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Determination of gas-saturated oil density at reservoir conditions and development of quality control index of PVT laboratory report

Muhammad Ali Al-Marhoun[1]

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Abstract
The oil density at the bubble point is an important thermodynamic property required in reservoir simulation and production engineering. A higher-accuracy estimate of this property would improve the accuracy of reservoir and production engineering calculations. The bubble point oil density is obtained either from separator tests of reservoir fluids or from differential gas liberation tests. A new procedure utilizing separator and differential tests is proposed whereby the experimental data yield a unique value with high accuracy for the bubble point oil density. A consistent correction of other PVT properties, which are influenced by the bubble point oil density, is required to reflect the unique density value. A quantitative quality control index is defined to measure the quality of PVT laboratory reports. This is achieved by utilizing the unique property of the bubble point oil density, which is usually ignored.

Keywords Bubble point oil density · Differential gas liberation test · Separator test · Quality control index · PVT laboratory report

List of symbols

api	Stock tank oil gravity (API)
b	Slope of a straight line
B_{ob}	Bubble point oil formation volume factor (bbl/stb)
$m_{o,g}$	Oil or gas mass
n	Number of separator stages
QCI	Quality control index
$\check{R}$	Separator stage gas/oil ratio (scf/stb)
R_s	Solution gas/oil ratio (scf/stb)
$v_{o,g}$	Oil or gas volume
x	Independent variable
y	Dependent variable
$\hat{y}$	Predicted value of a dependent variable y
α	Separator or differential correction factor
γ	Separator stage gas specific gravity
γ_g	Gas specific gravity (air = 1)
γ_o	Oil specific gravity (water = 1)
γ_{ob}	Oil specific gravity at the bubble point
γ_{ob_global}	Optimum oil specific gravity at the bubble point
ε	Error or difference between measured and predicted values
ρ_o	Oil density (g/cm^3)
ρ_{ob}	Oil density at the bubble point (g/cm^3)
ρ_w	Water density (g/cm^3)

Introduction

The oil density at the bubble point is an important property that is required in reservoir engineering calculations and in engineering design for oil production, fluid transportation, surface processing and material balance calculations. The oil density is defined as the mass per unit volume at a specified pressure and temperature.

$$\rho_o = \frac{m_o + m_g}{v_o + v_g} \tag{1}$$

The gas-saturated oil density or bubble point oil density, ρ_{ob}, is defined as the mass per unit volume at the bubble point pressure. It is usually expressed in terms of lb/ft^3 or g/cm^3. Oil specific gravity or oil relative density relates the density of oil to that of the density of water. The conversion of oil specific gravity to oil density is:

✉ Muhammad Ali Al-Marhoun
marhoun@restec.com

[1] Reservoir Technologies, Saihat, Saudi Arabia

$$\rho_{ob} = \gamma_{ob} * \rho_w \tag{2}$$

For practical purposes, the water density ρ_w is approximately 1 g/cm^3. In the oil industry, the terms density and specific gravity are often used interchangeably in absolute values even though their units are not the same.

Under a given condition, the oil density at the bubble point is calculated by the material balance equation. The material balance equation is expressed as a function of the oil specific gravity at stock tank conditions, a total solution gas oil ratio, the gas gravity and the oil formation volume factor at the bubble point pressure.

$$\gamma_{ob} = \frac{\gamma_o + 2.18 \times 10^{-4} R_s \gamma_g}{B_{ob}} \tag{3}$$

The four parameters (γ_o, R_s, γ_g, B_{ob}) are obtained either from separator tests of reservoir fluids or from differential gas liberation tests.

The classic works of gas-saturated oil density determination are derived mainly from the material balance equation. Standing (1947), Ahmed (1989) and McCain (1991) presented correlations for calculating the oil density at the bubble point pressure based on a material balance as described by Eq. 3, with the replacement of the bubble point oil formation volume factor, *Bob* by an estimate from empirical correlations. Standing and Katz (1942) presented a method to calculate the oil density at the bubble point based on the principle of an ideal solution. Rostami et al. (2012, 2013) used neural networks and Gaussian process regression to estimate the oil density.

