



An inclusive consistency check procedure for quality control methods of the black oil laboratory data

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Abstract

Invalid PVT data provide high uncertainty in field development studies such as reservoir fluid compartmentalization, reserve estimation, reservoir simulation, production engineering, and surface facility design. Then, consistency check should be conducted to ensure the validity of PVT data and to identify the most representative PVT sample(s). In this paper, preliminary and complementary consistency check of PVT laboratory methods was applied to design a new comprehensive validity check procedure for verification of the reservoir fluid properties. This procedure would be ascertained whether or not the data could be used as the most representative fluid sample in further studies. The data used in this study were collected from seven undersaturated oil reservoirs, and challenges were observed through the 28 full set of available PVT laboratory data. In our study quality checking procedure of PVT samples consists of different methods such as graphical method, recombination and material balance check for well stream composition test, Buckley, modified Wilson and Hoffman plot, Watson characterization factor, Y-function of CCE test, Y-function of DL test, compositional material balance of DL test, overall mass balance for density, Bo and GOR of DL test and density check for separator test. After implementing the applicable proposed checking procedure to detect the validity of laboratory PVT sample, only 9 out of 28 PVT samples were satisfied all the preliminary and complementary check methods. Furthermore, a practical strategy, to select representative reservoir fluid sample, was also provided and discussed based on the consistency check, well condition check and comparison of fluid properties.

Keywords PVT · Representative fluid sample · Reservoir fluid · Consistency check · Laboratory data · Black oil

List of symbols

B_o	Oil formation volume factor
B_{ob}	Oil formation volume factor at saturation point
B_g	Gas formation volume factor
GOR	Gas–oil ratio
R_s	Solution GOR
M_w	Molecular weight
μ_o	Oil viscosity
μ_{ob}	Oil viscosity at saturation pressure
γ_o	Oil specific gravity
γ_g	Gas specific gravity

F_i	Hoffman factor
T_{bi}	Normal boiling point
T_{ci}	Critical temperature
T_{sp}	Test temperature
T_{sc}	Standard temperature
K	K value
P_b	Bubble point pressure
P_{ci}	Critical pressure
P_{sat}	Saturation pressure
P_{sc}	Standard condition pressure
Ω	Acentric factor
T_r	Dimensionless reduced temperature
V_b	Cell volume at pressure P_b
V_t	Total cell volume at pressure P
ρ	Density (lb/ft ³)
X_i	Mole fraction in liquid phase
Y_i	Mole fraction in vapor phase
Z_i	Mixture mole fraction
STC	Standard conditions
b	Bubble point

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c Critical
sep Separator

Introduction

Reservoir fluid PVT properties are required as part of any field development stage such as accurate reserve estimation, reservoir modeling studies, material balance calculation, production engineering, surface facility design, and optimization and reservoir management which are affected by applying valid PVT laboratory results. It is realistic that PVT laboratory results can be associated with some errors, and then, finding the valid PVT sample(s) is an important issue in upstream/downstream studies. Otherwise, using invalid PVT sample(s) would generate more uncertainty in reservoir studies such as reservoir fluid compartmentalization, reserve estimation, reservoir simulation and surface facility design. The sources of errors could be related to implementation PVT test, the measurement techniques and sampling condition which are needed to be evaluated. Therefore, it is essential to check the validation and representation of the PVT fluid sample(s) before applying PVT sample properties. Related to the sampling condition, Lawrence et al. (2008) have emphasized the proper sampling stage as the most essential step of reliable PVT samples acquiring. They have listed some essential issues of the fluid sampling and then have discussed their suggesting measures and the techniques for solving the issues. Related to the PVT samples implementation, there are some studies which have discussed the different aspects of the PVT samples validity. Lawrence and Gupta (2009) have recommended the Hoffman plot as an applicable tool to investigate the quality of the surface samples and any flash laboratory data. Plotting of the various measured properties versus pressure is the simplest way to discover the reliability of laboratory method and the existence of outlier data (Drohm et al. 1988; McCain Jr 2002; Bagoos et al. 2014; Nnabuo et al. 2014; Akpabio et al. 2015). To analyze the experimental measurements more precisely various complementary methods have been suggested during the decades. Application of the material balance in the DL test has been proposed by Bagoos et al. (2014), Drohm et al. (1988) and Lawrence and Gupta (2009). The validity of the CCE test could be verified by Y-function of the CCE test. Application of Y-function for the CCE test has been discussed in many papers and textbooks (Amyx et al. 1960; McCain Jr 1990; Danesh 1998), but recently Potsch et al. have recommended the application of Y-function for DL test analyzing. Potsch et al. have stated that Y-function of DL test in real case PVT data behaves linearly as like as the Y-function of CCE test. Therefore, comparison of Y-function of CCE and DL tests could be applicable for the consistency check of petroleum PVT samples (Potsch et al. 2017).

Regarding most of the previous studies, it has been concluded that there is no inclusive study which discussed the validity of the whole aspects of black oil PVT samples. Any published study has considered just some few aspects of the PVT samples and presented the checking methods of those aspects. Therefore, in this study, reviewing all introduced quality checking methods, an inclusive procedure to identify the consistency of the black oil PVT samples, is suggested. Basically, the proposed methods for a consistency check of the PVT laboratory data in the previous studies are classified into two categories: preliminary and complementary. In this study, both preliminary and complementary methods are taken into account to design the consistency check procedure for the quality control of the reservoir fluid properties. In addition, the commercial software packages check the validity of the tuned models based on the mathematical prospective. They did not consider the consistency of the imported experimental data, thermodynamically. Therefore, it is essential to check the consistency of experimental information, comprehensively, before implementation of reported data in further studies. This procedure ascertains whether or not the data can be used as the most representative fluid sample in further studies. In this study, quality checking procedure of PVT samples is applied on constant composition expansion experiment (CCE), differential liberation experiment (DL), separator test, fluid viscosity test, and well stream composition experiment consists of the following steps:

1. Preliminary check
 - a. Graphical method
 - b. API and GOR check
2. Complementary check
 - a. Recombination and material balance check
 - b. Thermodynamic consistency check of composition
 1. Buckley, modified Wilson and Hoffman plot
 2. Watson characterization factor
 - c. Y-function of CCE test
 - d. Y-function of DL test
 - e. Compositional material balance of DL test
 - f. Overall mass balance of DL test
 1. Density check
 2. Formation volume check
 3. Solution gas check
 - g. Density check for separator test

After following quality check procedure for PVT sample(s), acquiring a practical way to select representative reservoir fluid sample(s) is another achievement of this study. This paper also proposes the different methods used to perform a consistency check of the PVT fluid sample and shows the practical way to select representative reservoir fluid.

