Reservoir oil bubblepoint pressures revisited; solution gas–oil ratios and surface gas specific gravities

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Abstract

A large number of recently published bubblepoint pressure correlations have been checked against a large, diverse set of service company fluid property data with worldwide origins. The accuracy of the correlations is dependent on the precision with which the data are measured. In this work a bubblepoint pressure correlation is proposed which is as accurate as the data permit.

Certain correlations, for bubblepoint pressure and other fluid properties, require use of stock-tank gas rate and specific gravity. Since these data are seldom measured in the field, additional correlations are presented in this work, requiring only data usually available in field operations. These correlations could also have usefulness in estimating stock-tank vent gas rate and quality for compliance purposes.

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Keywords: Oil property correlation; Bubblepoint pressure; Solution gas–oil ratio; Surface gas specific gravity; Non-parametric regression

1. Introduction

A large number of correlations for estimation of bubblepoint pressures of reservoir oils have been offered in the petroleum engineering literature over the last few years to go with a handful of correlations published earlier. Many of these new correlations are based on data from a single geographical area. Most of these correlations were derived using petroleum service company laboratory fluid property data.

The primary goal of this paper is to evaluate these correlations. For this purpose a large set of service company data has been assembled. The data set is truly worldwide with samples from all major producing areas of the world; thus, it permits evaluation of the necessity of geography-specific correlations. We are indebted to the several authors listed in Table 2.3 who provided geographical data.

An even more exciting question is whether the predictive power of such correlations can be significantly improved or whether the known accuracy limit is inherently determined by the quality of the available data.

Related to the bubblepoint pressure prediction from observable field data is the issue of estimating stock-tank gas rate and specific gravity (shown as $R_{ST}$...
and $\gamma_{GST}$ in Fig. 1.1) Certain correlations, for bubble-point pressure and other fluid properties, require knowledge of these quantities. Since these data are seldom measured in the field, additional correlations are presented in this work, requiring only data usually available in field operations.

An additional and potentially important application of these new correlations could be in estimating stock-tank vent gas rate and quality for compliance purposes.

This paper is organized as follows. The methodology is described in Section 1. Section 2 deals with various aspects of bubblepoint correlations, evaluation of published methods, improvement of existing meth-

Table 2.1
The bubblepoint pressure data set has a wide range of values of the independent variables

<table>
<thead>
<tr>
<th>Laboratory measurement</th>
<th>Minimum</th>
<th>Mean</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution gas–oil ratio at bubblepoint, scf/STB</td>
<td>10</td>
<td>588</td>
<td>2216</td>
</tr>
<tr>
<td>Bubblepoint pressure, psia</td>
<td>82</td>
<td>2193</td>
<td>6700</td>
</tr>
<tr>
<td>Reservoir temperature, °F</td>
<td>60</td>
<td>185</td>
<td>342</td>
</tr>
<tr>
<td>Stock-tank oil gravity, °API</td>
<td>6.0</td>
<td>35.7</td>
<td>63.7</td>
</tr>
<tr>
<td>Separator gas specific gravity</td>
<td>0.555</td>
<td>0.838</td>
<td>1.685</td>
</tr>
</tbody>
</table>

Fig. 1.1. Notation for variables.

Table 2.2
A comparison of published bubblepoint pressure correlations using data described in Table 2.1 reveals the more reliable correlations

