NEW CORRELATIONS FOR DEW-POINT, SPECIFIC GRAVITY
AND PRODUCING YIELD FOR GAS CONDENSATES

A Thesis

by

ADRIANA PATRICIA OVALLE CORTISSOZ

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2002

Major Subject: Petroleum Engineering
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ABSTRACT

New Correlations for Dew-Point, Specific Gravity and Producing Yield for Gas Condensates. (December 2002)

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This work presents four newly developed correlations to estimate dew-point pressure, current specific gravity and producing yield of gas condensate reservoirs.

The first correlation may be used to predict the dew-point pressure of the reservoir gas at reservoir temperature using readily available field data. There have been several attempts to correlate dew point pressures to original reservoir gas composition. The results have been reasonably accurate, but there was no evidence in the literature that a correlation based on reservoir gas specific gravity has been attempted.

The second correlation can be used to estimate the specific gravity of the gas currently in the reservoir, after some depletion, using the original reservoir gas specific gravity and the ratio of the current pressure to the dew-point pressure. There have been several attempts to correlate the compositions of partially depleted reservoir gases with the composition of the original reservoir gas with good results. It follows that the proposed correlation of specific gravities of the partially depleted reservoir gas could be done with fairly good accuracy.

The third correlation can be used to predict the producing yield using the current reservoir gas specific gravity. There was no evidence in the literature that anyone has attempted to do this correlation.
The fourth correlation estimates directly the producing yield from readily available field data. No literature has been found regarding this correlation.

The proposed correlations were developed using 190 complete constant volume depletion studies and 425 partial reports of composition found in the literature. Therefore a total of 615 sets of data were available for correlating dew-point pressures and 190 complete reports were used for correlating specific gas gravities and producing yields.
DEDICATION

I wish to dedicate my thesis to:

The almighty God, I praise you with all my heart,
I thank you father for all your blessings;

Nestor, my life companion for all his support, encouragement, sacrifice,
and especially for his unconditional love, I love you;

My parents, my brother and all my family members for their motivation, help,
love and support, I love you all.
ACKNOWLEDGEMENTS

I wish to express my sincere gratitude and appreciation to:

Dr. William McCain, chair of my advisory committee, for his continued help and support throughout my research. It was an honor to work with him.

Dr. Peter Valko, member of my advisory committee, for his unconditional help and active participation and guidance during my investigation.

All my teachers during my period of studies in the faculty, for guiding me through the destiny that I choose and for giving me the opportunity of being one of the receptors of their knowledge and experiences.
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CHAPTER I

INTRODUCTION

In reservoir engineering a variety of data is needed to accurately estimate reserves and forecast production. Field characterization consists of reservoir rock analysis and fluid analysis. The determination of gas condensate dew-point pressure, gas specific gravity and producing yield is essential for fluid characterization, gas reservoir performance calculations, and for the design of production systems.

Initially, the gas condensate is totally gas in the reservoir. As reservoir pressure decreases, the gas condensate exhibits a dew-point. The dew-point of a gas condensate fluid occurs when a gas mixture containing heavy hydrocarbons is depressurized until liquid is formed, that is, a substantial amount of gas phase exists in equilibrium with an infinitesimal amount of liquid phase. As pressure is reduced, liquid condenses from the gas to form a free liquid in the reservoir. Normally, there is no effective permeability to this liquid phase and it is not produced. If the pressure continues to decrease, a second dew-point will be reached and the liquid can be re-vaporized. This lower dew-point pressure is usually well below the reservoir abandonment pressure; thus it would be of no interest in reservoir performance.

Traditionally, the dew-point pressure of a gas condensate is experimentally determined in a laboratory in a process called constant mass expansion (CME) test using a visual window-type PVT cell.

This thesis follows the style of Journal of Petroleum Technology.
Another study is the constant volume depletion test (CVD) which verifies the thermodynamic equilibrium at each pressure depletion level, and describes the change of composition of the reservoir gas with every decreasing pressure step, along with the molecular weight of the gas and therefore its specific gravity. The surface gas/liquid ratio and yield are then calculated at every reservoir pressure step with specified surface conditions.

The laboratory measurements of gas condensate properties provide the most accurate and reliable determination of reservoir fluid properties. However, due to economical and technical reasons, quite often this information cannot be obtained from laboratory measurements. The experimental determination of these properties requires a representative sample of the reservoir gas with a sufficient volume to complete the analysis, which sometimes is difficult to obtain. The measurements are relatively time consuming, expensive and sometimes subjected to errors. Thus, there is a need for a simple and accurate method of predicting the dew-point pressure for gas condensate reservoirs, specific gravity and producing yield. In this case, these values can be predicted from the empirically derived correlations.

Four correlations were derived in this research to predict the dew-point pressure, the reservoir gas specific gravity and the producing yield at the first separator. For this purpose, a dataset was created from worldwide laboratory tests of gas condensate reservoirs and the correlations were derived from a non-parametric statistical model called GRACE.

The gathered data set includes 190 complete reports of Constant Volume Depletion tests and 425 partial reports of dew-point composition found in the literature. Therefore a total of 615 sets of data were available for correlating dew-point pressures and 190 reports, that is 1041 depletion steps, were used for correlating producing oil/liquid ratios and specific gas gravities. The dew-point pressure ranges between 1400 and
11000 psia and the range of temperature of the reservoirs studied is between 93 and 348°F, covering a wide range of temperatures and pressures expected in the field.

A non-parametric regression was used as an approach to construct a suitable model description of the available information, due to its capability of predicting the dependent variable as a function of the independent variables. The GRACE program was the tool used to develop all four correlations. Several attempts were done to achieve the best result in each correlation, that is, the objective was to minimize the Average Absolute Relative Error and get the Absolute Relative Error close to zero. Once those conditions were met, an analysis of the adjustment results for each independent and dependent variable was performed.

As a comparative analysis, separator conditions were changed obtaining results reasonably similar with the first set of equations generated. Also, the dew-point pressure correlation generated in this study was compared with other correlations giving better accuracy in the prediction.
CHAPTER II

BACKGROUND

This chapter presents the basic concepts and foundations of this research. It begins with the phase behavior of gas condensates, followed by a description of the different tests performed on gas samples followed by a description of the methods used to obtain the different parameters involved. Then it moves to the description of the statistical method used to develop the correlations that were the basis of this research and finally a description some of the previous studies made on this subject is given.

2.1 GAS CONDENSATES

The importance of gas condensate reservoirs has grown continuously since late 1930's. Development and operation of these reservoirs for maximum recovery require engineering and operating methods significantly different from oil or dry gas reservoirs. The single most striking factor about gas condensate systems is that they exist either wholly or preponderantly as vapor phase in the reservoir at the time of discovery. This key fact nearly always governs the development and operating programs for recovery of hydrocarbons from such reservoirs, the properties of the fluids determine the best program in each case. A thorough understanding of fluid properties is required for optimum engineering of gas condensate reservoirs.
2.2 PROPERTIES AND BEHAVIOR OF GAS CONDENSATE FLUIDS

2.2.1 Gas Condensate Phase Diagram

The phase diagram of a condensate gas is somewhat smaller than that for oils, and the critical point is further down the left side of the envelope. These changes are a result of condensate gases containing fewer of the heavy hydrocarbons than do the oils. The phase diagram of a gas condensate has a critical temperature less than the reservoir temperature and a cricondenbtherm greater than the reservoir temperature. See Figure 2-1. Initially, the gas condensate is totally gas in the reservoir, point 1. As reservoir pressure decreases, the gas condensate exhibits a dew-point, point 2. The dew-point of a gas condensate fluid occurs when a gas mixture containing heavy hydrocarbons is depressurized until liquid is formed, that is, a substantial amount of gas phase exists in equilibrium with an infinitesimal amount of liquid phase. As pressure is reduced, liquid condenses from the gas to form a free liquid in the reservoir. Normally, there is no effective permeability to this liquid phase and it cannot be produced. If the pressure continues to decrease, a second dew-point will be reached and the liquid can be re-vaporized. This lower dew-point pressure is, usually, below the reservoir abandonment pressure and would be of no interest in reservoir performance.

2.2.2 Field Identification of Gas Condensates

The lower limit of the initial producing gas/liquid ratio for a gas condensate is approximately 3,200 scf/STB. The upper limit is approximately 120,000 scf/STB, but values of over 150,000 scf/STB have been observed. Gas/liquid ratios this high indicate that the phase diagram is much smaller than shown in Figure 2-1. Gases with higher gas/liquid ratios have cricondenbthers close to reservoir temperature and release very little condensate liquid in the reservoir.
Producing gas/liquid ratios for a gas condensate will increase, and therefore the yield will decrease, after the reservoir pressure falls below the dew-point pressure of the gas.

Stock tank liquid gravities are normally between 40° and 60° API and increase after reservoir pressure falls below the dew-point pressure.

The original heptanes plus fraction of the reservoir gas is lower than 12.9%.
2.3 GAS CONDENSATE TESTS

Proper testing of gas condensate wells is essential to ascertain the state of the hydrocarbon system at reservoir conditions and to plan the best production and recovery program for the reservoir. Without proper well tests and samples, it would be impossible to determine the phase conditions of the reservoir contents at reservoir pressure and temperature accurately and to estimate the amount of hydrocarbon materials in place accurately.

Tests are made on gas condensate wells for a number of specific purposes: to obtain representative samples for laboratory analysis to identify the composition and properties of the reservoir fluids, to make field determinations on gas and liquid properties and to determine formation and well characteristics, including productivity, producibility and injectivity.