PVT experiments

Constant mass expansion (CME) or constant composition expansion (CCE) experiment is the pressure–volume relations carried out in virtually all PVT studies irrespective of fluid type. CCE test is used to measure the total fluid volume and compressibility over a wide range of pressures extending beyond the initial reservoir condition. To perform CCE experiment a cell is filled with a known mass of reservoir fluid at above the saturation pressure condition, ensuring that the fluid is in single phase. Then, the volume of the mixture is increased stepwise below the saturation pressure by decreasing the pressure at a constant temperature (Fig. 1). At each step, equilibrium must be obtained and the total volume at each pressure step is recorded. Just below the bubble point, the measured volume will increase more rapidly because gas evolves from the oil, yielding higher fluid compressibility. In CCE test, no portion of the fluid is removed from the cells till end of the test and temperature is held constant during the experiment (Lang 1985; Whitson 1988; Shariati and Peters 2002; Ahmadi et al. 2014).

Differential liberation experiment (DLE)

DLE is the classical depletion experiment for reservoir oils, designed to approximate the behavior of reservoir fluid at reservoir conditions and the volumetric changes during depletion process of an oil reservoir (Dake 1978).

A PVT cell is filled with an oil sample which is brought to a single phase. Then, the experiment is started at the saturation pressure and the pressure is decreased stepwise until equilibrium is reached at constant temperature. At each pressure stage, the system volume expands and all gas evolved at each step is removed (Fig. 2). In this procedure, the volume (ΔV_g), moles (Δn_g) and specific gravity of the removed gas (γ_g) are recorded. Sometimes gas compositions of dissolving gas are also measured. Finally, at atmospheric pressure, oil volume and specific gravity of the “residual oil” are measured (or calculated) at 15.5 °C. Based on measured data, other properties are calculated, including oil formation volume factor, solution gas–oil ratio, oil density, gas Z factor, gas specific gravity, gas viscosity and gas formation volume factor, which are resulted from the differential liberation test.

Multistage separator test

Multistage separator test is performed on live oil samples primarily to provide a basis for converting differential–liberation data from a subsurface reservoir to surface condition at a stock tank. Also, the number and the conditions of separators are determined to achieve a maximum volume of oil with minimum GOR and maximum API at stock tank (Imo-Jack and Emelle 2013). For separator test initially, the reservoir sample is brought to saturation conditions and the volume is measured. Then, the cell pressure and temperature were further reduced to the first-stage separator conditions. All of the gas is removed and the oil volume at the separator stage is recorded, as well as the volume, number of moles and specific gravity of the removed gas. The remaining oil in the cell was taken to the next separator stage (separator conditions), and the procedure was repeated again. The gas is again removed and quantified. Oil volume is recorded, and the process is repeated until stock tank conditions are reached. The final oil volume and specific gravity are

Fig. 1 Constant composition expansion (CCE) experiment

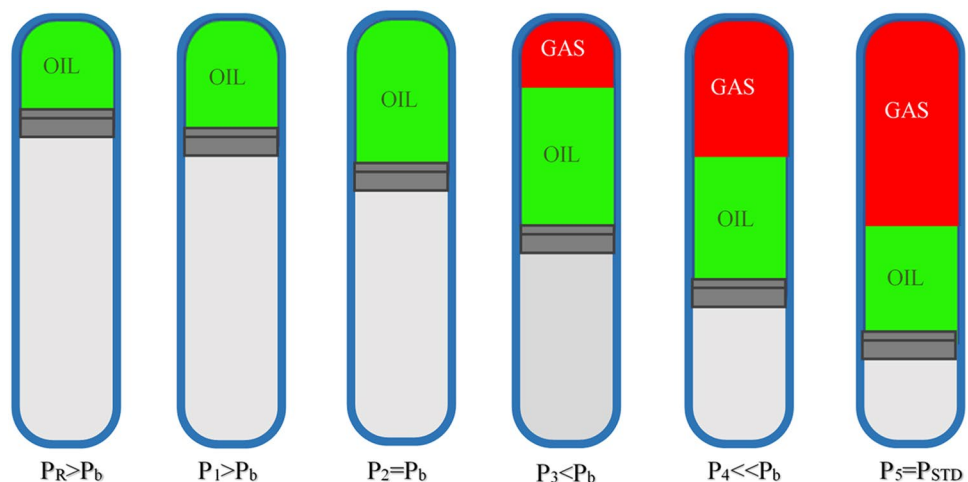
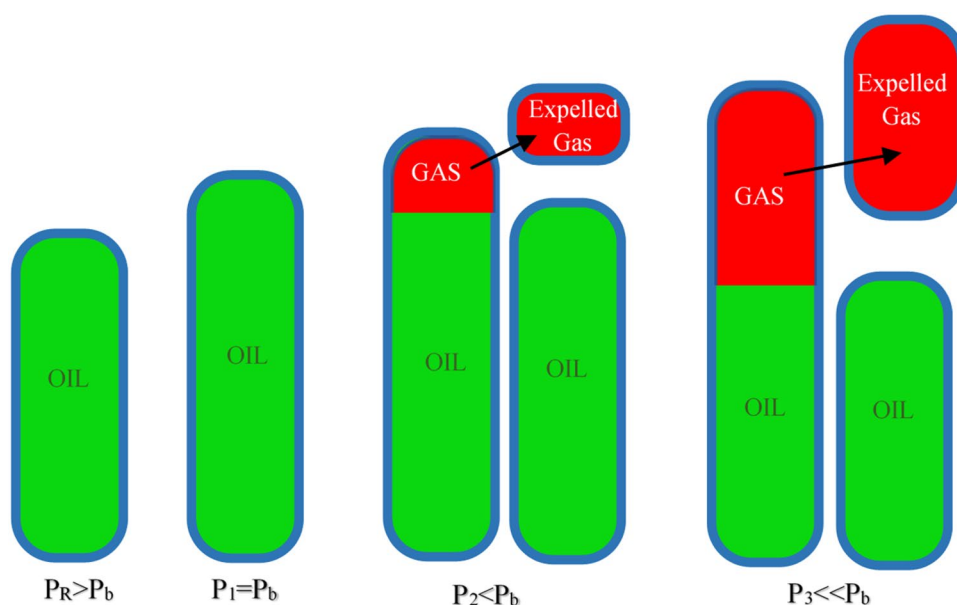


Fig. 2 Differential liberation experiment (DLE)



measured at standard conditions (Lang 1985; Whitson and Brulé 2000; Nnabuo et al. 2014).

