect measurement using compositional analysis from a gas chromatograph (GC) combined with an equation of state (EOS).

Chilled Mirror Method

This method is conceptually quite simple and consists of flowing a gas stream past a mirror that is being cooled or chilled. The temperature at which the first condensation or dew is observed on the mirror is the dew point. In this method the estimation of crondenbar is done by generating the phase envelope and then estimating the cricondenbar from it. But this method of first generating the phase envelope would be difficult since a series of measurements at various pressures would be required. The chilled mirror method yields the best results when tests are performed by qualified operators. (Todd et al, 2009).

Figure 2—The Bureau of Mines Dew Point Meter
***Source*: AMETEK, (2009) ″Dew point testers [brochure].″ AMETEK Inc, Pittsburgh, PA,**

Gas Chromatograph - Equation of State (GC-EOS) Method

This method uses a gas chromatograph (GC) for compositional analysis in conjunction with an equation of state (EOS) to calculate the cricodenbar. For the most part, the accuracy of this method depends on the accurate characterization of the C_{6+} components which are typically determined using any of the appropriate methods for C_{6+} characterization. Either a Peng-Robinson (PR) or Soave-Redlich-Kwong (SRK) equation of state is typically used for the calculations.

Developing the Prediction Model

The data used in this work was generated using the FORTRAN compiler. A program was written to generate different natural gas composition combinations in the range described in Table 1. Hydrocarbon compositions from methane C_1, through octane C_8 as well as non hydrocarbons like carbon IV oxide CO_2 and Nitrogen N_2 were used in this study. The sum of the mole fractions of all the components in the mixture was set at 1, Eq 6.

Table 1—Range of Natural Gas Percentage Composition

Components	Minimum	Maximum
Methane (C_1)	83	94
Ethane (C_2)	2	8
Propane (C_3)	0	5
Iso Butane (i- C_4)	0	2
Normal Butane (n- C_4)	0	4
Iso Pentane (i-C_5)	0	1
Normal Pentane (n-C_5)	0	0.93
Normal Hexane (n-C_6)	0	0.08
Normal Heptane (n-C_7)	0	0.013
Normal Octane (n- C_8)	0	0.011
Nitrogen (N_2)	0	7
Carbon IV Oxide (CO_2)	0	1.8

$$\sum (x_i) = 1 \tag{6}$$

The methane (C_1) composition was generated using Eq.7 given below and bounded by Eq. 6 for all the possible combination of natural gas mixture considered.

$$C_1 = 1 - \sum (CO_2 + N_2 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 + C_8) \tag{7}$$

Similarly other component mole fraction was also generated using equation 7 and subjecting it to the boundary condition given in equation 6. The possible combination with the ranges of inputs data in Table 1 would obviously be infinite; hence the data generated was carefully selected to give a better representation of real natural gas composition. The specific gravity used in this work ranged from 0.58 to 0.69.

The specific gravity of the natural gas compositions used was calculated from the equation

$$\alpha_g = \frac{M_a}{28.96} \tag{8}$$

Where

$$M_a = \sum_{i=1} x_i M_i \tag{9}$$

The cricondenbar for each gas composition was calculated by the SRK equation of state tool in the phase envelope utility of ASPEN HYSIS software. The values of the calculated specific gravity were found to have a polynomial relationship with the calculated cricondenbar equation 10.