2.3.1 Test Procedures

a) Well Conditioning

Proper well conditioning is essential to obtain representative samples from the reservoir. The best production rates before and during the sampling procedure have to be considered individually for each reservoir and for each well. Usually the best procedure is to use the lowest rate that results in continuous removal of liquids from the wellbore. Minimum drawdown of bottom-hole pressure during the conditioning period is desirable and the produced gas/liquid ratio should remain constant (within about 2%) for several days; less permeable reservoirs require longer periods. The farther the well deviates from constant gas/liquid ratio, the greater the likelihood that the samples will not be representative.
Recombined separator samples from gas condensate wells are considered more representative of the original reservoir fluid than subsurface samples.

Accurate measurements of hydrocarbon gas and liquid production rates during the well-conditioning and well-sampling tests are necessary because the laboratory tests will later be based on fluids recombined in the same ratios as the hydrocarbon streams measured in the field. The original reservoir fluid cannot be simulated in the laboratory unless accurate field measurements of all separator streams are taken. If the produced gas/liquid ratio from field measurements is in error by as little as 5%, the dew-point pressure determined in the laboratory may be in error by as much as 100 psi. Water production rates should be measured separately and produced water excluded as much as possible from hydrocarbon samples sent to the laboratory.

Separator pressure and temperature should remain as constant as possible during the well-conditioning period; this will help maintain constancy of the stream rates and thus of the observed hydrocarbon gas/liquid ratio. If the well is being prepared during a period when atmospheric temperatures vary considerably from night to day, reasonably consistent average temperatures and pressures on the several vessels during the conditioning period should be adequate.

b) Sampling

After the conditioning period has proceeded long enough to show that the producing conditions are steady, exacting measurement methods must be used to obtain representative samples. Certain minimum items of information in addition to all stream rates are essential, including regular readings of the pressures and temperatures of all vessels sampled, and of tubing heads and casing heads where available, and a recorded history of the well conditions before and during sampling, along with the actual mechanics of the sampling steps.

Care must be taken that the compositions of gas and liquid samples obtained are representative and are properly preserved for laboratory analyses.
The volumes of fluid requested for laboratory testing should be acquired during the sampling period, plus a reasonable amount (25% or more) of extra sample materials in separate containers for emergency use should some of the main samples be lost by leakage or other adversity between the field site and the laboratory.

In taking samples for recombination to evaluate a gas condensate reservoir, the samples of gas and samples of liquid usually are taken from the first stage of separation. A representative portion of all the hydrocarbons produced from the well will be contained in these two samples. The first step in the laboratory study is to evaluate the samples taken. The hydrocarbon composition of the separator samples should then be determined by chromatography or low-temperature fractional distillation or a combination of both.

The dew-point pressure and the pressure-volume relations are determined by a constant-composition-expansion test. A constant-volume-depletion test simulates the change in reservoir fluid composition as the pressure decreases at constant reservoir temperature.

2.3.2 Constant Composition Expansion Test (CCE)

The laboratory personnel next measure the pressure-volume relations of the reservoir fluid at reservoir temperature with a visual cell. This is a constant-composition-expansion or constant-composition-expansion, and furnishes the dew-point of the reservoir fluid at reservoir temperature and the total volume of the reservoir fluid as a function of pressure. The volume of liquid at pressures below the dew-point as a percent of the total volume may also be measured. Phase diagrams can be developed by measuring the liquid volumes at several temperatures.
2.3.3 **Constant Volume Depletion Test (CVD)**

Pressure depletion of gas condensate reservoirs may be simulated in the laboratory by use of high-pressure visual cell. The basic assumption for these depletion studies is that the retrograde liquid that condenses in the reservoir rock will not achieve a sufficiently high saturation to become mobile.

The depletion study is performed by expanding the reservoir fluid in the cell. This is done by increasing the volume of the cell until the first depletion pressure is reached. The cell volume is then reduced and, at the same time, gas is removed from the top of the cell until the volume of the cell is returned to the volume when the test was begun at the dew point pressure. The fluid in the cell is brought to equilibrium and the volume of the retrograde liquid is measured. The gas volume removed from the cell is measured at the depletion pressure and reservoir temperature. The gas removed is charged to analytical equipment where its composition is determined and its volume is measured at standard pressure and temperature. Figure 2-2 illustrates two of several possible stages in the constant-volume-depletion test.

This series of expansions and constant pressure displacements is repeated at each depletion pressure until an arbitrary abandonment pressure is reached.

In addition to the composition of the produced well stream at the final depletion pressure, the composition of the condensate liquid was also measured. These data are included as a control composition in the event the study is used for compositional material-balance purposes.
2.4 SURFACE SEPARATION

The separation of gas and liquid in surface is done in series of flash vaporizations in an oil or gas field. The fluid from the wellhead is brought to equilibrium in the separator at separator temperature and pressure. The produced fluid is called separator feed.

The pressure of the separator is controlled with a pressure-regulating device through which the produced gas flows. Normally, separator temperature is determined by the temperature of the feed, the atmospheric temperature and cooling due to vaporization and expansion of part of the feed stream. Separator temperature can be controlled by heating or refrigeration.

![Diagram of separator stages](image)

Figure 2-2. Constant volume depletion test.
Sometimes several separators are operated in series at successively lower pressures to obtain the maximum amount of liquid.

Figure 2-3 shows an example of a three-stage separator process. If the pressure of the last separator is greater than atmospheric pressure, the stock tank acts as a stage of separation.

Separator calculations are performed to determine the optimum operating pressure for processing a particular hydrocarbon mixture.
2.5 CALCULATION OF GAS CONDENSATE SURFACE PARAMETERS

2.5.1 Flash Calculation

The flash process consists of defining the amounts and compositions of the equilibrium phases, liquid and gas, given the pressure, temperature and overall composition.

The composition of the feed stream to the first separator is determined from recombined separator samples or obtained from a CVD test for reservoir pressures below dew-point pressure.

The pressures and temperatures of the two separators and the stock tank must be known to predict the equilibrium ratios which depend on pressure, temperature and type of mixture.

The mole fractions of component $i$ in the liquid phase and gas phases are $x_i$ and $y_i$ respectively, and the equilibrium ratio is defined as:

$$K_i = \frac{y_i}{x_i}$$ \hspace{1cm} \text{Eq. 2-1}

$x_i$ and $y_i$ can be calculated using the material balance constraint.

$$x_i = \frac{z_i}{1 + f_g (K_i - 1)}$$ \hspace{1cm} \text{Eq. 2-2}

$$y_i = \frac{z_i K_i}{1 + f_g (K_i - 1)}$$ \hspace{1cm} \text{Eq. 2-3}

Where $f_g$ is the mole fraction of the fluid in the gas phase.

Using Eq. 2-2 and Eq. 2-3, the constraint is given by:
\[ \sum_{i=1}^{N_C} (y_i - x_i) = 0 \] \hspace{1cm} \text{Eq. 2-4}

The Rachford-Rice equation is obtained as:

\[ F(f_g) = \sum_{i=1}^{N_C} \frac{z_i (K_i - 1)}{1 + f_g (K_i - 1)} = 0 \] \hspace{1cm} \text{Eq. 2-5}

Eq. 2-5 is monotonically decreasing and a root for \( f_g (0 < f_g < 1) \) exists provided that:

\[ \sum_{i=1}^{N_C} K_i z_i > 1 \] \hspace{1cm} \text{Eq. 2-6}

\[ \sum_{i=1}^{N_C} \frac{z_i}{K_i} > 1 \] \hspace{1cm} \text{Eq. 2-7}

Eq. 2-5 is easily solved for \( f_g \) by using a Newton-Raphson iteration scheme:

\[ f_g^{t+1} = f_g^t - \frac{F(f_g^t)}{\frac{\partial F(f_g)}{\partial f_g}} \bigg|_{f_g^t} \] \hspace{1cm} \text{Eq. 2-8}

With

\[ \frac{\partial F(f_g)}{\partial f_g} = \sum_{i=1}^{N_C} z_i \left( \frac{(K_i - 1)^2}{1 + f_g (K_i - 1)^2} \right) \] \hspace{1cm} \text{Eq. 2-9}

Usually very few iterations are required to solve Eq. 2-8 for \( f_g \). If violation of the conditions given by Eq. 2-6 and Eq. 2-7 occurs, the fluid is either a sub-cooled liquid \( (f_g = 0) \) or a superheated vapor \( (f_g = 1) \).
2.5.2 Gas Characterization

a) Molecular Weight

Since a gas mixture is composed of molecules of various sizes, the apparent molecular weight can be calculated from the composition of gas.

\[ M_g = \sum_{i=1}^{N_c} M_i \ast y_i \]  

.. Eq. 2-10

Where \( M_i \) is the molecular weight of each component \( i \).

b) Gas Specific Gravity

The specific gravity of a gas is defined as the ratio of the density of the gas to the density of dry air with both densities measured at the same temperature and pressure. This equation is strictly true only if both the gas and air act like ideal gases or have the same values of z factor at the selected pressure and temperature. It follows that

\[ \gamma_g = \frac{M_g}{29} \]  

.. Eq. 2-11

where 29 is the apparent molecular weight of dry gas.

c) Gas/liquid Ratio

The calculation of the gas/liquid ratio of the primary and secondary separator and of the stock tank requires a six step procedure. This procedure is discussed as follows.

- **Step 1**: The calculation of the quantities and compositions of the gas and liquid leaving the separators is required. The composition of the feed stream to the separator, separator temperature and separator pressure are used. Eq.2-5 through Eq. 2-9 are used to calculate a flash vaporization to obtain the vapor and gas fractions. The compositions of the gas and liquid phases are then
calculated from Eq. 2-2 and Eq. 2-3. The feed for the secondary separator is the composition of liquid leaving the first separator.