Fluid viscosity test

Fluid viscosity test result is used for the modeling of fluid flow throughout the reservoir. Oil viscosities are usually measured at reservoir temperature over a range of pressures both above and below the saturation pressure extending down to near-atmospheric pressure. Measurements below saturation pressure are made under differential conditions, i.e., matched as closely as possible to the stage pressures used for the differential vaporization.

For *well stream composition* determination, first of all, reservoir oil should be flashed and solution gas and residual oil composition should be analyzed, while during separation oil, gas volume and oil density should be measured for GOR calculation. Then oil and gas composition recombined according to measured GOR and reservoir oil composition will be determined by recombination calculation. Oil molecular weight should be measured by osmometric or freezing point method.

Laboratory data set

The data used in this study are gathered from seven undersaturated oil reservoirs from southwest of Iran fields. Some challenges and relevant problems can be observed through the 28 full set of PVT laboratory data. Table 1 summarizes the general information of available

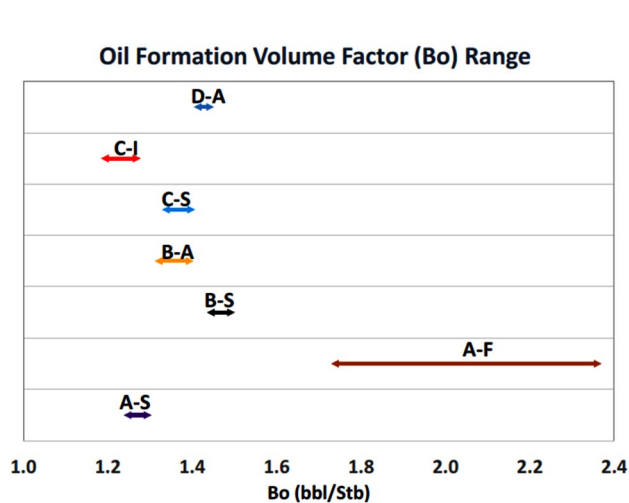
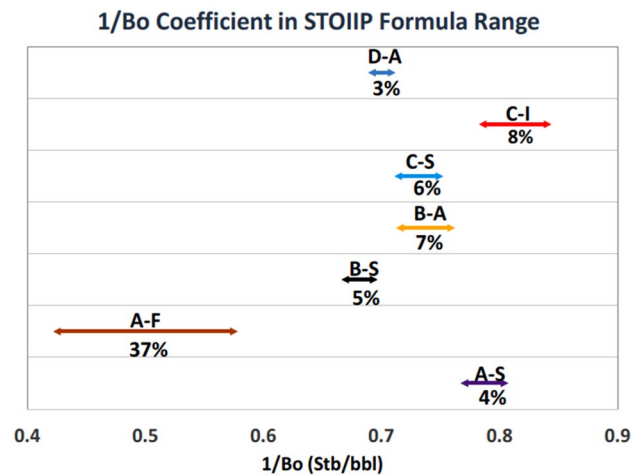
PVT samples. All used and reported properties of PVT samples are measured data. Oil densities range of available samples is from 0.53 to 0.85 gr/cc, and APIs are in the range of 19°–39°. The GORs and saturation pressure of these samples are in the range of 300–2000 scf/stb and 1000–4600 psi, respectively. Also, these samples are related to the range of 3000–9500 psi of reservoir pressure.

How is the importance of PVT consistency check

Reservoir fluid properties form the basis of many petroleum engineering calculations and future decision. The evaluation of oil and gas reserves, fluid flow through porous media, multiphase flow in pipe, surface and sub-surface equipment design and production system optimization all depend heavily upon reservoir fluid physical properties. Quality and consistency check of reservoir fluid properties is very important to ensure the validity of PVT data and to identify the most representative reservoir fluid properties sample(s). Formation volume factor (B_o) is one of the most highly important parameter of fluid properties affecting original oil in place calculations. Finding the most representative reservoir fluid properties sample prevents wrong original oil in place estimation and causing reservoir performance uncertainties. PVT data used in this study show variation in measured values for B_o of the unique reservoir (Fig. 3). Thus, estimated stock tank oil initially in place (STOIIP) can vary from 3 to 37% depending on the PVT set data of each reservoir (Fig. 4) which is emphasizing the importance of quality and consistency

Table 1 Summary of PVT sample properties

Sample nos.	Saturation pressure (PSI)	Solution GOR (SCF/STB)	Oil density @ PB (PSI)	Oil formation vol. factor @PB (BBL/STB)	MW C12+	SP GRAV. C12+	API from sep. (°)
A1-S	1032	293	0.82	1.25	617	0.99	21
A2-S	1106	293	0.81	1.24	510	0.94	21
A3-S	2100	434	0.80	1.30	380	0.99	19
A1-F	4590	1916	0.58	2.19	280	0.89	38
A2-F	4035	1678	0.56	2.15	270	0.88	39
A3-F	4393	1996	0.53	2.37	275	0.90	39
A4-F	3900	1519	0.59	2.08	305	0.89	38
A5-F	3026	1090	0.64	1.73	332	0.89	37
B1-S	2390	569	0.75	1.44	780	1.05	–
B2-S	2617	664	0.57	1.48	380	0.98	–
B3-S	1905	535	0.74	1.44	290	0.93	–
B4-S	2816	737	0.73	1.50	596	0.99	–
B1-A	2311	474	0.79	1.31	885	1.07	–
B2-A	2568	618	0.75	1.40	425	0.99	–
C1-S	1635	480	0.74	1.39	320	0.95	–
C2-S	1439	434	0.73	1.41	335	0.95	–
C3-S	1795	480	0.76	1.40	442	0.95	23
C4-S	1721	412	0.77	1.33	351	0.94	25
C5-S	1908	514	0.76	1.40	438	0.95	26
C6-S	1473	451	0.76	1.34	418	0.95	–
C7-S	1450	367	0.77	1.36	499	0.96	26
C8-S	1496	417	0.74	1.38	471	0.95	–
C1-I	1268	288	0.79	1.28	372	0.99	24
C2-I	1379	339	0.80	1.28	330	0.96	–
C3-I	1396	334	0.85	1.20	365	0.98	20
C4-I	1360	269	0.79	1.19	264	0.97	–
D1-A	2548	720	0.72	1.40	440	0.92	32
D2-A	2781	833	0.71	1.45	422	0.93	–

**Fig. 3** Bo range of PVT samples of each reservoir**Fig. 4** STOIP calculation difference based on PVT sample of each reservoir

check of reservoir fluid properties. It is usual that PVT data of reservoir fluid samples are associated with errors. Therefore, proceeded to apply the available PVT data in reservoir studies, the validity of PVT samples must be rechecked. According to the importance of PVT parameter in reservoir characterization and study, inclusive procedure will be designed by this paper to verify reservoir fluid properties.