Under the same conditions of reservoir temperature, pressure and fluid compositions, the oil density at the bubble point is unique regardless of the method used to determine its value. The bubble point oil density obtained from separator tests or from differential gas liberation tests is not the same. Therefore, to obtain trustworthy fluid properties, the need to have an optimum accurate value of oil density for data consistency is inevitable. Current industrial practice is to average oil density values obtained from differential liberation expansion and all separator tests available. No adjustment or correction is made to other PVT properties that are influenced by the selected average oil density. This practice leads to inconsistency in reservoir calculations, well testing and other calculated physical properties.

This paper presents a new calculation method that depends on the material balance for finding the oil density at the bubble point pressure. The material balance equation is mathematically manipulated to produce a straight line that passes through the origin point (0, 0). A linear least-squares regression is used to develop the optimum unique value for the oil density at the bubble point utilizing the data from all separator and differential gas liberation tests.

A consistent correction procedure of other PVT properties is introduced to reflect the unique density value. A quantitative quality control index is defined to measure the quality of PVT laboratory reports. This is achieved by utilizing the unique value of oil density at the bubble point, which is usually ignored.

Data acquisition

Experimental data of two oil samples, volatile oil and black oil, were collected. Detailed data analysis and calculation of the volatile oil sample are presented, while the black oil data analysis and calculation are only briefly illustrated to avoid repetition.

For the volatile oil sample, experimental data from a single differential gas liberation test and three separator tests of reservoir fluid are collected. In the differential liberation experiment, reservoir liquid is brought to the reservoir temperature and bubble-point pressure. Then, the pressure gradually decreases in steps, any liberated gas is removed from the oil, and the incremental liberated gas volume and its specific gravity are recorded at each step or stage. Table 1 presents the laboratory data for the experimental differential gas liberation test.

To convert the experimental differential gas liberation test data, Table 1, to differential dissolved gas data, Table 2, Eqs. 4 and 5 are used to calculate each separation stage gas/oil ratio and gas specific gravity, respectively, as shown in columns 2 and 3. The stock tank oil specific gravity, column 6, is calculated from Eq. 6, and the oil specific gravity at each pressure, column 7, is calculated from Eq. 3:

$$R_{sj} = \sum_i \check{R}_{s_i} \tag{4}$$

$$\gamma_{gj} = \frac{\sum_i \check{R}_{s_i} \tilde{\gamma}_{g_i}}{\sum_i \check{R}_{s_i}} \tag{5}$$

$i = j{:}n$ and $j = 1{:}n$, where $\check{R}$ is the stage gas/oil ratio, γ is the gas gravity, and j is the separation stage number.

$$\gamma_o = \frac{141.5}{\text{api} + 131.5} \tag{6}$$

In the separator test, reservoir liquid is brought to the reservoir temperature and bubble-point pressure. Then, the liquid is flashed through one or two or three stages of separation, with the last stage at 14.7 psi and 60 °F. For the purpose of this study, the multistage separator tests are collapsed to one stage for simple illustration by utilizing the following equations, where '*i*' indicates the separator stage:

Table 1 Experimental differential gas liberation test

Pressure range psi		Liberated gas volume scf/stb	Incremental gas gravity	Saturated relative volume at lower pressure	API at 14.7 psi and 60 °F	Oil specific gravity at 14.7 psi and 60 °F (Eq. 6)	Saturated relative volume at upper pressure
4644	4595	218	1.048800	3.5840			3.745
4595	4515	393	1.034300	3.3010			
4515	4415	348	1.021300	3.0520			
4415	4215	435	0.977800	2.7510			
4215	4015	297	0.950000	2.5530			
4015	3715	322	0.913000	2.3510			
3715	3415	246	0.874900	2.1960			
3415	3015	252	0.836900	2.0460			
3015	2615	201	0.812900	1.9290			
2615	2115	214	0.799100	1.8070			
2115	1615	197	0.801200	1.7060			
1615	1115	163	0.820800	1.6140			
1115	615	150	0.896000	1.5270			
615	208	148	1.235100	1.4160			
208	14.7	273	2.741000	1.1320	42.000	0.815562	