<table>
<thead>
<tr>
<th>Predicted bubblepoint pressure</th>
<th>ARE, %</th>
<th>AARE, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>McCain et al. (Eqs. 7–12) (1998)</td>
<td>3.5</td>
<td>12.4</td>
</tr>
<tr>
<td>Velarde et al. (1999)</td>
<td>1.2</td>
<td>12.5</td>
</tr>
<tr>
<td>Labeadi (1990)</td>
<td>0.0</td>
<td>12.6</td>
</tr>
<tr>
<td>Standing* (1947)</td>
<td>-2.1</td>
<td>12.7</td>
</tr>
<tr>
<td>Lasater** (1958)</td>
<td>-1.3</td>
<td>13.3</td>
</tr>
<tr>
<td>Levitan and Murtha (1999)</td>
<td>4.2</td>
<td>13.9</td>
</tr>
<tr>
<td>Al-Shammai (1999)</td>
<td>-1.4</td>
<td>14.3</td>
</tr>
<tr>
<td>Vazquez and Beggs (1980)</td>
<td>7.1</td>
<td>14.6</td>
</tr>
<tr>
<td>Omar and Todd* (1993)</td>
<td>5.4</td>
<td>15.5</td>
</tr>
<tr>
<td>De Ghetto et al. (1994)</td>
<td>8.6</td>
<td>15.6</td>
</tr>
<tr>
<td>Kartosamudjo and Schmidt (1994)</td>
<td>4.4</td>
<td>15.7</td>
</tr>
<tr>
<td>Dindoruk and Christman* (2001)</td>
<td>0.9</td>
<td>16.1</td>
</tr>
<tr>
<td>Glaso (1980)</td>
<td>4.8</td>
<td>16.8</td>
</tr>
<tr>
<td>Fashad et al.* (1996)</td>
<td>-5.6</td>
<td>17.8</td>
</tr>
<tr>
<td>Al-Marhoun* (1988)</td>
<td>8.8</td>
<td>17.8</td>
</tr>
<tr>
<td>Dokla and Osman* (1992)</td>
<td>0.3</td>
<td>21.8</td>
</tr>
<tr>
<td>Almeihadeb* (1997)</td>
<td>-0.6</td>
<td>22.3</td>
</tr>
<tr>
<td>Khairy et al.* (1998)</td>
<td>4.9</td>
<td>23.1</td>
</tr>
<tr>
<td>Macary and El Batanoney* (1992)</td>
<td>12.6</td>
<td>23.1</td>
</tr>
<tr>
<td>Hanafy et al.* (1997)</td>
<td>10.6</td>
<td>28.8</td>
</tr>
<tr>
<td>Petrosky and Farshad* (1998)</td>
<td>17.7</td>
<td>37.7</td>
</tr>
<tr>
<td>Yi (2000)</td>
<td>42.4</td>
<td>45.2</td>
</tr>
</tbody>
</table>

*Author restricted the correlation to a specific geographical area.
**Not valid for °API<18°.
ods, discussion of data quality, and investigation of the geographical factor. Sections 3 and 4 present new correlations for solution gas–oil ratio and weighted average surface gas specific gravity.

2. Statistical methods

This work systematically uses a relatively novel technique to reveal the underlying statistical relationships among variables corrupted by random error. The method of alternating conditional expectations (ACE) developed by Breiman and Friedman (1985)—as other similar non-parametric statistical regression methods—is intended to alleviate the main drawback of parametric regression, i.e., the mismatch of assumed model structure and the actual data. In non-parametric regression a-priori knowledge of the functional relationship between the dependent variable $y$ and independent variables, $x_1, x_2, \ldots x_m$, is not required. In fact, one of the main results of non-parametric regression is determination of the actual form of this relationship.

A model predicting the value of $y$ from the values of $x_1, x_2, \ldots x_m$ is written in the generic form

$$y = f^{-1}(z) \quad \text{where} \quad z = \sum_{n=1}^{m} z_n \quad \text{and} \quad z_n = f_n(x_n)$$

The functions $f_1(\cdot), f_2(\cdot), \ldots f_m(\cdot)$ are called variable transformations yielding the transformed independent variables $z_1, z_2, \ldots z_m$. The function $f(\cdot)$ is the transformation for the dependent variable. In fact the main interest is its inverse: $f^{-1}(\cdot)$, yielding the dependent variable $y$ from the transformed dependent variable $z$.

Given $N$ observation points, we wish to find the “best” transformation functions $f_1(\cdot), f_2(\cdot), \ldots, f_m(\cdot)$ and $f^{-1}(\cdot)$, but first not as algebraic expressions, rather as relationships defined point-wise. The method of alternating conditional expectations (ACE) constructs and modifies the individual transformations to achieve maximum correlation in the

Fig. 2.1. Calculated bubblepoint pressures from Eq. (2-1) compare well with measured bubblepoint pressures (1745 data records).
transformed space. Graphically this means that the plot of \( z = \sum_{i=1}^{m} f_i(x_n) \) against \( z' = f(y_{\text{measured}}) \) should be as near to the 45° 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 needed to obtain the transformed variables and 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. In other words, 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), used here 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 transformations, and can be well approximated, for instance, by low order polynomials.