Consistency check investigation

Methodology

It is usual that PVT data of reservoir fluid samples are associated with errors. Therefore, proceeded to apply the available PVT data in reservoir studies, the validity of PVT samples must be rechecked. Until today, many

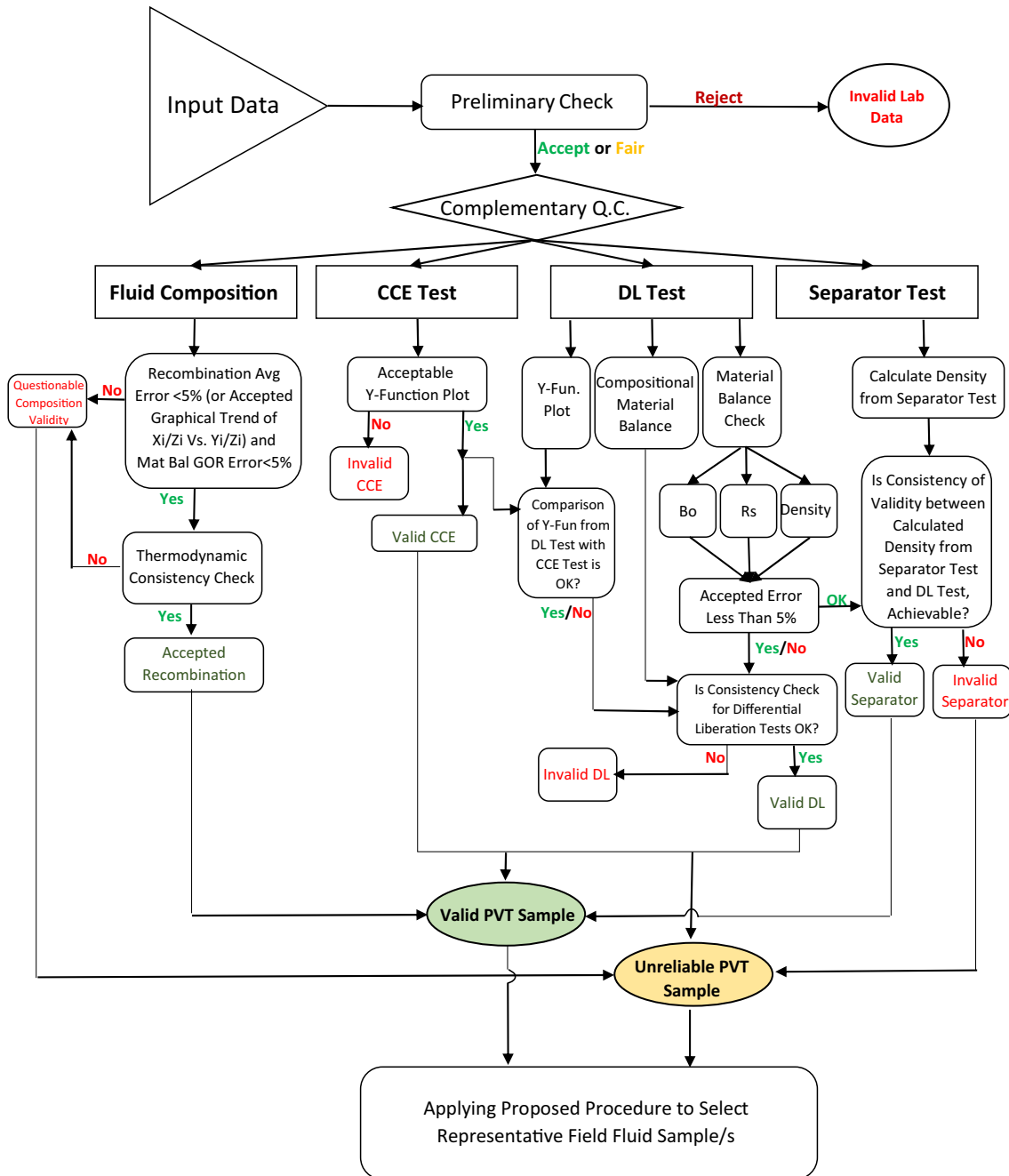


Fig. 5 Reservoir representative fluid samples selection flowchart

different methods have been developed to analyze the consistency of PVT sample properties. Considering most of the introduced methods, the following procedure is suggested by this paper to check the validity of the black oil PVT samples (Fig. 5). Workflow starts with preliminary check to screen the samples graphically. After that, complementary tests perform to verify the consistency of fluid properties comprehensively. In this work, properties of the CCE and DL test are considered as the most essential parameter for verifying the validity of the samples. By following the suggested workflow, samples are categorized as “valid,” “invalid” or “unreliable” samples. The *valid sample* is assigned to samples which pass the whole required criteria, while *invalid sample* is related to fluid samples which their preliminary, CCE or DL test is rejected. Third type of fluid samples, *unreliable sample*, as like as the valid samples has consistent CCE and DL test, but the consistency of preliminary, composition or separator test is questionable. It should be noted that “errors” in this procedure are defended as follows:

$$\text{Error} = |1 - \text{Calculated Data/Measured Data}| \times 100$$

It should be noted, after the consistency check of the PVT samples, valid PVT data of the same reservoir should be compared to select the most representative samples. The final result of the suggested procedure is to find some reliable PVT samples which could be applied in reservoir comprehensive studies. Different steps of the flow procedure and passing criteria of each test would be discussed in the following sections:

Preliminary check

Graphical method

Graphical method is the simplest method of consistency check for laboratory PVT data which analyze the validity of the fluid properties behavior. In this method, considering the logical behavior of the petroleum reservoir fluids, trend of the reported properties of each sample is compared with the expected behavior of the reservoir fluids. Most important properties which are checked in this manner are solution gas–oil ratio, liquid density, oil formation volume factor and gas compressibility factor of the DL test, relative volume and liquid isothermal compressibility of the CCE test and measured liquid viscosity of the viscosity test.

The logical trend for the solution gas–oil ratio and oil formation volume factor of the DL test is a straight line below the bubble point pressure. However, the B_o and GOR data points of fluid samples could have some deviations from the straight line for light oil with $\text{API} > 31$. The best way for consistency verification of B_o and GOR trend is to plot the R_s versus B_o for each sample. Graph of the R_s versus B_o must also follow a straight line in a consistent fluid sample of the black oil reservoir.