- **Step 2:** The same procedure as described in Step 1 is done for the second separator and for the stock tank. The feed for the stock tank is the composition of liquid leaving the second separator.

- **Step 3:** The calculation of the quantities and compositions of the gas and liquid in the stock tank is required. The feed of the stock tank is the composition of liquid leaving the second separator. The stock-tank temperature and atmospheric pressure must be used for calculations. The same procedure for flash vaporization calculation describes before is used.

- **Step 4:** The density and molecular weight of the stock-tank oil are then calculated.

1. The pseudo-liquid density is required and it is calculated from Witte's\(^1\) correlation.

\[
\rho_{po} = \frac{\rho_{C3^+}}{1 + 2.138156 W_1^{1.1027205} + 0.453717 W_2^{1.092823}} \quad \text{Eq. 2-12}
\]

Where,

\(\rho_{po}\) is the pseudo-liquid density and \(\rho_{C3^+}\) is the density of the propane and heavier (including hydrogen sulfide) fraction of liquid at 60\(^\circ\)F and atmospheric pressure, both in lb/ft\(^3\). \(W_1\) and \(W_2\) are defined in Eq. 2-13 and 2-14.

\[
W_1 = \frac{W_{C1}}{W_{mix}} \quad \text{Eq. 2-13}
\]

Where,
\( W_{C1} \) is the mass of the methane in lb methane/lb-mole of mix (mole fraction times molecular weight) and \( W_{\text{mix}} \) is the mass of the mixture in lb of mix/lb mole of mix.

Weight fraction of ethane in the ethane and heavier includes non-hydrocarbon components.

\[
W_2 = \frac{W_{C2} + W_{N2}}{W_{\text{mix}} - W_{C1} - W_{CO2}} \quad \ldots \quad \text{Eq. 2-14}
\]

Where,

\( W_{N2} \) is the mass of the nitrogen in lb nitrogen/lb-mole of mix and \( W_{CO2} \) is the mass of the carbon dioxide in lb carbon dioxide/lb-mole of mix.

2. Stock-tank oil gravity and API can be computed from stock tank oil density at standard conditions.

\[
\gamma_{STO} = \frac{\rho_o}{\rho_w} = \frac{\rho_o}{62.368 \text{lb} / \text{ft}^3} \quad \ldots \quad \text{Eq. 2-15}
\]

\[
^oAPI = \frac{141.5}{\gamma_{STO}} - 131.5 \quad \ldots \quad \text{Eq. 2-16}
\]

Where,

\( \rho_w \) is the density of pure water at standard conditions.

- **Step 5:** The gas/liquid ratios for the primary and secondary separator and for the stock tank are calculated.

Normally, gas/liquid ratio is calculated as standard cubic feet of gas per barrel of stock-tank oil. The ratio
\[ R_{SP1} = \frac{2138 f_{g1} \rho_{STO}}{f_{L1} f_{L2} f_{L3} M_{STO}} \]  
Eq. 2-17

\[ R_{SP2} = \frac{2138 f_{g2} \rho_{STO}}{f_{L2} f_{L3} M_{STO}} \]  
Eq. 2-18

\[ R_{ST} = \frac{2138 f_{g3} \rho_{STO}}{f_{L3} M_{STO}} \]  
Eq. 2-19

Where,

\( f_{gi} \) is the vapor fraction at the separator \( i \), \( f_{Li} \) is the liquid fraction at the separator \( i \) and \( M_{STO} \) is molecular weight of the liquid in the stock-tank.

Notice that Eq. 2-17 through 2-19 are multiplied by a constant equals to 2138. This value corresponds to the conversion factor from lb moles of separator gas per lb mole of stock-tank oil to standard cubic feet of gas per barrel of stock tank oil.

The total producing gas/liquid ratio is the sum of the gas/liquid ratios from all separators and the stock tank.

\[ R = R_{SP1} + R_{SP2} + R_{ST}. \]  
Eq. 2-20

d) Yield

The surface volume ratio for gas condensates is usually expressed as an oil/gas ratio, or yield, defined as follows:

\[ Y = \frac{1,000,000}{\text{Gas - Liquid - Ratio} \left[ \frac{STB}{MMscf} \right]} = \frac{1,000,000}{R}. \]  
Eq. 2-21
The producing yield defines the instantaneous ratio of the surface oil volume produced divided by the surface gas volume produced.

At pressures above the dew-point the producing yield is constant, and as the pressure decreases below the dew-point the yield decreases.

2.6 STATISTICAL METHOD

Conventional multiple regression for any variable requires a functional relationship to be presumed among all the related variables. Due to the inexact nature of the relationship between petrophysical variables, it is not always possible to identify the correct functional form between dependent and independent variables in advance. When large variations in petrophysical properties are exhibited, parametric regression often fails or leads to unstable and erroneous results, especially for multivariate cases. Therefore, a non-parametric approach for estimating optimal transformations of petrophysical data is needed to obtain the maximum correlation between observed variables. An iterative procedure involving the Alternating Conditional Expectation (ACE) is an approach that does not require *a priori* assumptions of a functional form; and the optimal transformations are derived solely based on the data set.

2.6.1 ACE Technique

The ACE algorithm, originally proposed by Breiman and Freiman\(^2\), provides a method for estimating optimal transformations for multiple regression that result in a maximum correlation between a dependent (response) random variable \(y\) and multiple independent (predictor) random variables \(x_1, x_2, \ldots, x_m\).

A model predicting the value of \(y\) from the values \(x_1, x_2, \ldots, x_m\) is written in the generic form
\[ y = f^{-1}(z) \] \hspace{2cm} \text{Eq. 2-22}

Where,

\[ z = \sum_{n=1}^{m} z_n \] \hspace{2cm} \text{Eq. 2-23}

And

\[ z_n = f_n(x_n) \] \hspace{2cm} \text{Eq. 2-24}

The functions \( f_1(.) \), \( f_2(.) \), ..., \( f_m(.) \) are called variable transformations yielding the transformed independent variables \( z_1, z_2, ..., z_m \). The function \( f(.) \) is the transformation for the dependent variable. In fact the main interest is the inverse: \( f'(.) \), yielding the dependent variable \( y \) from the transformed dependent variable \( z \).

Given \( N \) observation points, it is desirable to find the best transformation functions \( f_1(.) \), \( f_2(.) \), ..., \( f_m(.) \) and \( f'(.) \), but first not as an algebraic expression, rather as relationships defined point-wise. The method of ACE constructs and modifies the individual transformations to achieve maximum correlation in the transformed space.

Graphically this means that the plot of \( z = \sum_{n=1}^{m} f_n(x_n) \) against \( z' = f(y_{measured}) \) should be as near to the 45 degree straight line as possible. The resulting individual transformations are given in the form of a point-by-point plot and/or table, thus in any subsequent application (graphical or algebraic) interpolation is needed to obtain the transformed variables and it is needed to apply the inverse transformation to predict \( y \). Obviously, the smoother the transformation the more justified and straightforward the interpolation is, therefore some kind of restriction on smoothness is built into the ACE algorithm. That is, based on the concept of conditional expectation, the correlation in transformed space is maximized by iteratively adjusting the individual transformations subject to a smoothness condition.
The particular realization of the algorithm, GRACE (Xue, et al., 1997)\(^3\), used in this work consists of two parts. The first part provides the transformations in the form of tables and the second part allows the user to construct the final algebraic approximations using curve fitting in a commercial spreadsheet program. Fortunately, many physically sound problems have rather simple shapes of the individual transformation and can be well approximated, for instance, by low order polynomials.

2.6.2 Reconciliation

Data reconciliation is a well-known statistical procedure, see for instance Leibman et al (1992)\(^4\), Crowe (1996)\(^5\), Weis et al (1996)\(^6\) and Vachhani et al (2001)\(^7\). GRACE also has an option to 'reconcile' the observed data set to the gleaned-out underlying statistical dependency. The option provides reconciled values for all the observations by suggesting slight changes in the observed values. The adjustment is done such that in the transformed space the reconciled observations follow the 45 degree straight line perfectly, while the overall change in each observed value is kept to a minimum (Xue, et al, 1997)\(^3\). The plot of adjusted versus observed variable offers a deeper insight into the effect of measurement noise and/or the possibility of a hidden variable.

2.6.3 Statistical Measures

Some statistical measures of correlations used through this work are defined as follows.

The Average Relative Error, ARE, %:

\[
ARE = \frac{100}{N} \sum_{i=1}^{N} \frac{y_{measured} - y_{calculated}}{y_{measured}} \hspace{1cm} \text{Eq. 2-25}
\]

The Average Absolute Relative Error, AARE, %:
AARE = \frac{100}{N} \sum_{i=1}^{N} \left| \frac{y_{\text{measured}} - y_{\text{calculated}}}{y_{\text{measured}}} \right| \quad \text{........................................Eq. 2-26}

ARE characterizes the accuracy (bias) and AARE describes the precision (scatter) of predicted values obtain from a particular correlation.

In the same way, ARE and AARE are calculated for the data reconciliation and are called ARA and AARA respectively.

The Average Relative Adjustment, ARA, %:

\[ ARA = \frac{100}{N} \sum_{i=1}^{N} \frac{y_{\text{measured}} - y_{\text{adjusted}}}{y_{\text{measured}}} \quad \text{........................................Eq. 2-27} \]

The Average Absolute Relative Adjustment, AARA, %:

\[ AARA = \frac{100}{N} \sum_{i=1}^{N} \left| \frac{y_{\text{measured}} - y_{\text{adjusted}}}{y_{\text{measured}}} \right| \quad \text{........................................Eq. 2-28} \]

2.7 LITERATURE REVIEW

There have been a few previous studies on retrograde dew point pressure correlations.