Data reconciliation is a well-known statistical procedure, see for instance Liebman et al. (1992), Crowe (1996), Weiss et al. (1996) and Vachhani et al. (2001). 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 transformed space the reconciled observations follow the 45° straight line perfectly, while the overall change in each observed value is kept to a minimum (Xue et al., 1997). 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.

Fig. 2.2. The bubblepoint pressure correlation, Eq. (2-1), is reliable (regarding unbiasedness ) across the spectrum of reservoir temperatures.
Statistical measures of correlations used throughout the paper are:

**Average relative error, ARE, %**

\[
ARE = \frac{100}{N} \sum_{i=1}^{N} \frac{y_{\text{calculated}} - y_{\text{measured}}}{y_{\text{measured}}} 
\]

**Average absolute relative error, AARE, %**

\[
AARE = \frac{100}{N} \sum_{i=1}^{N} \left| \frac{y_{\text{calculated}} - y_{\text{measured}}}{y_{\text{measured}}} \right| 
\]

ARE characterizes the accuracy (bias) and AARE describes the precision (scatter) of predicted values obtained from a particular correlation. All correlations are presented for the variables measured in the units indicated in the Nomenclature. It is also possible (and more correct) to consider any presented correlation as a relationship between dimensionless quantities, where the reference values are; for pressure 1 psi, for solution gas–oil ratio 1 scf/STB, for temperature 1 °F (with offset at 0 °F), and for oil gravity 1 ° API. With such interpretation in mind, even \(\ln p_b\) (the natural logarithm of dimensionless bubblepoint pressure) can be easily understood.

### 3. Bubblepoint pressures

A large number of correlations for estimating bubblepoint pressures of reservoir oils have been offered in the petroleum engineering literature over the last few years to go with a handful of correlations published earlier. Many of these new correlations are based on data from a single geographical area. Most of these correlations were derived using laboratory fluid property data reported by service companies.

![Graph](image-url)

**Fig. 2.3.** The bubblepoint pressure correlation, Eq. (2-1), is reliable (regarding scatter) across the spectrum of reservoir temperatures.
3.1. Evaluation of published correlations

A large set of service company fluid property data has been assembled. The data set is truly worldwide with samples from all major producing areas of the world. The wide range of values of the variables in this data set, described in Table 2.1, span virtually all the values to be expected in new discoveries/developments. Note that the fluid types vary from heavy oil to volatile oil range.

Bubblepoint pressures calculated with many of the published correlations using the measured values of independent variables were compared with the laboratory-measured bubblepoint pressures. The results of this comparison are given in Table 2.2 arranged in the order of increasing average absolute relative error (AARE). None of the correlations shown in Table 2.2 was derived using the full data set of Table 2.1; however, many were prepared using subsets of this data set.

3.2. Improvement of existing correlations

With the thought that a correlation of improved accuracy could be derived, the best four correlations from Table 2.2 were refitted to the entire data set. Standing (1947) deduced the form of his equation using graphical methods. Velarde et al. (1999) used a modification of the Standing (1947) equation originally proposed by Petrosky and Farshad (1998); Labeadi (1990) used the Standing (1947) technique and deduced new values for the slope and intercept. The coefficients of the Standing (1947), Velarde et al. (1999) and Labeadi (1990) equations were recalculated using nonlinear least-squares minimization. In these cases the improvements in the predictions of bubble point pressure were marginal.

There was some improvement in bubblepoint pressure prediction using the GRACE technique (first used for this purpose in McCain et al., 1998, Eq. (7–12)) when the coefficients were determined using

Fig. 2.4. The bubblepoint pressure correlation, Eq. (2-1), is reliable (regarding unbiasedness) across the spectrum of solution gas–oil ratios at the bubblepoint, $R_{sb}$. 
the full data set. The new equations for estimating bubblepoint pressure are given below.

\[ \ln p_b = 7.475 + 0.713z + 0.0075z^2 \] where

\[ z = \sum_{n=1}^{4} z_n \quad \text{and} \quad z_n = C0_n + C1_n \text{VAR}_n + C2_n \text{VAR}_n^2 + C3_n \text{VAR}_n^3 \] (2 - 1)

The average relative error (ARE) is 0.0 %, and the average absolute relative error (AARE) is 10.9 %. Fig. 2.1 shows that there is no bias and the precision is adequate.