Table 2 Experimental differential dissolved gas presentation

Pressure psi	Dissolved gas volume scf/stb (Eq. 4)	Gas gravity (Eq. 5)	Saturated relative volume at pressure	°API at 14.7 psi and 60 °F	Oil specific gravity at 14.7 psi and 60 °F (Eq. 6)	Oil specific gravity at pressure (Eq. 3)
4644	3857	1.065504	3.7450			0.457000
4595	3639	1.066505	3.5840			0.463622
4515	3246	1.070404	3.3010			0.476525
4415	2898	1.076300	3.0520			0.490016
4215	2463	1.093697	2.7510			0.509925
4015	2166	1.113400	2.5530			0.525380
3715	1844	1.148394	2.3510			0.543261
3415	1598	1.190497	2.1960			0.560241
3015	1346	1.256698	2.0460			0.578843
2615	1145	1.334604	1.9290			0.595486
2115	931	1.457696	1.8070			0.615060
1615	734	1.633894	1.7060			0.631304
1115	571	1.866003	1.6140			0.649218
615	421	2.211610	1.5270			0.667020
208	273	2.741000	1.4160			0.691165
14.7	0	0.000000	1.1320	42.000	0.815562	0.720461

$$R_s = \sum_i R_{s_i} \quad (7)$$

$$\gamma_g = \frac{\sum_i R_{s_i} \gamma_{g_i}}{\sum_i R_{s_i}} \quad (8)$$

Table 3 presents the laboratory data for three separator tests of volatile oil sample fluid collapsed into a single-stage test and summarizes differential data at the bubble point pressure.

For the black oil sample, experimental data from a single differential gas liberation test and a single separator test of reservoir fluid are collected. The choice of oil sample is dictated by the fact that in a large number of recent PVT

Table 3 Experimental data of separator and differential tests of the volatile oil sample

Test	Separator no. 1	Separator no. 2	Separator no. 3	Differential
Reservoir temperature (°F)	300	300	300	300
Bubble point pressure (psi)	4644	4644	4644	4644
Bubble point oil formation volume factor (bbl/stb)	2.368	2.372	2.38	3.745
Stock tank oil gravity, API at 14.7 psi and 60 °F	50.400	50.600	49.800	42.000
Gas oil ratio (scf/stb)	2045	2043	2017	3857
Specific gravity of gas (air = 1)	0.687123	0.694873	0.704692	1.065504
Oil density at the bubble point (g/cm^3) (Eq. 3)	0.457866	0.458062	0.458122	0.457000
Stock tank oil density at 14.7 psi and 60 °F (g/cm^3) (Eq. 6)	0.777900	0.777046	0.780474	0.815562

laboratory reports, only a single flash test and a single differential liberation test are described. Table 4 presents summarized laboratory data at the bubble point pressure.

Current correction procedure for oil density at the bubble point

For any separator or differential test, the following material balance equation holds:

$$\gamma_{\text{ob}_i} = \frac{\gamma_{\text{o}_i} + 2.18 \times 10^{-4} R_{\text{s}_i} \gamma_{\text{g}_i}}{B_{\text{ob}_i}} \tag{9}$$

The current industry procedure for estimating the global oil density at the bubble points under reservoir conditions is one of the following two methods:

1. the average of all bubble point densities calculated from all separators and differential tests:

$$\gamma_{\text{ob\_global}} = \frac{1}{n} \sum_{1}^{n} \gamma_{\text{ob}_i}, \quad i = 1, 2, \ldots, n \tag{10}$$

2. the weighted average of 50% of all separator tests and 50% of all differential tests even if there is only one differential test:

$$\gamma_{\text{ob\_global}} = \frac{1}{2n_1} \sum_{1}^{n_1} \gamma_{\text{ob}_i} + \frac{1}{2n_2} \sum_{1}^{n_2} \gamma_{\text{ob}_j} \tag{11}$$

where separator tests: $i = 1, 2, \ldots, n_1$, differential tests: $j = 1, 2, \ldots, n_2$.

The correction method used in the industry as outlined is inconsistent with other PVT properties that were influenced by the corrected oil density, such as γ_{o} and γ_{g}.