2.7.1 Organick and Golding\textsuperscript{8} Correlation

Organick and Golding presented a correlation predicting saturation pressures for condensates and volatile oil reservoir fluids based on the temperature and on two generalized composition characteristics: the molal average boiling point and the modified equivalent molecular weight. Thus, the dew-point pressure prediction is
related directly to the temperature and the composition of the mixture, requiring a compositional analysis of the fluid in the reservoir.

2.7.2 Nemeth and Kennedy\textsuperscript{9} Correlation

The investigation presented in this paper was performed to develop a relationship between the dew-point pressure of a gas condensate and its composition, temperature and characteristics of the heptanes-plus fraction. 579 dew-point pressures were used to develop the correlation with the help of a multiple regression program. The final equation containing 11 coefficients is suitable to predict dew-point pressure of gas condensates using variables normally measured in the laboratory.

2.7.3 Elsharkawy\textsuperscript{10} Correlation

This paper presents an empirical model to estimate the dew-point pressures for gas condensate reservoirs as a function of routinely measured gas analysis and reservoir temperature. The proposed model was developed using experimentally measured and collected data of 340 gas condensate samples covering wide range of gas properties and reservoir temperature. The prediction of the dew-point pressure was done as a function of the reservoir temperature, composition of the mixture, molecular weight and specific gravity of the heptane plus fraction. The accuracy of the proposed model was compared to an equation of state results and various correlations.

2.7.4 Humoud\textsuperscript{11} Correlation

The paper presents an empirical correlation to predict the dew-point pressure of a gas condensate fluid from readily available field data. These correlation relates the dew-
point pressure of a gas condensate directly to its reservoir temperature, pseudo-reduced pressure and temperature, primary separator gas oil ratio, the primary separator pressure and temperature, and relative densities of separator gas and heptanes plus fraction. Seventy-four data sets, representing different gas condensates of the Middle East, were used in this research. Each data set included field production data, gas compositional data, and results of CME tests. Multiple least-square linear/nonlinear regression was utilized to develop this dew-point pressure correlation.

2.7.5 Marrufo\textsuperscript{12} \textit{et al} Correlation

This paper presents correlations to determine the dew point pressure and C7+ content of gas condensate reservoirs, achieved from production parameters: stock tank condensate gravity, initial producing gas condensate ratio, separator gas specific gravity, and reservoir temperature. The total PVT data was 106 analyses that were validated through mathematical recombination and mass balance.

From all five dew-point pressure prediction, it is seen that Organick and Golding, Nemeth and Kennedy, and Elsharkawy correlations depend on compositional analysis of the reservoir fluid which is the step to be avoided in the development of this work.

Humoud and Marrufo \textit{et al} correlations are compared with the dew-point correlation developed in this study.
CHAPTER III

DEVELOPMENT OF CORRELATIONS

3.1 DATA DESCRIPTION

The data set includes 190 complete reports of Constant Volume Depletion tests and 425 partial reports of dew-point measurements. Therefore a total of 615 sets of data were available for correlating dew-point pressures and 190 reports, with a total of 1041 depletion steps, were used for correlating producing oil-liquid ratios and specific gas gravities. The dew-point pressures range between 1,400 and 11,000 psia and the range of temperatures of the reservoirs studied is between 93 and 348°F, covering most of the range of temperatures and pressures expected in the field. The following table summarizes the data obtained from all the tests.

<table>
<thead>
<tr>
<th>Table 3-1 Data Statistics from CVD tests</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature [°F]</strong></td>
</tr>
<tr>
<td>Minimum</td>
</tr>
<tr>
<td>93.0</td>
</tr>
<tr>
<td>1114.7</td>
</tr>
<tr>
<td>H₂S</td>
</tr>
<tr>
<td>CO₂</td>
</tr>
<tr>
<td>N₂</td>
</tr>
<tr>
<td>C₁</td>
</tr>
<tr>
<td>C₂</td>
</tr>
<tr>
<td>C₃</td>
</tr>
<tr>
<td>iC₄</td>
</tr>
<tr>
<td>nC₄</td>
</tr>
<tr>
<td>iC₅</td>
</tr>
<tr>
<td>nC₅</td>
</tr>
<tr>
<td>C₆</td>
</tr>
<tr>
<td>C₇</td>
</tr>
<tr>
<td>MW&lt;C₇</td>
</tr>
<tr>
<td>SG&lt;C₇</td>
</tr>
</tbody>
</table>
3.2 METHODOLOGY

3.2.1 Initial Conditions

The surface separator conditions had to be selected in order to make the calculations of the gas/liquid ratios at each separation stage because the K-factors are dependent on pressure and temperature. Two separators at different pressures and temperatures and a stock tank at standard conditions were chosen as surface separation configuration (Figure 2-3). The following table summarizes the initial conditions chosen to make the calculation of the different parameters.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>90</td>
<td>1065.7</td>
<td>80</td>
</tr>
<tr>
<td>H₂S</td>
<td>0.69082</td>
<td>4.70348</td>
<td>23.0125</td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>1.67161</td>
<td>14.50559</td>
<td>71.4026</td>
<td></td>
</tr>
<tr>
<td>N₂</td>
<td>3.74146</td>
<td>98.12877</td>
<td>580.66649</td>
<td></td>
</tr>
<tr>
<td>C₁</td>
<td>3.36762</td>
<td>33.93364</td>
<td>177.52948</td>
<td></td>
</tr>
<tr>
<td>C₂</td>
<td>0.82975</td>
<td>6.2007</td>
<td>28.71822</td>
<td></td>
</tr>
<tr>
<td>C₃</td>
<td>0.34773</td>
<td>1.75326</td>
<td>7.88901</td>
<td></td>
</tr>
<tr>
<td>iC₄</td>
<td>0.1909</td>
<td>0.67001</td>
<td>2.79424</td>
<td></td>
</tr>
<tr>
<td>nC₄</td>
<td>0.14981</td>
<td>0.49333</td>
<td>2.04451</td>
<td></td>
</tr>
<tr>
<td>iC₅</td>
<td>0.07802</td>
<td>0.19981</td>
<td>0.7714</td>
<td></td>
</tr>
<tr>
<td>nC₅</td>
<td>0.06245</td>
<td>0.15704</td>
<td>0.61089</td>
<td></td>
</tr>
<tr>
<td>C₆</td>
<td>0.02842</td>
<td>0.04827</td>
<td>0.16552</td>
<td></td>
</tr>
<tr>
<td>C₇⁺</td>
<td>0.00075</td>
<td>0.00049</td>
<td>0.00126</td>
<td></td>
</tr>
</tbody>
</table>
3.2.2 Calculations

The molecular weight and the specific gravity of the gas for each pressure level were calculated from the CVD tests with Eq.2-10 and Eq.2-11.

The gas/liquid ratios at every separator step and at stock tank condition were calculated with the Rachford-Rice flash calculation, iterating with a Newton-Raphson algorithm, following the flash calculation procedure described in section 2.5.1 and the gas/liquid ratio procedure described in section 2.5.2c). The stop criterion for convergence in the Newton-Raphson algorithm used is that the difference between steps $|f_{v}^{i+1} - f_{v}^{i}|$ is less than $1 \times 10^{-8}$. As those calculations are iterative for each pressure level, a program in Visual Basic was developed to obtain the gas/liquid ratios in an efficient manner (Appendix A).

3.2.3 Data-Base

The final database obtained to develop the new correlations consists of 615 laboratory tests from which molecular weight, specific gravity of the gas in the reservoir, producing yield at the three surface stages and stock tank gravity were derived. The statistics of those values are presented in Table 3-3.
Table 3-3 Statistics from Calculations

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Mean</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{MW}_{\text{GR}}$</td>
<td>17.940</td>
<td>25.416</td>
<td>45.490</td>
</tr>
<tr>
<td>$\gamma_{\text{GR}}$</td>
<td>0.619</td>
<td>0.876</td>
<td>1.569</td>
</tr>
<tr>
<td><strong>Separator 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vapor Fraction [mole fraction]</td>
<td>0.561</td>
<td>0.896</td>
<td>0.989</td>
</tr>
<tr>
<td>Liquid Fraction [mole fraction]</td>
<td>0.011</td>
<td>0.100</td>
<td>0.439</td>
</tr>
<tr>
<td>Gas-Liquid Ratio [scf/STB]</td>
<td>2,395</td>
<td>25,619</td>
<td>119,783</td>
</tr>
<tr>
<td><strong>Separator 2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vapor Fraction [mole fraction]</td>
<td>0.231</td>
<td>0.414</td>
<td>0.603</td>
</tr>
<tr>
<td>Liquid Fraction [mole fraction]</td>
<td>0.397</td>
<td>0.586</td>
<td>0.769</td>
</tr>
<tr>
<td>Gas-Liquid Ratio [scf/STB]</td>
<td>131</td>
<td>737</td>
<td>2,260</td>
</tr>
<tr>
<td><strong>Stock Tank</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vapor Fraction [mole fraction]</td>
<td>0.036</td>
<td>0.111</td>
<td>0.292</td>
</tr>
<tr>
<td>Liquid Fraction [mole fraction]</td>
<td>0.707</td>
<td>0.889</td>
<td>0.964</td>
</tr>
<tr>
<td>Gas-Liquid Ratio [scf/STB]</td>
<td>23</td>
<td>115</td>
<td>435</td>
</tr>
<tr>
<td>Total Gas-Liquid Ratio</td>
<td>3,220</td>
<td>120,485</td>
<td>26,471</td>
</tr>
<tr>
<td>Stock-Tank Condensate Gravity [°API]</td>
<td>37.750</td>
<td>60.018</td>
<td>78.670</td>
</tr>
</tbody>
</table>

3.2.4 GRACE Program

A non-parametric regression was used as an approach to construct a suitable model description of the available information, due to its capability of predicting the dependent variable as a function of the independent variables. The GRACE program was the tool used to develop all four correlations. Several attempts were made to achieve the best result for each correlation. The objectives were to minimize the Average Absolute Relative Error and the Absolute Relative Error for each correlation. Once these conditions were met, an analysis of the equilibration results for each independent and dependent variable was performed. The equilibration consists of a graph plotting the adjusted value against the measured value for each variable, describing how much the variable was adjusted from the measured value to fit the model. The plot will have to fit a 45 degree straight-line. Therefore, an independent variable that did not comply with this property was not considered to generate the correlation, because it was not helping the estimation of the dependent variable.
3.3 DEVELOPMENT OF CORRELATIONS

3.3.1 Correlation 1, Dew-Point Pressure

The first correlation to be performed is the estimation of the reservoir gas dew-point pressure from readily available field data.