The relative errors cited above and given in Table 2.2 pertain to the entire data set. The reliability of correlations across the spectrum of the independent variables is also important. The data set was sorted by reservoir temperature and partitioned into 16 subsets of approximately equal size. The accuracy of Eq. (2-1) as well as several of the more popular correlations were tested with these subsets. Figs. 2.2 and 2.3 show AREs and AAREs for five of the correlations. The results obtained with Eq. (2-1) stay constantly near zero ARE and consistently have the lowest AARE. Figs. 2.4 and 2.5 show the same results for the data set partitioned into 16 equal subsets by solution gas–oil ratio at the bubblepoint. Figs. 2.6 and 2.7 show that the bubblepoint pressure correlation of this study is reliable when the data set is partitioned by stock-tank oil gravity, °API.

3.3. Universal versus geographical correlations

The petroleum industry has long debated whether fluid property correlations should be universal or
based on data from a single geographical area. Several of the geographically based correlations listed in Table 2.2 fit the full data set fairly well even though they were developed with data sets limited in both size and range. This implies that a well-done correlation does not have to apply to a single geographical area.

The bubblepoint pressure correlation of this study was tested against those subsets of the Table 2.1 data set which could be identified by geographical area. The results are in Table 2.3. The AAREs are approximately the same for the correlation worldwide or by geographical regions. Thus, it appears that geographical correlations are unnecessary and that a universal correlation is adequate. Al-Shammasi (1999) arrived at the same conclusion.

3.4. Evaluation of the data used for developing the correlations

An AARE of almost 11% for a correlation to predict values of such an important property as bubblepoint pressure is disturbingly high. Can some other correlating equation and/or technique produce an improved correlation? The answer lies in examination of the data used to develop the correlations.

Virtually all the published bubblepoint pressure correlations, including this study, used fluid property data from oilfield service companies. The quality of these data is not research grade. This is not meant to denigrate the service companies. These companies use laboratory equipment and procedures designed to provide data with precision adequate for the engineering calculations for which the data are gathered and at a reasonable cost to the customer.

An interesting feature of the GRACE software is the option to adjust the values of all the observed independent and dependent variables simultaneously, such that the adjusted set perfectly fits the correlation, i.e., the ARE and AARE are both zero, while each observed value is changed a minimum amount. This process is called data reconciliation. The average relative adjustments, necessary to zero the rela-

Fig. 2.6. The bubblepoint pressure correlation, Eq. (2-1), is reliable (regarding unbiasedness) across the spectrum of stock-tank oil gravities.
The amount of adjustment indicated is an averaged measure of the precision with which that variable was measured/controlled during the laboratory procedure. The extremely low values of average necessary adjustment (bias) show that the measurement errors in the data are randomly distributed, i.e. there is virtually no bias. The average absolute relative adjustment for each variable is well within the precision to be expected in the laboratory procedures.

Figs. 2.8–2.12 show the relationships between the laboratory measured values and the adjusted values for each of the five variables. Those plots do not have the usual meaning of calculated versus measured values.
Fig. 2.8. Reservoir temperatures adjusted to satisfy a "perfect" correlation compared with original measured reservoir temperatures.

Fig. 2.9. Stock-tank oil gravities adjusted to satisfy a "perfect" correlation compared with original measured stock-tank oil gravities.
Fig. 2.10. Separator gas specific gravities adjusted to satisfy a “perfect” correlation compared with original measured separator gas specific gravities.

Fig. 2.11. Solution gas–oil ratios adjusted to satisfy a “perfect” correlation compared with original measured solution gas–oil ratios.
The importance of the information displayed in Table 2.4 and Figs. 2.8–2.12 is that the larger than convenient AARE of the bubblepoint correlation is not due to the special form of the equation or the technique of data fitting, but stems from the quality of the data used to derive the correlation. Further attempts to develop bubblepoint pressure correlations would be futile unless a comparable amount of research quality data is collected.