As the first step of sample validity check, behavior of R_s and B_o of whole available samples was checked. Totally, three different behaviors were observed in PVT sample sets. Fluid samples with $\text{API} < 31$ have mostly the linear trend line below the bubble point, similar to behavior of sample B3-S with $\text{API} = 21$ as shown in Fig. 6. This sample has a valid B_o and R_s trend of ordinary black oil fluid.

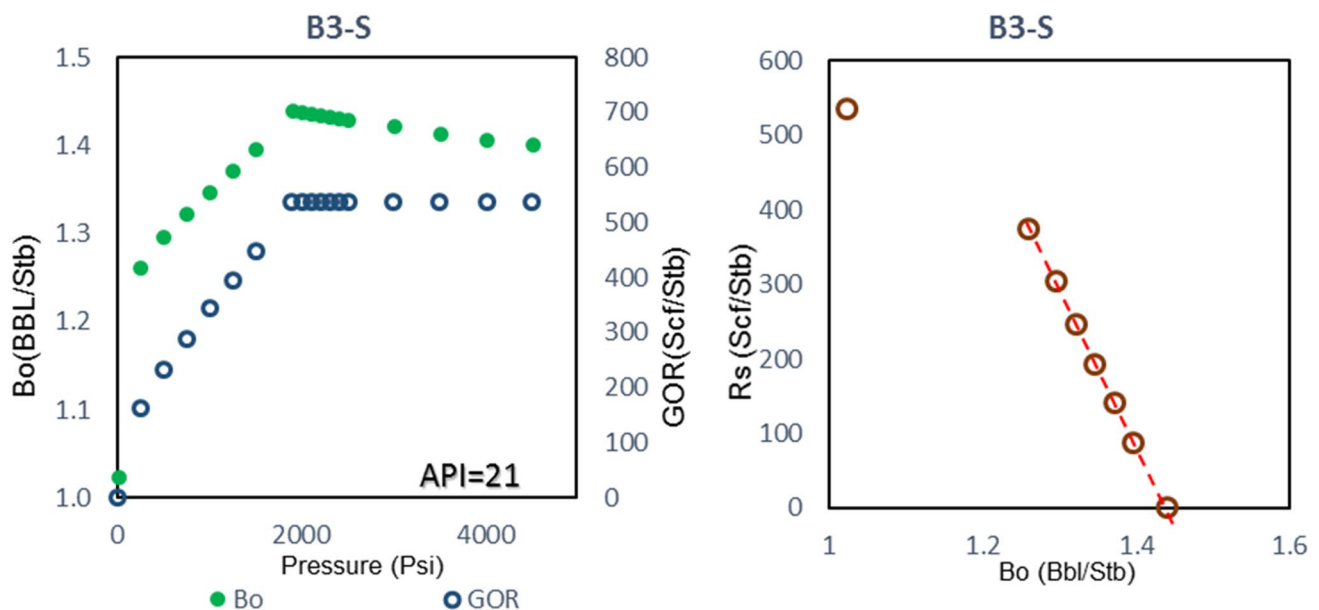


Fig. 6 GOR and B_o behavior of oil with $\text{API} < 31$ -DL test—(B3-S)

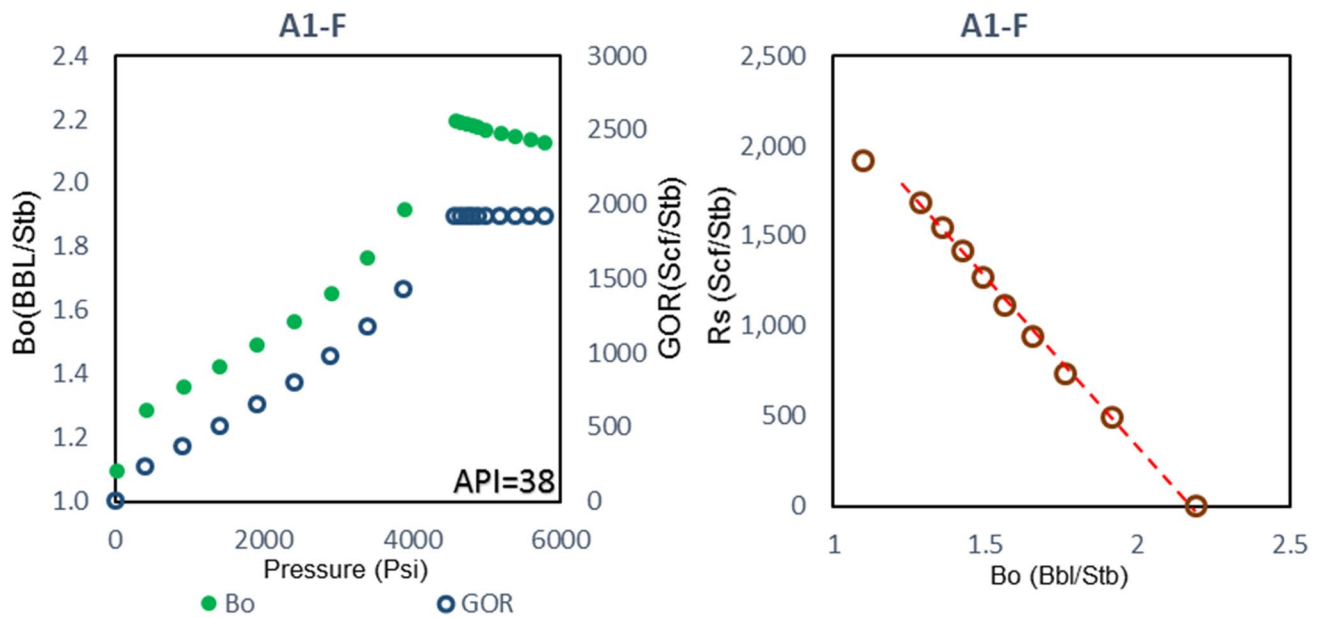


Fig. 7 GOR and Bo behavior of oil with API > 31-DL test—(A1-F)