Statistics of Available Variables

The following table summarizes the statistics of the available variables to build the correlation from 615 dew-point composition analysis.

<table>
<thead>
<tr>
<th>Reservoir Temperature [°F]</th>
<th>Minimum</th>
<th>Mean</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>93</td>
<td>266.7</td>
<td>348</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dewpoint Pressure [psia]</th>
<th>Minimum</th>
<th>Mean</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,870</td>
<td>5,093</td>
<td>10,980</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reservoir Gas Specific Gravity of Dewpoint gas</th>
<th>Minimum</th>
<th>Mean</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.609</td>
<td>0.95</td>
<td>1.623</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gas-Liquid Ratio of first separator calculated using Dewpoint gas [scf/STB]</th>
<th>Minimum</th>
<th>Mean</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,289</td>
<td>21,253</td>
<td>113,346</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stock Tank condensate gravity calculated using Dewpoint gas [°API]</th>
<th>Minimum</th>
<th>Mean</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>35.64</td>
<td>55.07</td>
<td>76.48</td>
<td></td>
</tr>
</tbody>
</table>

Results

After an extensive search for the best correlation to predict the reservoir gas dew-point pressure, the function that best estimates this gas property is described below.

- **Dependent Variable:**
ln $P_d$: logarithm of reservoir gas dew-point pressure

- **Independent Variables:**

  ln $RSP_{1d}$: logarithm of first separator gas/liquid ratio calculated using dewpoint gas, scf/STB.

  API$_d$: Stock-tank condensate gravity calculated using dewpoint gas, °API.

  $\gamma_{gd}$: Reservoir gas specific gravity of dewpoint gas.

- **Transforms**

  The following plots (Figure 3-1 to Figure 3-4) present the transforms for each independent variable.

  ![Graph](image)

  Figure 3-1 Optimal transform of first separator gas/liquid ratio calculated using dewpoint gas.
Figure 3-2 Optimal transform of stock-tank condensate gravity calculated using dewpoint gas.

Figure 3-3 Optimal transform of reservoir gas specific gravity calculated using dewpoint gas.
Correlation

\[ \ln P_d = 0.00477 \text{SumTr}^2 + 0.32239 \text{SumTr} + 8.48 \]  \hspace{1cm} \text{Eq. 3-1}

\[ \text{SumTr} = \ln RSP_{1d - Tr} + API_{d - Tr} + \gamma_{gd - Tr} \]  \hspace{1cm} \text{Eq. 3-2}

\[ \ln RSP_{1d - Tr} = -0.01691 (\ln RSP_{1d})^2 - 0.87528 (\ln RSP_{1d}) + 9.8895 \]  \hspace{1cm} \text{Eq. 3-3}

\[ API_{d - Tr} = 0.00151 (API_{d})^2 - 0.29709 (API_{d}) + 11.7 \]  \hspace{1cm} \text{Eq. 3-4}

\[ \gamma_{gd - Tr} = -0.81744 (\gamma_{gd})^2 - 2.91450 (\gamma_{gd}) + 3.5202 \]  \hspace{1cm} \text{Eq. 3-5}

Figure 3-5 presents a comparison of measured dewpoint pressure with dewpoint pressure from the new correlation.
**Relative errors**

AARE = 9.05%

ARE = 0.0%

**Equilibration**

The following plots (Figure 3-6 to Figure 3-9) present the equilibration process for all variables in the correlation.
Figure 3-6 Equilibration of first separator gas/liquid ratio calculated using dewpoint gas.

Figure 3-7. Equilibration of stock-tank condensate gravity calculated using dewpoint gas.
Figure 3-8. Equilibration of reservoir gas specific gravity calculated using dewpoint gas.

Figure 3-9 Equilibration of dewpoint pressure
The following table summarizes the statistics of the equilibration process.

<table>
<thead>
<tr>
<th>Variable</th>
<th>AARA %</th>
<th>ARA %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pd</td>
<td>4.47</td>
<td>0.13</td>
</tr>
<tr>
<td>RSP1d</td>
<td>3.85</td>
<td>0.12</td>
</tr>
<tr>
<td>APId</td>
<td>0.66</td>
<td>0.003</td>
</tr>
<tr>
<td>$\gamma_{gd}$</td>
<td>1.27</td>
<td>0.005</td>
</tr>
</tbody>
</table>

The results in Table 3-5 show that all the measured variables adjust well to the predicted values calculated with the new correlation of dewpoint pressure.

3.3.2 Correlation 2, Reservoir Gas Specific Gravity

The second correlation to be performed is the estimation of the reservoir gas specific gravity at any depletion pressure from readily available field data.

Statistics of Available Variables

Table 3-6 summarizes the statistics of the available variables to create the correlation from the composition analysis of 851 depletion stages.
Table 3-6 Correlation 2 – Statistics of Available Variables

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Mean</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir Temperature [F]</td>
<td>126</td>
<td>247.2</td>
<td>348</td>
</tr>
<tr>
<td>Pressures [psia]</td>
<td>1,114.7</td>
<td>3,083.3</td>
<td>9,014.7</td>
</tr>
<tr>
<td>Dewpoint Pressure [psia]</td>
<td>1,930.7</td>
<td>5,568.6</td>
<td>10,980.0</td>
</tr>
<tr>
<td>Ratio of Pressures</td>
<td>0.13</td>
<td>0.56</td>
<td>0.94</td>
</tr>
<tr>
<td>Reservoir Gas Specific</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravity at pressures</td>
<td>0.618</td>
<td>0.827</td>
<td>1.293</td>
</tr>
<tr>
<td>below dewpoint</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reservoir Gas Specific</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravity at dewpoint</td>
<td>0.6436</td>
<td>1.044</td>
<td>1.5687</td>
</tr>
<tr>
<td>Ratio of Reservoir Gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Gravities</td>
<td>0.5</td>
<td>0.812</td>
<td>0.993</td>
</tr>
</tbody>
</table>

Results

After an extensive search for the best correlation to predict the reservoir gas specific gravity, the function that best estimates this gas property is described below.

- **Dependent Variable:**

  $\gamma_{gr}$: Ratio of Reservoir Gas Specific Gravities, defined as:

  \[
  \gamma_{gr} = \frac{\gamma_g(P)}{\gamma_g(P_d)} \quad \text{.................................................. Eq. 3-6}
  \]

- **Independent Variables:**

  $P_r$: Ratio of reservoir pressures, defined as:

  \[
  P_r = \frac{P}{P_d} \quad \text{.................................................. Eq. 3-7}
  \]

$\gamma_{gd}$: Reservoir Gas Specific Gravity of dewpoint gas.
• Transforms

The following plots (Figure 3-10 to Figure 3-12) present the transforms for each independent variable.

Figure 3-10 Optimal transform of pressure ratio.
Figure 3-11 Optimal transform of reservoir gas specific gravity of dewpoint gas.

Figure 3-12 Optimal inverse transform of ratio of reservoir gas specific gravities.
**Correlation**

\[ \gamma_{gr} = -0.00851 \text{SumTr}^2 + 0.12085 \text{SumTr} + 0.81805 \] \[\text{Eq. 3-8}\]

\[ \text{Sum} \_ \text{Tr} = P_r \_ \text{Tr} + \gamma_{gd} \_ \text{Tr} \] \[\text{Eq. 3-9}\]

\[ P_r \_ \text{Tr} = 2.74921 (P_r)^3 - 2.373343 (P_r)^2 + 2.1688 (p_r) - 0.92913 \] \[\text{Eq. 3-10}\]

\[ \gamma_{gd} \_ \text{Tr} = -15.24672 (\gamma_{gd})^4 + 70.96942 (\gamma_{gd})^3 - 120.65049 (\gamma_{gd})^2 + 84.86958 (\gamma_{gd}) - 19.79538 \] \[\text{Eq. 3-11}\]

Figure 3-13 presents a comparison of the measured reservoir gas specific gravity with the reservoir gas specific gravity calculated with the new correlation.

![Figure 3-13 Reservoir gas specific gravity correlation.](image-url)
• **Relative errors**

  $\text{AARE} = 4.43\%$

  $\text{ARE} = 0.0\%$

• **Equilibration**

  The following plots (Figure 3-14 to Figure 3-16) present the equilibration process of the correlation.

  *Figure 3-14 Equilibration of pressure ratio.*
Figure 3-15 Equilibration of reservoir gas specific gravity of dewpoint gas.

Figure 3-16 Equilibration of ratio of reservoir gas specific gravities.
The following table summarizes the statistics of the equilibration process.