4. Solution gas–oil ratios from field data

Many reservoir fluid property correlations require a value of solution gas–oil ratio at the bubblepoint as one of the input variables. Values of this property can be obtained from field data as the sum of the producing gas–oil ratios from the separator and stock-tank as shown in Eq. (3-1). This is illustrated in Fig. 1.1.

\[ R_{sb} = R_{SP} + R_{ST} \]  \hspace{1cm} (3 – 1)

Eq. (3-1) is valid only if \( R_{SP} \) and \( R_{ST} \) are measured while the reservoir pressure is above the bubblepoint pressure of the reservoir oil.

The separator gas production rate and stock-tank oil production rate are nearly always measured since they are normally sales products. Thus, \( R_{SP} \) is usually known with some accuracy. Unfortunately the gas rate from the stock-tank is seldom measured as this gas is usually vented. The stock-tank vent gas ratio, \( R_{ST} \), can contribute as much as 20% of

Table 3.1
Separator/stock-tank data set has a wide range of values of the independent variables

<table>
<thead>
<tr>
<th>Laboratory measurement</th>
<th>Minimum</th>
<th>Mean</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Separator pressure, psig</td>
<td>12</td>
<td>130</td>
<td>950</td>
</tr>
<tr>
<td>Separator temperature, °F</td>
<td>35</td>
<td>92</td>
<td>194</td>
</tr>
<tr>
<td>Stock-tank oil gravity, °API</td>
<td>6.0</td>
<td>36.2</td>
<td>56.8</td>
</tr>
<tr>
<td>Separator gas–oil ratio, scf/STB</td>
<td>8</td>
<td>559</td>
<td>1817</td>
</tr>
<tr>
<td>Stock-tank gas–oil ratio, scf/STB</td>
<td>2</td>
<td>70</td>
<td>527</td>
</tr>
<tr>
<td>Surface gas specific gravity</td>
<td>0.566</td>
<td>0.879</td>
<td>1.292</td>
</tr>
<tr>
<td>Separator gas specific gravity</td>
<td>0.561</td>
<td>0.837</td>
<td>1.237</td>
</tr>
<tr>
<td>Stock-tank gas specific gravity</td>
<td>0.581</td>
<td>1.256</td>
<td>1.598</td>
</tr>
</tbody>
</table>
$R_{sb}$ depending primarily on separator conditions. Thus, a correlation for $R_{ST}$, based on readily available field data, is required to determine $R_{sb}$ from field data.

Eq. (3-2) was developed using the GRACE technique with a data set from 898 laboratory reservoir fluid studies. Information about this data set may be found in Table 3.1.

$$\ln R_{ST} = 3.955 + 0.83 z - 0.024 z^2 + 0.075 z^3$$

where $z = \sum^{3}_{n=1} z_n$ and

$$z_n = C_0 + C_1 \text{VAR}_n + C_2 \text{VAR}^2_n$$

Table 3.2

<table>
<thead>
<tr>
<th>Correlation</th>
<th>ARE, %</th>
<th>AARE, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eqs. (3-2) and (3-1)</td>
<td>0.0</td>
<td>5.2</td>
</tr>
<tr>
<td>Rollins et al. (1990)</td>
<td>9.9</td>
<td>11.8</td>
</tr>
<tr>
<td>Eq. (3-3)</td>
<td>0.0</td>
<td>9.9</td>
</tr>
<tr>
<td>Eq. (3-4)</td>
<td>-14.1</td>
<td>14.1</td>
</tr>
</tbody>
</table>

Fig. 3.1 shows the solution gas–oil ratios at bubblepoint pressure, $R_{sb}$, calculated with Eqs. (3-2) and (3-1) compared with measured values from the data set. The average error and average absolute error for this correlation are given in Table 3.2 along with the same measures for a previously published correlation, Rollins et al. (1990).

The procedure of estimating the solution gas–oil ratio at the bubblepoint, $R_{sb}$, using Eqs. (3-2) and (3-1) retains its accuracy across the range of separator conditions. The data set was partitioned into three subsets according to separator pressure; less than 50 psig, between 50 and 100 psig, and over 100 psig.
psig. The data set was also partitioned into two subsets according to separator temperature with 75 °F as the dividing line and three subsets on separator gas–oil ratio. Table 3.3 shows that the procedure has approximately the same accuracy in these eight subsets.