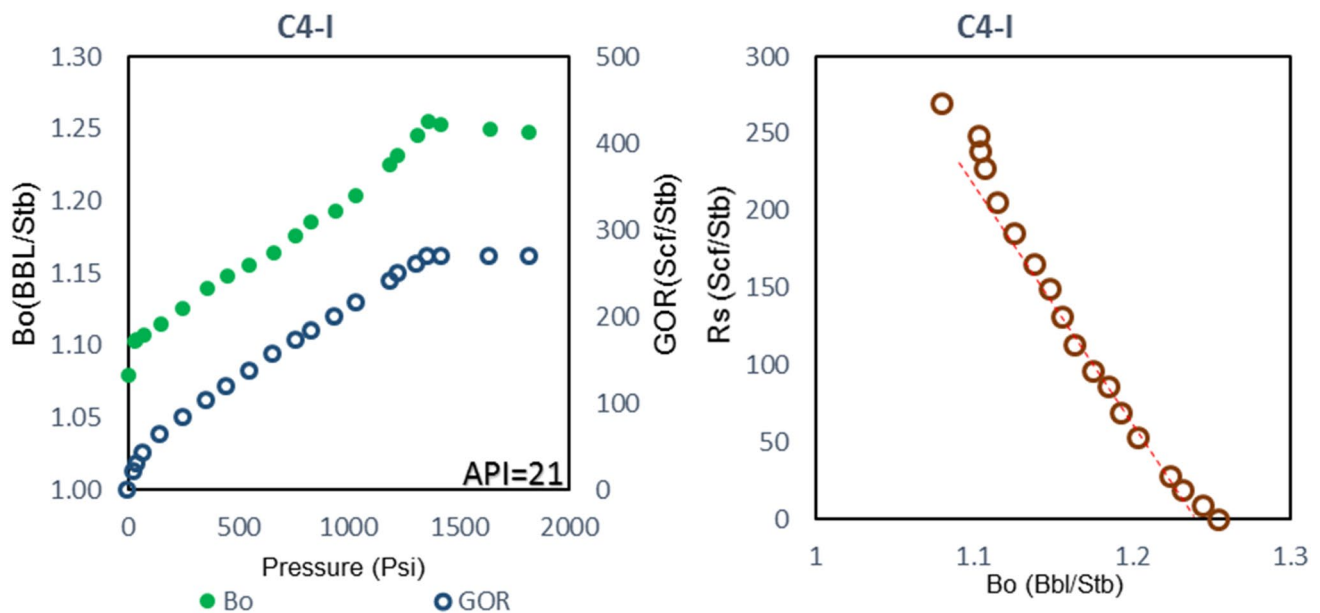


Fig. 8 Invalid trend of GOR and Bo for C4-I sample—DL test

Second type of behavior belongs to samples with API > 31. From Fig. 7 which is an example of this type of samples, B_o of sample A1-F does not follow the straight line of ordinary black oil fluids, but the R_s versus B_o relation of this sample yields a straight line. Therefore, it could be illustrated that sample A1-F in spite of its nonlinear B_o and GOR behavior is a valid sample. An example of the last type of observed behavior is plotted in Fig. 8. In this

type of samples, at least one of the R_s or GOR behavior does not follow the expected trend. Therefore, R_s versus B_o plot of this sample must be analyzed to examine the observed behavior more curiously. As it was discussed, R_s versus B_o must behave linearly, while the samples behave nonlinearly; therefore, it was concluded that this kind of samples is not reliable and has some major errors during their experimental measurements. Checking the whole

available samples shows that ONE out of 28 is not reliable, while other remaining samples have consistent behavior.

Basically, the liquid viscosity and density do not follow the exact straight line, but it expects that both of them increase by increasing the pressure above the bubble point pressure. Vazquez and Beggs (1980) have shown that plot of $\frac{\mu_o}{\mu_{ob}}$ versus $\frac{P}{P_b}$ gives a straight line for undersaturated black oil fluids which is used for data smoothing and validity check of the viscosity laboratory data. Trend of expected behavior for the liquid density and viscosity check plot (from Vasquez and Beggs) is shown in Figs. 9 and 10, respectively. Anyway, whole gathered samples have been analyzed and all of them follow the logical trend of liquid density and viscosity.

Another trend line which should be considered for the PVT tests is linearity of the undersaturated oil iso-thermal compressibility. Iso-thermal compressibility above the bubble point is calculated from the measured volume in the CCE test at pressures above the bubble point. After calculating iso-thermal compressibility, graph of the iso-thermal compressibility versus pressure should behave linearly with negative slope at $P \gg P_b$. Due to the gas compressibility effects, iso-thermal compressibility of live oils near the bubble points does not follow the exact straight line, but the behavior is consistent with fluid compressibility at higher pressure. Figure 11 shows two types of reported liquid iso-thermal compressibility. It is obvious that compressibility trend of sample C4-I could not belong to a valid CCE test. Checking whole available samples, sample C4-I is the only

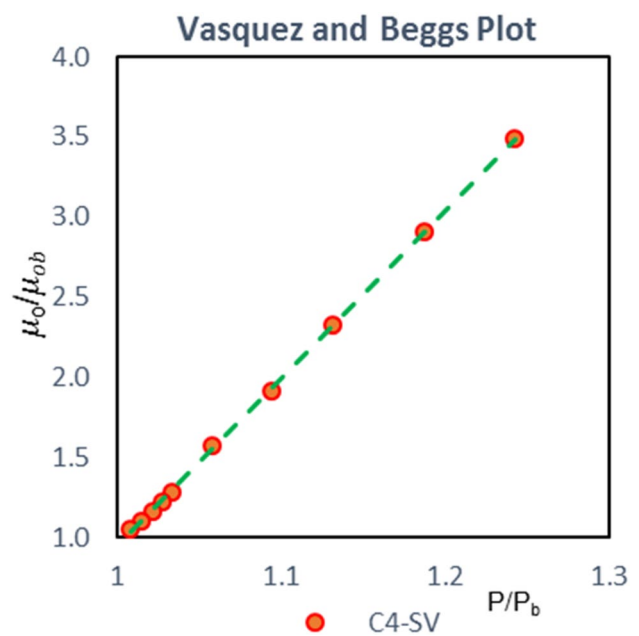


Fig. 10 Valid trend of oil viscosity from Vasquez and Beggs plot of C4-SV sample—DL test

PVT sample which has an unaccepted iso-thermal compressibility behavior. It should be noted that the unaccepted iso-thermal compressibility behavior can appear as a result of wrong relative volume or test pressure measurement above the saturation pressure in the CCE test.