The new correction method for oil density at the bubble point

Under the same conditions of reservoir temperature, pressure and fluid compositions, the oil density at the bubble point is calculated by the material balance equation, where the total mass of oil and gas is divided by the total volume. Therefore, for any separator or differential test, the material balance equation, Eq. 9, holds. The material balance equation is mathematically manipulated to produce a straight line that passes through the origin. Equation 9 can be written as

$$\gamma_{\text{o}_i} + 2.18 \times 10^{-4} R_{\text{s}_i} \gamma_{\text{g}_i} = \gamma_{\text{ob}_i} B_{\text{ob}_i} \tag{12}$$

Or

$$y_i = b x_i \tag{13}$$

Table 4 Experimental data of separator and differential tests of the black oil sample

Test	Separator no. 1	Differential
Reservoir temperature (°F)	220	220
Bubble point pressure (psi)	2820	2820
Bubble point oil formation volume factor (bbl/stb)	1.495	1.7
Stock tank oil gravity, API at 14.7 psi and 60 °F	38.400	34.900
Gas oil ratio (scf/stb)	815	650
Specific gravity of gas (air = 1)	0.932133	0.830000
Oil density at the bubble point (g/cm^3) (Eq. 3)	0.667863	0.569395
Stock tank oil density at 14.7 psi and 60 °F (g/cm^3) (Eq. 6)	0.832843	0.850361

where

$$y_i = \gamma_{o_i} + 2.18 \times 10^{-4} R_{s_i} \gamma_{g_i} \tag{14}$$

$$x_i = B_{ob_i} \tag{15}$$

$$b = \text{slope} = \gamma_{ob_i} \tag{16}$$

The objective of this study is to develop a method to determine the optimum value for oil density at the bubble point by utilizing all values of oil density obtained from all available separators and differential tests. Therefore, least-squares regression is used to find the best fit.

We minimize the sum of squares of the errors or differences between measured and predicted values:

$$\Sigma\varepsilon^2(b) = \sum_i \left(y_i - bx_i\right)^2 \tag{17}$$

Taking the derivative with respect to the unknown variable b and setting it equal to zero, we obtain

$$\frac{\partial \varepsilon^2}{\partial b} = \frac{\partial}{\partial b} \sum_i \left(y_i - bx_i\right)^2 = -2 \sum_i x_i \left(y_i - bx_i\right) = 0$$

$$\sum_i x_i y_i = b \sum_i x_i^2$$

$$b = \frac{\sum_i x_i y_i}{\sum_i x_i^2}$$

Therefore, the optimum and best value for oil density at the bubble point are

$$\gamma_{ob\_global} = \text{Slope} = \frac{\sum_i x_i y_i}{\sum_i x_i^2} \tag{18}$$

Correction of oil and gas gravities at standard conditions

PVT properties that were influenced by the modification of the value of oil density at the bubble point, such as γ_o and γ_g, are corrected for each separator test by introducing a correction factor as follows:

$$\alpha_i = \frac{\gamma_{ob_g lobal}}{\gamma_{ob_i}} \quad i = 1, 2, \ldots \text{(number of separator tests)} \tag{19}$$

The corrected values are

$$\gamma_{o_i(\text{corrected})} = \alpha_i \gamma_{o_i} \quad i = 1, 2, \ldots \text{(number of separator tests)} \tag{20}$$

$$\gamma_{g_i(\text{corrected})} = \alpha_i \gamma_{g_i} \quad i = 1, 2, \ldots \text{(number of separator tests)} \tag{21}$$

$$\gamma_{ob_g lobal} = \frac{\gamma_{o_i(\text{corrected})} + 2.18x10^{-4} R_{s_i} \gamma_{g_i(\text{corrected})}}{B_{ob_i}}$$
$$i = 1, 2, \ldots \text{(number of separator tests)} \tag{22}$$

$$\text{api}_{i(\text{corrected})} = \frac{141.5}{\gamma_{o_i(\text{corrected})}} - 131.5$$
$$i = 1, 2, \ldots \text{(number of separator tests)} \tag{23}$$

For the differential gas liberation test, the correction factor is

$$\alpha_{dif} = \frac{\gamma_{ob_{global}}}{\gamma_{ob_{dif}}} \tag{24}$$

The corrected values are

$$\gamma_{o\_dif(\text{corrected})} = \alpha_{dif} \gamma_{o\_dif} \tag{25}$$

$$\gamma_{g_j(\text{corrected})} = \alpha_{dif} \gamma_{g_j} \quad j = 1, 2, \ldots \text{(number of differential stages)} \tag{26}$$

$$\text{api}_{\text{dif (corrected)}} = \frac{141.5}{\gamma_{o\_\text{dif (corrected)}}} - 131.5 \tag{27}$$

$$\gamma_{op_j} = \frac{\gamma_{o_{\text{dif (corrected)}}} + 2.18x10^{-4} R_{s_j} \gamma_{g_j(\text{corrected})}}{B_{op_j}}$$
$$j = 1, 2, \ldots \text{(number of differential stages)} \tag{28}$$