Eqs. (3-2) and (3-1) and also the Rollins et al. (1990) correlation require knowledge of separator temperature and pressure. The users of fluid property correlations may not know the separator conditions. In this instance, Eq. (3-3) can be used. Eq. (3-3) was derived from the same data set, Table 3.1, using simple statistical methods.

\[ R_{sb} = 1.1618 \frac{R_{SP}}{} \quad (3 - 3) \]

Statistical measures for Eq. (3-3) with the data set used in its development are given in Table 3.2.

Ignoring the stock-tank gas, \( R_{ST} \) is illustrated with Eq. (3-4)

\[ R_{sb} = R_{SP} \quad (3 - 4) \]

This is not recommended; it is given here to show the possible error caused by such a procedure. As shown in Table 3.2, ignoring the stock-tank gas causes an error of almost 14% with the data set of Table 3.1. Notice that this error is always biased negative, i.e. the estimate of \( R_{sb} \) is always low.

5. Weighted average specific gravities of surface gases

Most fluid property correlations are based on use of the separator gas specific gravity. This property is usually measured accurately since it is required in the process of metering the separator gas production rates. However, a few methods of estimating fluid properties require values of the weighted average specific gravity of the surface gases as defined in Eq. (4-1).

\[ \gamma_{bg} = \frac{\gamma_{gSP} R_{SP} + \gamma_{gST} R_{ST}}{R_{SP} + R_{ST}} \quad (4 - 1) \]

The McCain and Hill (1995) equation for oil formation volume factors and the Glaso (1980) correlations of bubblepoint pressure and oil formation volume factor at the bubblepoint are two examples of fluid property estimates that require this weighted average property.

Unfortunately the specific gravity of the stock-tank gas is seldom measured in the field. A correlation is required if this property is to be used in other calculations. The correlation, given as Eq. (4-2), was developed using the GRACE procedure.

\[ \gamma_{ST} = 1.219 + 0.198 z + 0.0845 \ z^2 \]

\[ + 0.03 \ z^3 + 0.003 \ z^4 \quad \text{where} \quad z = \sum_{n=1}^{5} z_n \]

and \( z_n = C_{0n} + C_{1n} \text{VAR}_n + C_{2n} \text{VAR}_n^2 + C_{3n} \text{VAR}_n^3 + C_{4n} \text{VAR}_n^4 \quad (4 - 2) \)

<table>
<thead>
<tr>
<th>( n )</th>
<th>VAR</th>
<th>( C_0 )</th>
<th>( C_1 )</th>
<th>( C_2 )</th>
<th>( C_3 )</th>
<th>( C_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( \ln R_{SP} )</td>
<td>-17.275</td>
<td>7.9597</td>
<td>-1.1013</td>
<td>2.7735 × 10^{-2}</td>
<td>3.2287 × 10^{-3}</td>
</tr>
<tr>
<td>2</td>
<td>( \ln R_{SP} )</td>
<td>-0.3354</td>
<td>-0.3346</td>
<td>0.1956</td>
<td>-3.4374 × 10^{-2}</td>
<td>2.08 × 10^{-3}</td>
</tr>
<tr>
<td>3</td>
<td>API</td>
<td>3.705</td>
<td>-0.4273</td>
<td>1.818 × 10^{-2}</td>
<td>-3.459 × 10^{-4}</td>
<td>2.505 × 10^{-6}</td>
</tr>
<tr>
<td>4</td>
<td>( \gamma_{gSP} )</td>
<td>-155.52</td>
<td>629.61</td>
<td>-957.38</td>
<td>647.57</td>
<td>-163.26</td>
</tr>
<tr>
<td>5</td>
<td>( \gamma_{SP} )</td>
<td>2.085</td>
<td>-7.097 × 10^{-2}</td>
<td>9.859 × 10^{-4}</td>
<td>-6.312 × 10^{-6}</td>
<td>1.4 × 10^{-8}</td>
</tr>
</tbody>
</table>
The data set described in Table 3.1 was used to create this correlation, however, only 626 data points could be used since the stock-tank gas specific gravity was not measured in a number of the laboratory studies.