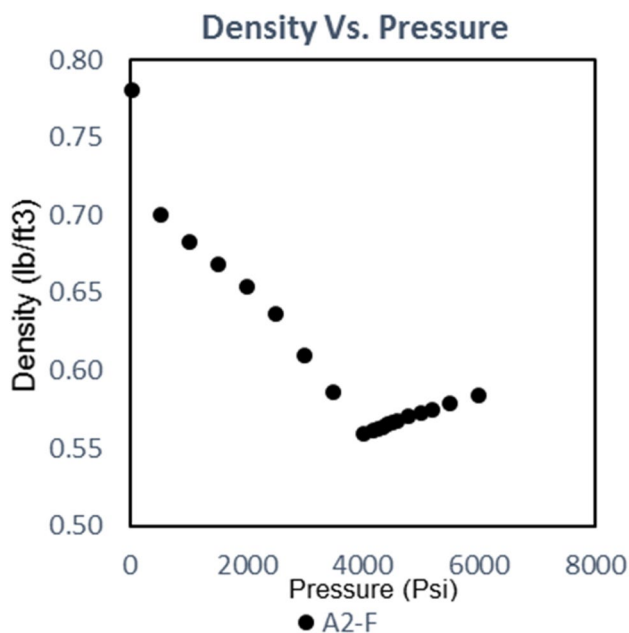


Fig. 9 Valid trend of oil density of A2-F sample—DL test

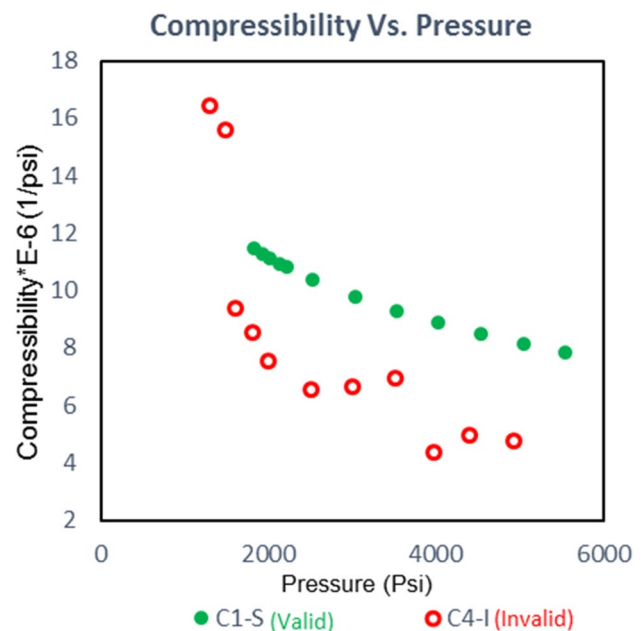


Fig. 11 Valid and invalid trend of oil iso-thermal compressibility factor of BO samples—CCE test

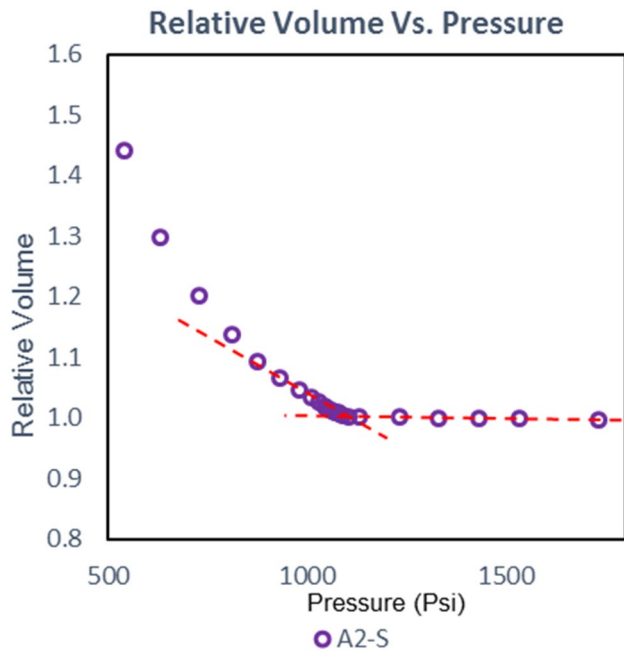


Fig. 12 Valid trend of relative volume—CCE test

In addition, behavior of the relative volume for the CCE test should also be checked. At pressures above the bubble point, relative volume should behave linearly, while below the bubble point slope of the linear trend would be changed and data points deviate from linear line at low pressures ($P \ll P_b$). However, the important part of the relative volume curves is around the bubble point pressure. For pressure above and below the bubble point, two different straight lines are passed through data points to intersect at bubble point pressure. Totally, accuracy and consistency of relative volume have an essential rule in sample saturation pressure identification. A view of the expected trend is shown in Fig. 12. Based on the observed trend in Fig. 6, the relative volume of whole samples was reliable and bubble point of samples was measured accurately.

In addition, analyzing the liquid properties, gas properties behavior of the DL test should also be considered to confirm the validity of the DL test. The gas compressibility factor (Z factor) of each step is the most important property of the DL test for the gas phase. Z factor is utilized in material balance calculation and volume converting equations. Z factor should be lower than one at low pressure and exhibits a valley-shape behavior (Fig. 13). Among all samples, only sample C4-I has a nonacceptable trend and point values which has Z factor of about 1.05 for the pressure range of 200–700 psi and reverse behavior of Z factor (Fig. 14). Other samples have followed the expected Z factor behavior.

Moreover, some data points of laboratory data are also compared to assess the validity of PVT samples. In this manner, residual oil API gravity of the DL and separator

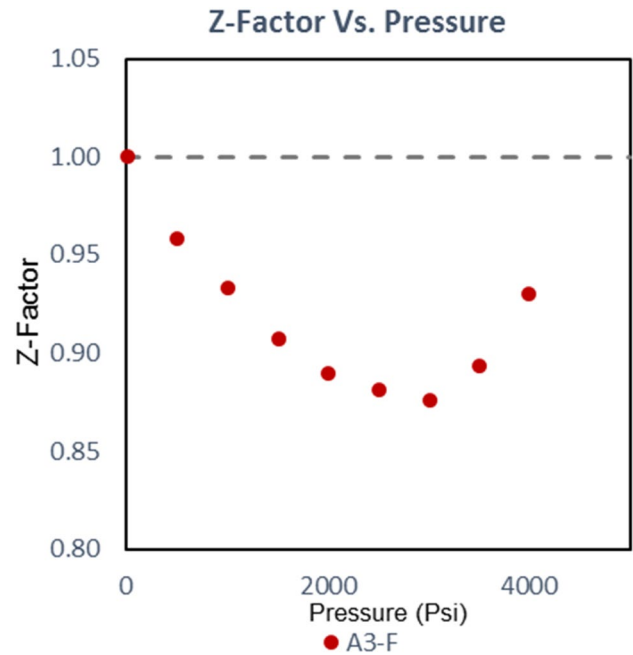


Fig. 13 Valid trend of gas compressibility factor—DL test

test and solution gas–oil ratio of the DL and CCE test were compared to each other. Lawrence and Gupta (2009) have stated that comparison of DL and separator residual oil gravity is an appropriate tool to verify the consistency of DL and separator test. Generally, DL test has been performed at higher temperature than separator test. Therefore, it is expected that residual oil API gravity of DL test