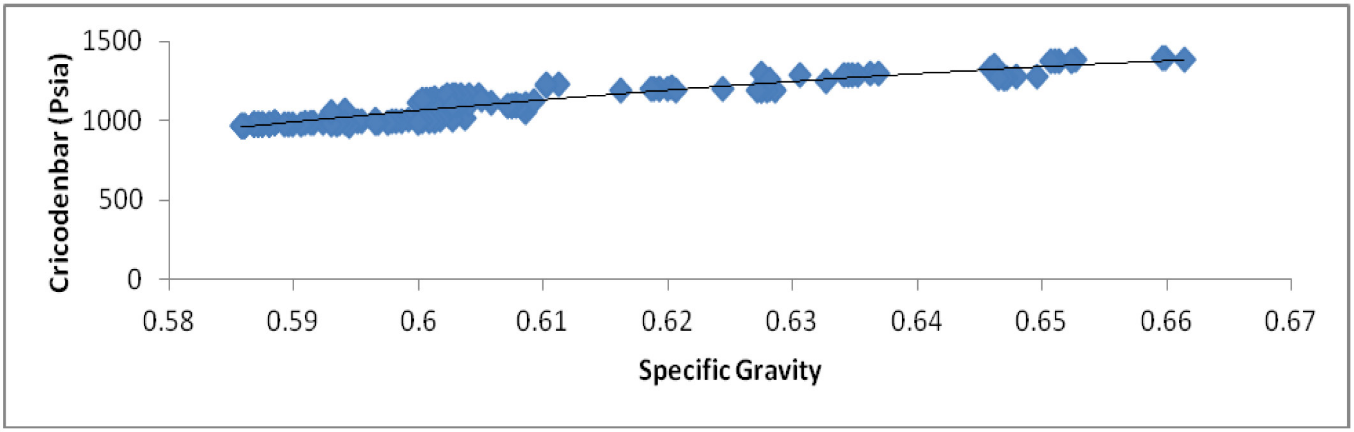


Figure 3—Relationship Between Specific Gravity and Cricondenbar

The relationship between the calculated cricondenbar and specific gravity is of the form;

$$P_{cb} = -a\alpha_g^2 + b\alpha_g - c \tag{10}$$

Where a = 28767, b = 41466 and c = 13459
Substituting equation 8 in equation 10, we have

$$P_{cb} = -aM_a^2 + bM_a - c \tag{11}$$

Where a = 34.3, b = 1431.84 and c = 13459
Calculated cricondenbar from fourteen (14) different gas compositions were used to validate the reliability of the model developed for predicting natural gas cricondenbar from specific gravity or apparent molecular weight within the range of gas composition used. Statistical error models given below were used to validate the accuracy of the model developed.

1. Minimum and maximum absolute error error
2. Average absolute deviation

$$AAD = \frac{1}{N}\sum\left(\left|\frac{P_{cal} - P_{HYS}}{P_{HYS}}\right|\right)$$

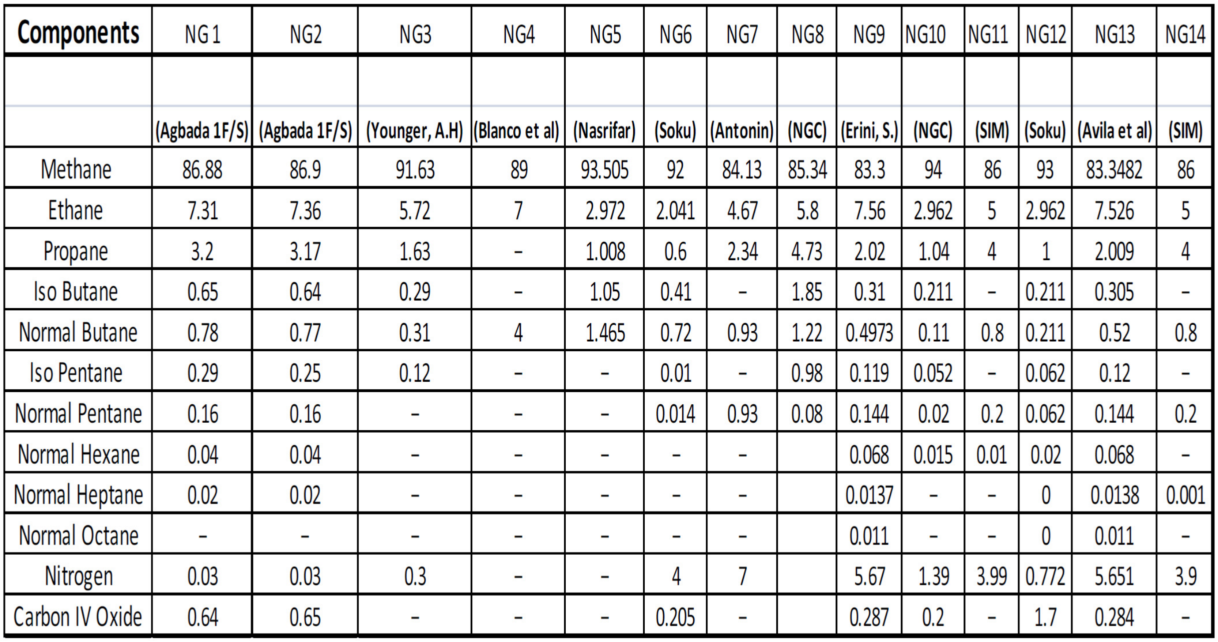
3. Average relative deviation

$$ARD = \frac{1}{N}\sum\left(\frac{P_{cal} - P_{HYS}}{P_{HYS}}\right)$$

Analysis of Result

The correlation between the calculated cricondenbar and specific gravity gave a good fit with a coefficient of determination (R^2) of 0.946. On applying the model developed to calculate the cricondenbar of 14 different gas samples in Table 2, and comparing these results with that obtained by using the SRK equation of state phase envelope utility tool in ASPEN HYSIS, the errors obtained in Table 3, gave a maximum absolute value of 11.1% and a minimum absolute value of 1.1%. The percentage average relative deviation was found to be 1.85 while the percentage average absolute deviation was 5.3.