<table>
<thead>
<tr>
<th></th>
<th>AARA %</th>
<th>ARA %</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ₀₀</td>
<td>2.17</td>
<td>0.26</td>
</tr>
<tr>
<td>Pr</td>
<td>9.97</td>
<td>0.09</td>
</tr>
<tr>
<td>γₚ₀</td>
<td>2.32</td>
<td>0.19</td>
</tr>
</tbody>
</table>

The results shown in Table 3-7 indicate that the laboratory results have random error, ARA close to zero and that inaccuracies in the measurement of pressures contribute significantly to the AARE of the gas specific gravity correlation.

3.3.3 Correlation 3, Yield Based on First Separator Gas Production

The third correlation to be performed is the estimation of the yield based on first separator gas production from readily available field data.

Statistics of Available Variables

Table 3-8 summarizes the statistics of the available data to create the correlation from the composition analysis of 851 depletion stages.
Table 3-8 Correlation 3 – Statistics of Available Variables

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Mean</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir Temperature [F]</td>
<td>126</td>
<td>247.1</td>
<td>348</td>
</tr>
<tr>
<td>Pressure [psia]</td>
<td>1,114.7</td>
<td>3,083.3</td>
<td>9,014.7</td>
</tr>
<tr>
<td>Reservoir Gas Specific Gravity</td>
<td>0.61</td>
<td>0.826</td>
<td>1.17</td>
</tr>
<tr>
<td>Specific Gravity of Dewpoint Reservoir Gas</td>
<td>0.643</td>
<td>1.044</td>
<td>1.568</td>
</tr>
<tr>
<td>Yield based on first separator gas production [STB/MMscf]</td>
<td>8.34</td>
<td>51.55</td>
<td>247.46</td>
</tr>
<tr>
<td>Yield based on first separator gas production calculated using dewpoint gas [STB/MMscf]</td>
<td>17.95</td>
<td>144.66</td>
<td>417.60</td>
</tr>
</tbody>
</table>

Results

After an extensive search of the best correlation to predict the yield based on first separator gas production, the function that best estimates this gas property is described below.

- **Dependent Variable:**

  \[ \ln Y1: \text{logarithm of yield based on first separator gas production, STB/MMscf.} \]

- **Independent Variables:**

  \[ \ln P: \text{logarithm of reservoir pressure, psia.} \]

  \[ \ln Y1_d: \text{logarithm of yield based on first separator gas production calculated using dewpoint gas, STB/MMscf.} \]

  \[ \gamma_{gr}: \text{Ratio of Reservoir Gas Specific Gravities, defined as:} \]
\( \gamma'_{gr} = \frac{\gamma'_g(P)}{\gamma_g(P_d)} \) .................................Eq. 3-12

- **Transforms**

The following plots (Figure 3-17 to Figure 3-20) present the transforms for each independent variable.

**Figure 3-17 Optimal transform of pressure**
Figure 3-18 Optimal transform of yield based on first separator gas production calculated using dewpoint gas.

Figure 3-19 Optimal transform of ratio of reservoir gas specific gravities.
Figure 3-20 Inverse transform of yield based on first separator gas production.

- Correlation

\[ \ln Y_1 = 0.007707 \text{SumTr}^3 - 0.065323 \text{SumTr}^2 + 0.648103 \text{SumTr} + 3.8172 \]

Eq. 3-13

\[ \text{SumTr} = \ln P_{_\text{Tr}} + \ln Y_{1_d}_{_\text{Tr}} + \gamma_{gr}_{_\text{Tr}} \]

Eq. 3-14

\[ \ln P_{_\text{Tr}} = 0.018604 (\ln P)^2 + 0.119692 (\ln P) - 2.170358 \]

Eq. 3-15

\[ \ln Y_{1_d}_{_\text{Tr}} = 0.279744 (\ln Y_{1_d})^2 - 0.474230 (\ln Y_{1_d}) - 4.160158 \]

Eq. 3-16

\[ \gamma_{gr}_{_\text{Tr}} = -1.925507 (\gamma_{gr})^2 + 12.9211846 (\gamma_{gr}) - 9.199058 \]

Eq. 3-17

Figure 3-21 presents a comparison of the measured yield based on first separator gas production with the yield based on first separator gas production calculated using the new correlation.
Figure 3-21 Correlation of yield based on first separator gas production.

- Relative errors

  AARE = 9.88%

  ARE = 0.0%

- Equilibration

  The following plots (Figure 3-22 to Figure 3-25) present the equilibration process of the correlation.
Figure 3-22 Equilibration of pressure.

Figure 3-23 Equilibration of yield based on first separator gas production calculated using dewpoint gas.
Figure 3-24 Equilibration of ratio of reservoir gas specific gravities

Figure 3-25 Equilibration of yield based on first separator gas production.
The following table summarizes the statistics of the equilibration process.

<table>
<thead>
<tr>
<th></th>
<th>AARA</th>
<th>ARA</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln Y1</td>
<td>4.9</td>
<td>0.5</td>
</tr>
<tr>
<td>ln P</td>
<td>5.9</td>
<td>0.31</td>
</tr>
<tr>
<td>ln Y1d</td>
<td>1.08</td>
<td>0.001</td>
</tr>
<tr>
<td>γgr</td>
<td>0.3</td>
<td>0</td>
</tr>
</tbody>
</table>

The results in Table 3-9 show that inaccuracies in measurement of pressures are the largest contribution to the AARE of the resulting correlation.

3.3.4 Correlation 4, Yield Based on First Separator Gas Production

A fourth correlation was generated to estimate the first separator yield after some depletion has occurred from readily available field data to avoid the use of multiple correlations to do the estimation.

Statistics of Available Variables

Table 3-10 summarizes the statistics of the available variables to build the correlation from the composition analysis of 851 depletion stages.
Table 3-10 Correlation 4 – Statistics of Available Variables

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Mean</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir Temperature [F]</td>
<td>126</td>
<td>247.1</td>
<td>348</td>
</tr>
<tr>
<td>Pressure [psia]</td>
<td>1,114.7</td>
<td>3,083.3</td>
<td>9,014.7</td>
</tr>
<tr>
<td>Specific Gravity of</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dewpoint Reservoir Gas</td>
<td>0.643</td>
<td>1.044</td>
<td>1.568</td>
</tr>
<tr>
<td>Yield based on first separator</td>
<td>8.34</td>
<td>51.55</td>
<td>247.46</td>
</tr>
<tr>
<td>gas production [STB/MMscf]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield based on first separator</td>
<td>17.95</td>
<td>144.66</td>
<td>417.60</td>
</tr>
<tr>
<td>gas production calculated using dewpoint gas [STB/MMscf]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stock-tank condensate gravity calculated using dewpoint gas [°API]</td>
<td>37.83</td>
<td>53.77</td>
<td>76.52</td>
</tr>
</tbody>
</table>

Results

After an extensive search of the best correlation to predict the yield at the first separator from field data, the function that best estimates this fluid property is described below.

- **Dependent Variable:**

  \[ \ln(Y_1) \text{ log of yield based on first separator gas production, STB/MMscf.} \]

- **Independent Variables:**

  \[ \ln(P) \text{ log of reservoir pressure, psia.} \]

  \[ \text{API}_d: \text{ Stock-tank condensate gravity calculated using dewpoint gas, °API.} \]

  \[ \gamma_{gd}: \text{ Reservoir Gas Specific Gravity of dewpoint gas.} \]

  \[ T: \text{ Reservoir Temperature, °F.} \]

- **Transforms**
The following plots (Figure 3-26 to Figure 3-30) present the transforms for each independent variable.

Figure 3-26 Optimal transform of reservoir pressure.

Figure 3-27 Optimal transform of stock-tank condensate gravity calculated using dewpoint gas.
Figure 3-28 Optimal transform of reservoir gas specific gravity of dewpoint gas.

Figure 3-29 Optimal transform of reservoir temperature.
Figure 3-30 Optimal inverse transform of ln of yield based on first separator gas production.

- **Correlation**

\[ \ln Y1 = 0.015359 \times \text{Sum}Tr^2 + 0.61967 \times \text{Sum}Tr + 3.684 \] \hspace{1cm} \text{...Eq. 3-18}

\[ \text{Sum}Tr = \ln P \_Tr + API\_d \_Tr + \gamma_{gd} \_Tr + T \_Tr \] \hspace{1cm} \text{...Eq. 3-19}

\[ \ln P \_Tr = 0.5136 \left( \ln P \right)^2 - 6.7095 \left( \ln P \right) + 20.809 \] \hspace{1cm} \text{...Eq. 3-20}

\[ API\_d \_Tr = 2.4889 E - 6 \left( API\_d \right)^4 - 0.0005438 \left( API\_d \right)^3 + 0.042311 \left( API\_d \right)^2 - 1.2965 \left( API\_d \right) + 11.175 \] \hspace{1cm} \text{...Eq. 3-21}

\[ \gamma_{gd} \_Tr = 4.3658 \left( \gamma_{gd} \right)^3 - 18.598 \left( \gamma_{gd} \right)^2 + 27.652 \left( \gamma_{gd} \right) - 13.365 \] \hspace{1cm} \text{...Eq. 3-22}

\[ T \_Tr = 1.4035 E - 6 \left( T \right)^2 + 0.0058453 \left( T \right) - 1.5309 \] \hspace{1cm} \text{...Eq. 3-23}
Figure 3-31 presents a comparison of the measured yield based on first separator gas production with the yield based on first separator gas production calculated using the new correlation.

![Correlation of yield based on first separator gas production.](image)

- **Relative errors**

  AARE= 19.89%  
  ARE= 0.0%  

- **Equilibration**

  The following plots (Figure 3-32 to Figure 3-36) present the equilibration process in the correlation.
Figure 3-32 Equilibration of reservoir pressure.

Figure 3-33 Equilibration of stock-tank condensate gravity calculated using dewpoint gas.
Figure 3-34 Equilibration of reservoir gas specific gravity of dewpoint gas.