Development of a quality control index for separator and differential tests

The fitted line of oil density at the bubble point is forced to pass through the origin point (0, 0). The assumption here is that a mass of zero volume should have a density of zero. This assumption leads to devising a quality control index by calculating how far the test coordinates are from the fitted line. The following equation represents the quality control index for test i:

$$\text{QCI}_i = 100 \left(1 - \frac{\left(\frac{y_i - \hat{y}_i}{y_i}\right)^2}{\sum_{j=1}^{n} \left(\frac{y_j - \hat{y}_j}{y_j}\right)^2} \right) \tag{29}$$

where $\hat{y}$ is the predicted value of the dependent variable y in the regression equation. It is the average value of the response variable.

$$\hat{y}_j = bx_i, \quad i = 1, 2, \ldots, n \tag{30}$$

Table 5 Optimum global oil specific gravity calculation for the volatile oil sample

Test	x_i (Eq. 15)	y_i (Eq. 14)	$x_i\,y_i$	x_i^2	$\hat{y}_i$ (Eq. 30)	QCI (Eq. 29)
Separator test #1	2.368000	1.084226	2.567447	5.607424	1.083492	90.23
Separator test #2	2.372000	1.086524	2.577235	5.626384	1.085323	73.93
Separator test #3	2.380000	1.090331	2.594989	5.664400	1.088983	67.38
Differential test	3.745000	1.711465	6.409438	14.025025	1.713547	68.45
Sum of column			14.149109	30.923233		
Global oil specific gravity	$\Sigma x_i\,y_i/\Sigma x_i^2$	0.45755594				

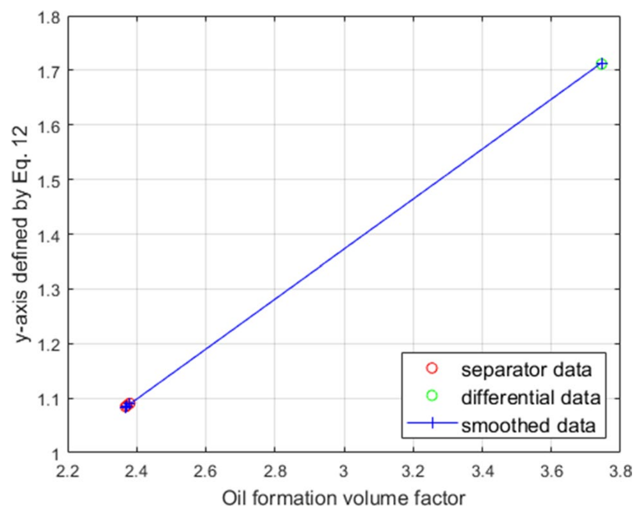

Fig. 1 Linear least-squares fit for the bubble point oil specific gravity

A quality control index, QCI, of 100 is a perfect test (separator or/and differential). The index is relative to all tests performed on the same sample anchored at the point of zero–zero origin.

Results and discussion

For the volatile oil sample, the optimum value for oil density at the bubble point is obtained by least-squares regression of the separator and differential test data, as shown in Table 5 and Fig. 1. The optimum value for oil specific gravity at the bubble point is calculated by Eq. 18 as follows:

$$b = \text{Slope} = \frac{14.1491}{30.9232} = 0.45755594$$

The original data of the separator and differential tests at the bubble point are summarized in Table 3. The corrections after determining the optimum oil specific gravity at the bubble point are presented in Table 6.