Table 2—Natural Gas Composition Used in this Study



Components	NG 1	NG2	NG3	NG4	NG5	NG6	NG7	NG8	NG9	NG10	NG11	NG12	NG13	NG14
	(Agbada 1F/S)	(Agbada 1F/S)	(Younger, A.H)	(Blanco et al)	(Nasrifar)	(Soku)	(Antonin)	(NGC)	(Erini, S.)	(NGC)	(SIM)	(Soku)	(Avila et al)	(SIM)
Methane	86.88	86.9	91.63	89	93.505	92	84.13	85.34	83.3	94	86	93	83.3482	86
Ethane	7.31	7.36	5.72	7	2.972	2.041	4.67	5.8	7.56	2.962	5	2.962	7.526	5
Propane	3.2	3.17	1.63	-	1.008	0.6	2.34	4.73	2.02	1.04	4	1	2.009	4
Iso Butane	0.65	0.64	0.29	-	1.05	0.41	-	1.85	0.31	0.211	-	0.211	0.305	-
Normal Butane	0.78	0.77	0.31	4	1.465	0.72	0.93	1.22	0.4973	0.11	0.8	0.211	0.52	0.8
Iso Pentane	0.29	0.25	0.12	-	-	0.01	-	0.98	0.119	0.052	-	0.062	0.12	-
Normal Pentane	0.16	0.16	-	-	-	0.014	0.93	0.08	0.144	0.02	0.2	0.062	0.144	0.2
Normal Hexane	0.04	0.04	-	-	-	-	-		0.068	0.015	0.01	0.02	0.068	-
Normal Heptane	0.02	0.02	-	-	-	-	-		0.0137	-	-	0	0.0138	0.001
Normal Octane	-	-	-	-	-	-	-		0.011	-	-	0	0.011	-
Nitrogen	0.03	0.03	0.3	-	-	4	7		5.67	1.39	3.99	0.772	5.651	3.9
Carbon IV Oxide	0.64	0.65	-	-	-	0.205	-		0.287	0.2	-	1.7	0.284	-

Table 3—Error Analysis

Components	Cricondenbar (Psia)		Error	
	This Work	HYSIS	% RD	% AD
NG 1	1363	1311	3.966438	3.966438
NG2	1359	1300	4.538462	4.538462
NG3	1119	1029	8.746356	8.746356
NG4	1316	1378	-4.49927	4.499274
NG5	1150	1214	-5.27183	5.271829
NG6	1088	1047	3.91595	3.91595
NG7	1371	1492	-8.10992	8.10992
NG8	1458	1503	-2.99401	2.994012
NG9	1355	1305	3.831418	3.831418
NG10	999	933	7.073955	7.073955
NG11	1329	1257	5.727924	5.727924
NG12	1099	989	11.12235	11.12235
NG13	1355	1339	1.194922	1.194922
NG14	1331	1378	-3.41074	3.41074

An average percentage relative error value of 1.85% suggests that this model can be accurate in predicting lean sweet natural gas cricondenbar. However, with a maximum error of 11%, this model should best be applied as a first approximation method for determining lean sweet natural gas cricondenbar within the range of gas composition defined in this work. This is mostly the range of lean (light) or processed natural gas. If precision is required, the more accurate and precise equation of state method for estimating natural gas cricondenbar should be employed. However with a percentage average absolute relative and absolute deviations of 1.85 and 5.3 respectively, this model can be used as a first approximation for cricondenbar estimation in compressor horsepower sizing and selection.

Conclusion

1. A simple to use rough estimate model for predicting the cricondenbar of sweet lean natural gas in the range defined in this study has been developed.
2. The accuracy of this model is within a percentage average relative deviation and average absolute deviation of 1.85 and 5.31 respectively.
3. This model can be used as a first check for predicting natural gas cricondenbar for compressor horsepower selection and sizing.

Nomenclature

M_a	apparent molecular weight
M_i	molecular weight of ith component
N	total number of data points
Φ	function of weight and lighter components
P_{cb}	cricondenbar (psia)
P	pressure (psia)
T_t	cricondentherm temperature (°R)
T_p	cricondenbar temperature (°R)
T_b	atmospheric boiling point of mixture (°R)
T^{I}_{b}	normal boiling point of ith component (°R)
T^{i}_{c}	pseudo critical/cricondentherm/cricondenbar temperature of mixture (°R)
xl	mole fraction of low boiling component
x	mole fraction
α_g	specific gravity

Subsscripts

HYS	HYSIS
CAL	Calculated

Acknowledgment

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