Values \(c_{gST}\) from Eq. (4-2) and values of \(R_{ST}\) from correlation Eq. (3-2) are used in Eq. (4-1) to estimate the weighted average specific gravity of the surface gases. The errors in the calculated values of weighted average surface gas specific gravities as compared with measured values are given in Table 4.1. Fig. 4.1 shows the relationship between calculated and measured weighted average surface gas specific gravities.

Eq. (4-2) require values of separator temperature and separator pressure. Occasionally the users of fluid property correlations will not have knowledge of separator conditions. In this case, Eq. (4-3) can be used to estimate the weighted average surface gas specific gravity (Table 4.2).

\[
\gamma_g = 1.066 \gamma_{gsp}
\]  

(4 – 3)

This equation was developed with the data illustrated in Table 3.1 using a simple statistical method. Average errors for the use of Eq. (4-3) along with average errors associated with using the separator gas specific gravity as a substitute for weighted average surface gas specific gravity, Eq. (4-4), are given in Table 4.1.

\[
\gamma_g = \gamma_{gsp}
\]  

(4 – 4)

Table 4.1 shows that ignoring the stock-tank gas specific gravity, i.e. Eq. (4-4), always results in

<table>
<thead>
<tr>
<th>Correlation</th>
<th>ARE, %</th>
<th>AARE, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eqs. (4-2), (3-2) and (4-1)</td>
<td>– 0.7</td>
<td>2.2</td>
</tr>
<tr>
<td>Eq. (4-3)</td>
<td>0.0</td>
<td>3.8</td>
</tr>
<tr>
<td>Eq. (4-4)</td>
<td>– 6.2</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Table 4.1 shows that ignoring the stock-tank gas specific gravity, i.e. Eq. (4-4), always results in
negative error; the estimated value of $c_g$ is always low.

6. Conclusions

(1) The use of Eq. (2-1) will result in reasonable estimates of bubblepoint pressure.

(2) The 10% AARE of Eq. (2-1) cannot be improved significantly. Given the precision with which the input data are measured, an AARE of 10% or more is to be expected. Further attempts at improving the AARE of a bubblepoint correlation using data of this quality will be futile.

(3) Generally, correlations based on data sets limited to a specific geographical area are not necessary. A carefully prepared universal correlation gives adequate results.

(4) The use of Eqs. (3-2) and (3-1) to convert the field measured separator gas–oil ratio, $R_{SP}$, into solution gas–oil ratio at the bubblepoint, $R_{sb}$, results in values of $R_{sb}$ which are as accurate as routinely measured in the laboratory.

(5) The use of Eq. (3-3) to estimate solution gas–oil ratio at the bubblepoint from separator gas–oil ratio data when separator conditions are not known is adequate for engineering calculations and is certainly preferred to ignoring the stock-tank gas–oil ratio.

(6) The use of Eqs. (4-2), (3-2) and (4-1) to estimate weighted average surface gas specific gravity results in an accuracy approaching laboratory measurement.

(7) The use of Eq. (4-3) to estimate weighted average surface gas specific gravity when separator conditions are not known gives reasonable results and is much preferred to ignoring the effect of stock-tank gas specific gravity.

Nomenclature

ARA average relative adjustment, %

AARA average absolute relative adjustment, %

ARE average relative error, %

AARE average absolute relative error, %

$p_b$ bubblepoint pressure, psia

$p_R$ reservoir pressure, psia

$p_{SP}$ separator pressure, psia

$p_{ST}$ stock-tank pressure, psia

$R_{sb}$ solution gas–oil ratio at bubblepoint, scf/STB

$R_{SP}$ gas–oil ratio, separator, scf/STB

$R_{ST}$ gas–oil ratio, stock-tank, scf/STB

API stock-tank oil gravity, °API

$\gamma_{gSP}$ separator gas specific gravity (air = 1)

$\gamma_{gST}$ stock-tank gas specific gravity (air = 1)

$\gamma_g$ weighted average surface gas specific gravity (air = 1)

$T_R$ reservoir temperature, °F

$T_{SP}$ separator temperature, °F

$T_{ST}$ stock-tank temperature, °F

$x$ independent variable

$y$ dependent variable

$z$ sum of transformed independent variables

$z'$ transformed dependent variable

References