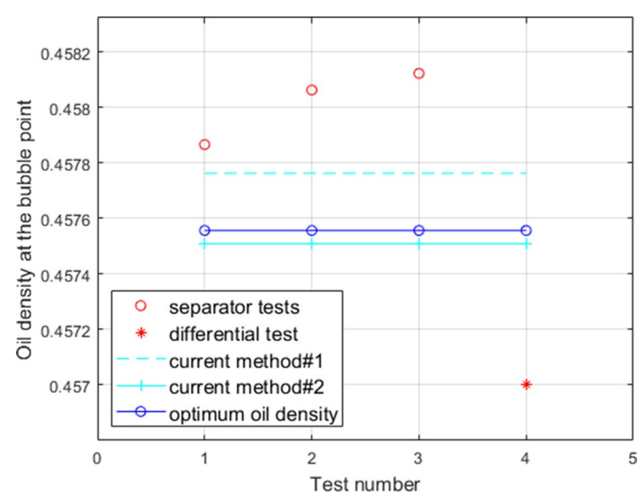

Fig. 2 Oil density at the bubble point for the volatile oil sample

Table 6 Modified data of separator and differential tests at the bubble point for the volatile oil sample

Test	Separator no. 1	Separator no. 2	Separator no. 3	Differential
Reservoir temperature (°F)	300	300	300	300
Bubble point pressure (psi)	4644	4644	4644	4644
Bubble point oil formation volume factor (bbl/stb)	2.368	2.372	2.38	3.745
Stock tank oil gravity, API at 14.7 psi and 60 °F	50.523	50.802	50.024	41.789
Gas oil ratio (scf/STB)	2045	2043	2017	3857
Specific gravity of gas (air = 1)	0.686658	0.694105	0.703820	1.066800
Oil density at the bubble point (g/cm^3) (Eq. 3)	0.457556	0.457556	0.457556	0.457556
Stock tank oil density at 14.7 psi and 60 °F (g/cm^3) (Eq. 6)	0.777374	0.776187	0.779509	0.816554
Quality control index (%) (Eq. 29)	90.23	73.9	67.33	68.55
Correction factor (Eqs. 19 and 24)	0.999323	0.998895	0.998763	1.001216

Table 7 Corrected differential dissolved gas data

Pressure psi	Dissolved gas volume scf/stb	Gas gravity	Saturated relative volume at pressure	API at 14.7 psi and 60 °F	Oil specific gravity at 14.7 psi and 60 °F	Oil specific gravity at pressure
4644	3857	1.066800	3.7450			0.457556
4595	3639	1.067802	3.5840			0.464186
4515	3246	1.071706	3.3010			0.477105
4415	2898	1.077609	3.0520			0.490612
4215	2463	1.095027	2.7510			0.510546
4015	2166	1.114755	2.5530			0.526019
3715	1844	1.149791	2.3510			0.543922
3415	1598	1.191945	2.1960			0.560922
3015	1346	1.258226	2.0460			0.579547
2615	1145	1.336228	1.9290			0.596210
2115	931	1.459469	1.8070			0.615808
1615	734	1.635881	1.7060			0.632072
1115	571	1.868273	1.6140			0.650008
615	421	2.214300	1.5270			0.667831
208	273	2.744334	1.4160			0.692006
14.7	0	0.000000	1.1320	41.789	0.816554	0.721337

Figure 2 presents the original oil specific gravity data obtained from the separator and differential tests. The current methods and the new method are also shown in the figure for comparison purposes.

Columns 3, 5, 6 and 7 of Table 2 are modified by Eqs. 26, 27, 6, and 28, respectively, to generate the corrected differential dissolved gas data (Table 7).

Equation 29 is applied to calculate the quality index for every separator and differential test, where Fig. 3 and Table 6 show their numerical values.

For the black oil sample, the optimum value for oil density at the bubble point is obtained by least-squares regression. The original data of the separator and differential tests at the bubble point are summarized in Table 4. The correction after obtaining the optimum oil specific gravity at the bubble point is presented in Table 8.

Figure 4 presents the original oil specific gravity data obtained from the separator and differential tests. The current methods and the new method are also shown in the figure for comparison purposes.

The correction of the oil density at the bubble point is inevitable whether the oil sample is black or volatile and whether the available tests are single or multiple. A comparison of the correction methods of the bubble point oil density for the two oil samples investigated is shown in Table 9.

In summary, a new smoothing method for the oil density at the bubble point based on a material balance is presented. This method yields an optimum unique oil density value at the bubble point. This method reflects other PVT properties; therefore, the PVT report becomes consistent across all experimental tests, namely differential, separators, liquid phase density, mixture density and specific volume. After adjustments, all separator and differential tests produce exactly the same value of density at the bubble point, whereas current methods fail to achieve a unique value for bubble point oil density. A major enhancement for quality control is performed within each PVT experiment and consequently observed among all tests.