Figure 3-35 Equilibration of reservoir temperature
Figure 3-36 Equilibration of yield based on first separator gas production.

The following table summarizes the statistics of the equilibration process.

Table 3-11 Equilibration Results

<table>
<thead>
<tr>
<th></th>
<th>AARA</th>
<th>ARA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>In Y1</td>
<td>9.66</td>
<td>0.5</td>
</tr>
<tr>
<td>ln P</td>
<td>3.25</td>
<td>0.016</td>
</tr>
<tr>
<td>APId</td>
<td>0.89</td>
<td>0.02</td>
</tr>
<tr>
<td>γgd</td>
<td>1.26</td>
<td>0.035</td>
</tr>
<tr>
<td>I</td>
<td>2.64</td>
<td>0.018</td>
</tr>
</tbody>
</table>

The results in Table 3-11 show that inaccuracies in the values of condensate yield based on first separator gas contribute significantly to the AARE of the correlation.
3.4 COMPARATIVE ANALYSIS

3.4.1 Change of Separator Conditions

The same methodology applied with the set of separator conditions given in Table 3-2 was done with a second set of conditions summarized in Table 3-12.

<table>
<thead>
<tr>
<th></th>
<th>First Separator K-values</th>
<th>Second Separator K-values</th>
<th>Stock-tank K-values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T [°F]</td>
<td>P [psia]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>514.7</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>59.7</td>
<td>14.7</td>
</tr>
<tr>
<td></td>
<td>6.24585</td>
<td>23.0125</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.79007</td>
<td>18.98874</td>
<td>71.4026</td>
</tr>
<tr>
<td></td>
<td>133.46187</td>
<td>580.66649</td>
<td></td>
</tr>
<tr>
<td></td>
<td>45.13617</td>
<td>177.52948</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.98854</td>
<td>28.71822</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.32623</td>
<td>7.88901</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.86925</td>
<td>2.79424</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.63187</td>
<td>2.04451</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.25246</td>
<td>0.7714</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.20256</td>
<td>0.61089</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0614</td>
<td>0.16552</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.00052</td>
<td>0.00126</td>
<td></td>
</tr>
</tbody>
</table>

The same procedure described before to generate the four correlations was repeated with the new calculated parameters. The results compared with the first set of initial conditions, that is the correlations agreed in polynomial degree for all transforms and correlations and the coefficients for every equation were within 2% of those from the original set of separator conditions. Therefore the correlations generated at first instance are reasonably independent of separator conditions.
3.4.2 Comparison with Other Correlations

The data set used to develop the new correlations were used to evaluate the accuracy of the two existing dew-point pressure correlations independent of composition: the Humoud Correlation and the Marrufo et.al correlation.

a) Humoud Correlation

Based on 74 experimental data points the model in his work is described as follows.

\[
\ln(P_d) = \beta_0 + \beta_1 \ln(T) + \beta_2 \ln(R_m) + \beta_3 \ln\left(\frac{P_{sp} \cdot T_{sp}}{P_{pr} \cdot T_{pr}}\right) + \frac{\beta_4}{T_{pr}} + \frac{\beta_5}{P_{pr}} + \frac{\beta_6}{\gamma_{C7+}}.
\]

...............Eq. 3-24

Where,
\[
\beta_0 = 43.777183, \quad \beta_1 = -3.594131, \quad \beta_2 = -0.247436, \quad \beta_3 = -0.053527
\]

\[
\beta_4 = -4.291404, \quad \beta_5 = -3.698703, \quad \beta_6 = -4.590091
\]

The mass gas-oil ration \( (R_m) \) is defined as:

\[
R_m = \frac{R_{sp} \cdot \gamma_{gsp}}{\gamma_{C7+}}. \quad \text{...............Eq. 3-25}
\]

The pseudoreduced pressure and temperature are defined as:

\[
P_{pr} = \frac{P_R}{P_{pc}}. \quad \text{...............Eq. 3-26}
\]

\[
T_{pr} = \frac{T_R}{T_{pc}}. \quad \text{...............Eq. 3-27}
\]

Correlations were developed by Humoud for estimation of the pseudo-critical properties as functions of reservoir gas specific gravity.
\[ P_{pc} = 694.5 - 55.3 \gamma_{gR} . \] \text{Eq. 3-28}

\[ T_{pc} = 208.5 + 213.7 \gamma_{gR} . \] \text{Eq. 3-29}

Using Humoud’s equations for the estimation of the dew-point pressure, the average absolute relative error was found to be 10.44% and the average relative error was 6.38% based on the data based used in this research.

\textbf{b) Marrufo \textit{et al.} Correlation}

The correlation that was generated that was generated by Marrufo \textit{et al.} using one hundred and one PVT analyses is:

\[ P_d = K_1 \left[ \frac{R}{C_{7^+}^K} \right] \ast K_6 \ast API \left(K_4 \ast \gamma_{K}^{K} - K_4 \ast C_{7^+}^{K} \right) \] \text{Eq. 3-30}

where

\[ K_1 = 346.7764689, \ K_2 = 0.0974139, \ K_3 = -0.294782419, \ K_4 = -0.047833243, \]
\[ K_5 = 0.281255219, \ K_6 = 0.00068358, \ K_7 = 1.906328237, \ K_8 = 8.417626216 \]

and the \( C_{7^+} \) content can be estimated from two correlations developed in the research:

\[ \% C_{7^+} = \left( \frac{R}{70680} \right)^{-0.8207} \] \text{Eq. 3-31}

\[ \% C_{7^+} = 10260 \ast (R \ast \gamma_{Sp}) \] \text{Eq. 3-32}

Marrufo’s paper does not explain the reason why two heptanes plus fraction correlations were generated. Both correlations were used to make the comparison with this research, giving the same results with each.

The average absolute relative error was found to be 24.9% and the average relative error was 7.8%, using both correlations for the \( C_{7^+} \) fraction, based on the data based used in this research.
The following table summarizes the comparative results from each correlation based on the data set used in this research.

Table 3-13 Statistical Accuracy of Dew Point Pressure Correlations

<table>
<thead>
<tr>
<th>Correlation</th>
<th>AARE</th>
<th>ARE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Humoud</td>
<td>10.4</td>
<td>6.4</td>
</tr>
<tr>
<td>Marruffo et al.</td>
<td>24.9</td>
<td>7.8</td>
</tr>
<tr>
<td>This study</td>
<td>9.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
CHAPTER IV

SUMMARY

4.1 CONCLUSIONS

Four correlations were developed in this study: dew-point pressure, reservoir gas specific gravity after some depletion and two producing yield in gas condensate reservoirs. Based upon the literature review and work performed in this thesis the following conclusions were drawn:

1. A reasonably accurate correlation to predict gas condensate dew-point pressure has been developed based on readily available field data.

2. A reasonably accurate correlation to estimate the reservoir specific gravity after some depletion has occurred has been developed based on field data and on the dew-point pressure correlation presented in this study.

3. Two different correlations have been developed to estimate the producing yield from a gas condensate reservoir. The first one predicts the producing yield from field data using the correlations developed previously. The second correlation was created directly from readily available field data.

4. The dew-point pressure correlation for gas condensate reservoirs has been compared with two existing correlations, providing a better accuracy than either.

5. Correlations of reservoir gas specific gravity and producing yield have not been previously reported in the literature.
6. The new correlations are independent of separator conditions.

7. The four correlations are based on a dataset that covers fairly well the pressures and temperatures that are normally present in gas condensate reservoirs.

8. The new correlations were based on data from locations worldwide, therefore they are independent of geographical location.
NOMENCLATURE

AARA = Average Absolute Relative Adjustment, %

AARE = Average Absolute Relative Error, %

ARA = Average Relative Adjustment, %

ARE = Average Relative Error, %

$f_{Li}$ = Liquid fraction at the separator $i$.

$f_g$ = Vapor fraction of the fluid.

$f_{gi}$ = Vapor fraction at the separator $i$.

$k_i$ = Equilibrium ratio for component $i$.

$M_g$ = Molecular weight of gas.

$M_i$ = Molecular weight of the component $i$.

$M_{STO}$ = Molecular weight of the liquid in the stock tank.

P = Pressure, psia.

$R_{SP1}$ = Gas/liquid ratio for the primary separator, scf/STB.

$R_{SP2}$ = Gas/liquid ratio for the secondary separator, scf/STB.

$R_{ST}$ = Gas/liquid ratio at Stock Tank, scf/STB.

$R$ = Total gas/liquid ratio, scf/STB.
$T =$ Temperature, °F except in Eq. 3-24, Eq. 3-27, Eq. 3-30, °R.

$W_{C1} =$ Mass of the methane in lb methane/ lb-mole of mix.

$W_{CO2} =$ mass of the carbon dioxide in lb carbon dioxide/ lb-mole of mix.

$W_{mix} =$ Mass of the mixture in lb of mix/lb mole of mix.

$W_{N2} =$ Mass of the nitrogen in lb nitrogen/ lb-mole of mix

$x_i =$ Mole fraction of component $i$ in the liquid phase.

$Y_i =$ Producing yield based on separator $i$ gas production, STB/MMscf.

$y_i =$ Mole fraction of component $i$ in the vapor phase.

$z_i =$ Mole fraction of component $i$.

$\gamma_g =$ Gas specific gravity.

$\gamma_{STO} =$ Stock-tank oil gravity

$\rho_{bs} =$ Liquid density at pressure and 60°F, lb/ft$^3$.

$\rho_{C3+} =$ Density of the propane, lb/ft$^3$.

$\rho_{PO} =$ Pseudo-liquid density, lb/ft$^3$.