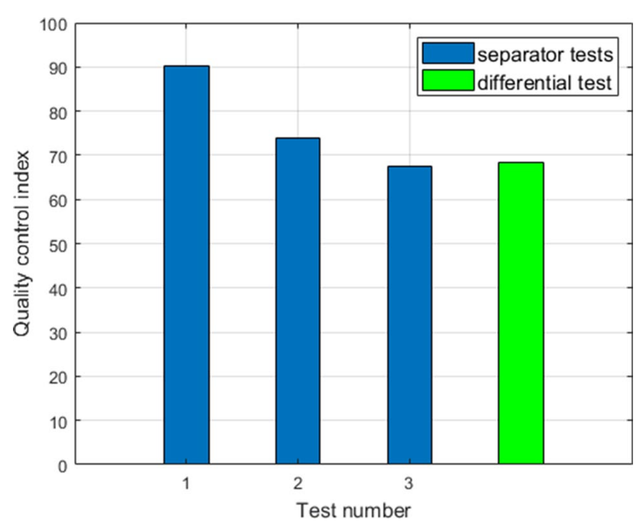

Fig. 3 Quality control index for the volatile oil sample

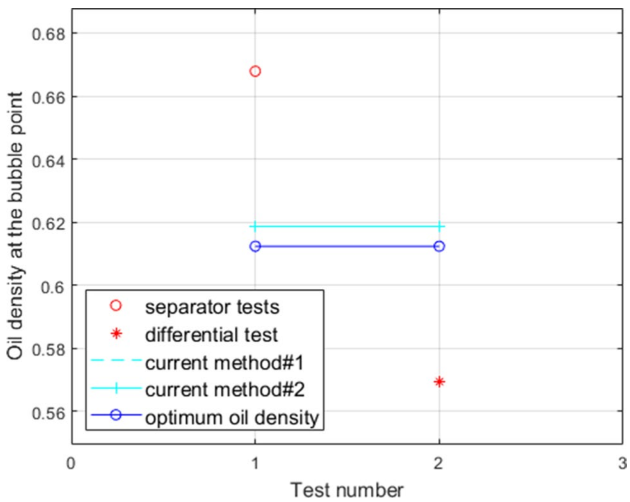

Fig. 4 Oil density at the bubble point for the black oil sample

Table 9 Comparison of correction methods

Oil sample and tests	Volatile oil multiple separator tests	Black oil single separator test
Separator no. 1	0.457866	0.667863
Separator no. 2	0.458062	
Separator no. 3	0.458122	
Differential	0.457000	0.569395
Correction method no. 1	0.457763	0.618629
Correction method no. 2	0.457508	0.618629
The new correction method	0.457556	0.612337

Conclusion

The following conclusions were drawn from this study.

- A new method based on material balance is introduced to determine the best value for oil density at the bubble point.
- A new correction procedure is introduced to adjust PVT properties that are influenced by the correction of oil density at the bubble point, such as gas specific gravity and oil specific gravity. This correction guarantees that the oil density at the bubble point is the same whether separator or differential data are used for calculation.
- A quantitative quality control index is defined and applied to measure the quality of the separator and differential tests of the PVT laboratory report.

Table 8 Modified data of separator and differential tests at the bubble point for the black oil samples

Test	Separator no. 1	Differential
Reservoir temperature (°F)	220	220
Bubble point pressure (psi)	2820	2820
Bubble point oil formation volume factor (bbl/stb)	1.495	1.7
Stock tank oil gravity, API at 14.7 psi and 60 °F	53.806	23.231
Gas oil ratio (scf/STB)	815	650
Specific gravity of gas (air = 1)	0.854635	0.892596
Oil density at the bubble point (g/cm^3) (Eq. 3)	0.612337	0.612337
Stock tank oil density at 14.7 psi and 60 °F (g/cm^3) (Eq. 6)	0.763601	0.914492
Quality control index (%) (Eq. 29)	37.43	62.57
Correction factor (Eqs. 19 and 24)	0.916860	1.075417

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