$\rho_{W} =$ Density of water at standard conditions.
REFERENCES


SUPPLEMENT REFERENCES


APPENDIX A

PROGRAM FOR CALCULATING THE PRODUCING GOR FROM THE RESERVOIR GAS COMPOSITION

' Based on:
' Surface Separator Calculations, Chapter 13
' from "The Properties of Petroleum Fluids" by Dr. McCain
'
' Last Modified: Adriana Ovalle
' February 2002
'
Sub Yield()

' Define variables
Dim k() As Double ' vector holding K values for a given P and T for a given component
Dim k1() As Double ' vector holding K values for a given P and T for a given component in separator 1.
Dim k2() As Double ' vector holding K values for a given P and T for a given component in separator 2.
Dim k3() As Double ' vector holding K values for a given P and T for a given component in Stock Tank.
Dim z() As Double ' vector holding the composition of every component in separator 1.
Dim ZSP1() As Double ' vector holding the composition of every component in separator 1.
Dim ZSP2() As Double ' vector holding the composition of every component in separator 2.
Dim ZST() As Double ' vector holding the composition of every component in Stock tank.
Dim X() As Double ' vector holding the liquid composition of every component.
Dim XSP1() As Double ' vector holding the liquid composition of every component in separator 1.
Dim XSP2() As Double ' vector holding the liquid composition of every component in separator 2.
Dim XST() As Double ' vector holding the liquid composition of every component in Stock tank.
Dim Y() As Double ' vector holding the vapor composition component.
Dim YSP1() As Double ' vector holding the vapor composition component in separator 1.
Dim YSP2() As Double ' vector holding the vapor composition component in separator 2.
Dim YST() As Double ' vector holding the vapor composition component in Stock Tank.
Dim MW() As Double ' vector holding the molar weight of every component.
Dim M() As Double ' vector holding the weight of every component.
Dim D() As Double ' vector holding the density of every component.
Dim V() As Double ' vector holding the volume of every component.
Dim i As Integer ' counter.
Dim j As Integer ' counter.
Dim n As Integer ' counter - number of tests.
Dim ng As Double ' fraction of gas.
Dim ng1 As Double ' fraction of gas in Separator 1.
Dim ng2 As Double ' fraction of gas in Separator 2.
Dim ng3 As Double ' fraction of gas in Stock tank.
Dim nl1 As Double ' fraction of liquid in Separator 1.
Dim nl2 As Double ' fraction of liquid in Separator 2.
Dim nl3 As Double ' fraction of liquid in Stock tank.
Dim D3P As Double ' Density of propanes plus.
Dim Sum1 As Double ' Equation for iteration.
Dim Sum2 As Double ' Equation for iteration.
Dim W1 As Double ' Weight fraction of methane in the mixture.
Dim W2 As Double ' Weight fraction of ethane and heavier includes nonhydrocarbon components.
Dim WT As Double ' Total weight of the mixture.
Dim VT As Double ' Total volume of the mixture.
Dim PLD As Double ' Pseudoliquid Density.
Dim sg As Double ' Specific Gravity of stock tank oil.
Dim API As Double ' Gravity of Stock Tank Oil.
Dim RSP1 As Double ' Gas Condenaste Ratio Separator 1.
Dim RSP2 As Double ' Gas Condenaste Ratio Separator 2.
Dim RST As Double ' Gas Condenaste Ratio Stock Tank.
Dim R As Double ' Gas Condenaste Ratio.
Dim T1 As Double ' Temperature in Rankine of Separator 1.
Dim T2 As Double ' Temperature in Rankine of Separator 2.
Dim TST As Double ' Temperature in Rankine of Stock Tank.
Dim T As Double ' Temperature in Rankine
Dim p As Double ' Pressure in psia
Dim P1 As Double ' Pressure in psia of Separator 1
Dim P2 As Double ' Pressure in psia of Separator 2
Dim PST As Double ' Pressure in psia of Stock Tank
Dim Row As Double

j = 12
ReDim k(1 To j) As Double
ReDim k1(1 To j) As Double
ReDim k2(1 To j) As Double
ReDim k3(1 To j) As Double
ReDim ZSP1(1 To j) As Double
ReDim ZSP2(1 To j) As Double
ReDim ZST(1 To j) As Double
ReDim X(1 To j) As Double
ReDim XSP1(1 To j) As Double
ReDim XSP2(1 To j) As Double
ReDim XST(1 To j) As Double
ReDim Y(1 To j) As Double
ReDim YSP1(1 To j) As Double
ReDim YSP2(1 To j) As Double
ReDim YST(1 To j) As Double
ReDim MW(1 To j) As Double
ReDim M(1 To j) As Double
ReDim D(1 To j) As Double
ReDim V(1 To j) As Double

' Read in input data from "Data" worksheet
n = Worksheets("Data").Cells(3, 4).Value

For i = 1 To j
MW(i) = Worksheets("Data").Cells(9, i + 3).Value
D(i) = Worksheets("Data").Cells(10, i + 3).Value
Next i

' Calculate the compositions and quantities of separator gas and liquid for both separators and stock-tank.

Row = Worksheets("Data").Cells(4, 4).Value
For j = Row To (Row - 1 + n)
For i = 1 To 12
ZSP1(i) = Worksheets("Data").Cells(j, i + 3).Value
If ZSP1(i) = 0 Then
k1(i) = 0
k2(i) = 0
k3(i) = 0
Else
k1(i) = Worksheets("Data").Cells(11, i + 3).Value
k2(i) = Worksheets("Data").Cells(12, i + 3).Value
k3(i) = Worksheets("Data").Cells(13, i + 3).Value
End If
Next i

MW(12) = Worksheets("Data").Cells(j, 16).Value
ng1 = converge(ZSP1(), k1())
nl1 = 1 - ng1
If ng1 <= 1 Then
Call composition(ZSP1(), k1(), XSP1(), YSP1(), ng1)
End If
For i = 1 To 12
ZSP2(i) = XSP1(i)
Next i
ng2 = converge(ZSP2(), k2())
nl2 = 1 - ng2
Call composition(ZSP2(), k2(), XSP2(), YSP2(), ng2)

For i = 1 To 12
ZST(i) = XSP2(i)
Next i
ng3 = converge(ZST(), k3())
nl3 = 1 - ng3
Call composition(ZST(), k3(), XST(), YST(), ng3)

'Calculate the density and molecular weight of the stock-tank oil at standard conditions.
Sum1 = 0
Sum2 = 0
For i = 1 To 12
M(i) = XST(i) * MW(i)
V(i) = M(i) / D(i)
Sum1 = Sum1 + M(i)
Next i
WT = Sum1
Sum1 = 0
Sum2 = 0
For i = 6 To 12
Sum1 = Sum1 + M(i)
Sum2 = Sum2 + V(i)
Next i
D3P = (Sum1 + M(1)) / (Sum2 + V(1))
W1 = M(4) / WT
W2 = (M(5) + M(3)) / (WT - M(4) - M(2))
PLD = D3P / (1 + 2.138156 * W1 ^ 1.1027205 + 0.45371 * W2 ^ 1.092823)
sg = PLD / 62.37
API = 141.5 / sg - 131.5
RSP1 = (2138 * ng1 * PLD) / (nl1 * nl3 * WT)
RSP2 = (2138 * ng2 * PLD) / (nl2 * nl3 * WT)
RST = (2138 * ng3 * PLD) / (nl3 * WT)
R = RSP1 + RSP2 + RST
With Worksheets("Data")
.Cells(j, 27).Value = ng1
.Cells(j, 28).Value = nl1
.Cells(j, 29).Value = RSP1
.Cells(j, 30).Value = ng2
.Cells(j, 31).Value = nl2
.Cells(j, 32).Value = RSP2
.Cells(j, 33).Value = ng3
.Cells(j, 34).Value = nl3
.Cells(j, 35).Value = RST
.Cells(j, 36).Value = R
.Cells(j, 37).Value = API
End With
End If
Next j

End Sub

Function converge(z() As Double, k() As Double) As Double
Dim ng As Double
Dim i As Double
Dim Sum1 As Double
Dim Sum2 As Double
Dim it As Double
Dim F As Double
Dim dF As Double
Dim ngn As Double

End Function
Dim ngs As Double
Dim Delta As Double
Dim temp As Double
Dim converged As Boolean

it = 0
ngs = 0.05
ng = 1.1
While ng > 1
ng = ngs
converged = False
Sum1 = 0
Sum2 = 0
For i = 1 To 12
Sum1 = Sum1 + k(i) * z(i)
If k(i) = 0 Then
Sum2 = Sum2
Else
Sum2 = Sum2 + z(i) / k(i)
End If
Next i

If (Sum1 > 1 And Sum2 > 1) Then
   While (converged = False And it < 8)
   F = 0
dF = 0
   For i = 1 To 12
   temp = (k(i) - 1) / (1 + ng * (k(i) - 1))
   F = F + z(i) * temp
dF = dF - z(i) * temp * temp
   Next i
   Delta = F / dF
   ngn = ng - Delta
   If ((Abs(Delta) + Abs(F)) < 0.00000001) And (ng <= 1) Then
      converged = True
   End If
   ng = ngn
   it = it + 1
   Wend
Else
   If Sum1 <= 1 Then
   ng = 0
   Else
   ng = 1
   End If
End If
End If
End If
ngs = ngs + 0.05
it = 0
Wend
converge = ng
End Function

Sub composition(z() As Double, k() As Double, X() As Double, Y() As Double, ng As Double)  
For i = 1 To 12  
If z(i) = 0 Then  
X(i) = 0  
Y(i) = 0  
Else  
X(i) = z(i) / (1 + ng * (k(i) - 1))  
Y(i) = k(i) * X(i)  
End If  
Next i  
End Sub
VITA

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