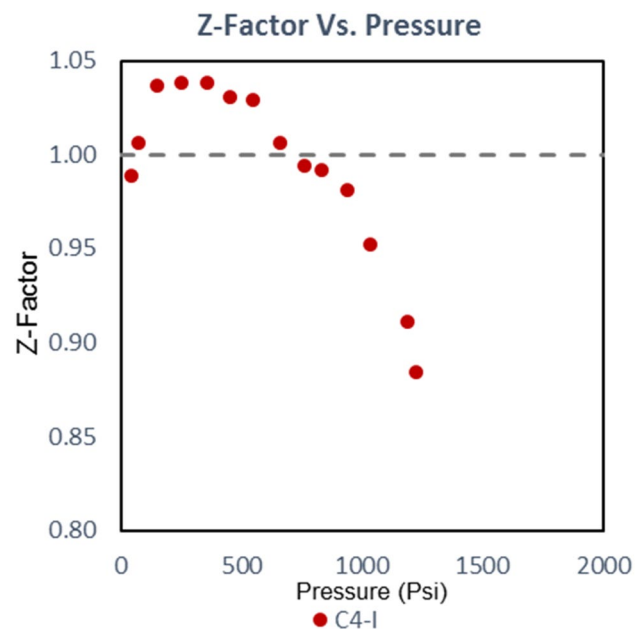


Fig. 14 Invalid trend of gas compressibility factor—DL test

is lower than from the separator test one. The same as API, GOR of the DL and CCE test should also be compared. Generally, if the DL and CCE test has been performed at the same temperature, liberated gas volume of the DL test must be higher than the CCE test. In fact, DL test should have highest liberated gas volume compared to CCE and separator tests. Comparing DL, separator, and CCE test of whole 28 samples, two samples, B1-S, and C1-I, include some nonacceptable properties which are summarized in Table 6. For these two samples, GOR from flash composition test is higher than GOR from DL test which theoretically should be lower.

By applying the preliminary check to whole samples, it was concluded that reported data of sample C4-I include some major errors which mean that validity of sample C4-I is rejected and could not be a representative fluid sample of the reservoir. Although two other samples, B1-S and C1-I, have some inconsistencies in their properties, but the validity of these samples is not rejected. It is suggested that these types of samples assigned as fair samples and need to be checked by complementary consistency test methods. If other methods confirm the consistency of these samples, then the samples could be used in representative sample selection step.

However, it should be noted that the preliminary check is not a sufficient method to validate whole aspects of consistency of the PVT samples. Today, many precise methods have been developed to validate the consistency of different PVT laboratory tests specifically. In the following, some complementary methods to assess the consistency and reliability of whole common laboratory tests which are performed on black oil samples are discussed.

Complementary checks

Fluid composition analysis

Fluid composition analysis is another vital step of PVT test consistency check. Simplest way to verify the accuracy of the composition is to check the reported compositions solely and the sum of the total composition. In addition, summation of total composition should be equal to 100%.

Furthermore, two other types of technique have been developed to check fluids composition consistency. Material balance check is one of the most accurate techniques that use the feed and flashed fluids composition to check the accuracy of flashed component compositions and reported GOR of flashing process, mathematically. In second type of developed techniques, thermodynamic methods have been used to verify the accuracy of composition. These methods use the K value principles to check qualitatively the consistency of

the compositions which are reviewed in more detail in the following sessions.

Recombination and material balance check

Recombination and material balance check is the most accurate technique to analyze compositional consistency of flashed fluid compositions. Considering the component material balance, below equation could be derived:

$$\frac{Y_i}{Z_i} = \left(-\frac{L}{V}\right) \frac{X_i}{Z_i} + \frac{F}{V} \quad (1)$$

Based on the above equation, a plot of Y_i/Z_i versus X_i/Z_i should yield a straight line with a slope of $-L/V$ and an intercept of F/V . Therefore, any observed deviations from straight line correspond to inaccuracy of reported compositions. However, reservoir fluid compositions could also be calculated from the mathematical recombination of flashed vapor and liquid compositions. Equations of recombination process are as follows:

$$z_i = F_g y_i + (1 - F_g) x_i \quad (2)$$

$$F_g = \frac{1}{1 + 136,986 \frac{\gamma_o}{M_{w_o} R_s}} \quad (3)$$

After calculation of reservoir components compositions from flashed vapor and residual oil compositions, a perfectly straight line could be drawn by material balance equation. After that, the obtained line is used for identifying deviation of reported and recombined reservoir fluid compositions. Based on experiences, an average deviation of 5% is acceptable for fluid samples, while greater deviations illustrate the unreliability of the fluid samples.

In addition, accuracy of reported GOR is also checked by material balance test. In the material balance equation, slope of the straight line is negative molar ratio of the flashed liquid to the flashed gas. Therefore, the reciprocal of the slope could be used to calculate GOR by converting the molar ratio to volume ratio of flashed fluids. Calculated GOR in the valid recombined samples should not deviate more than 5% from the reported GOR at reservoir composition test.

The material balance test errors are originated from different sources during composition measurements at laboratory. Deviation of reservoir oil compositions from the calculated recombined composition could be affected by surface oil molecular weight. Further, the errors of the GOR may be caused by errors in the measurement of the molecular weight and density of the flashed oil (Fig. 15).

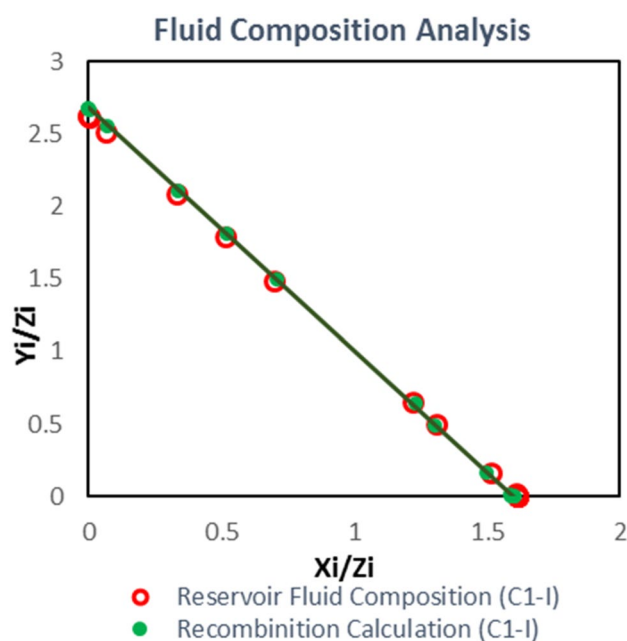


Fig. 15 Reliable fluid sample compositions—recombination test

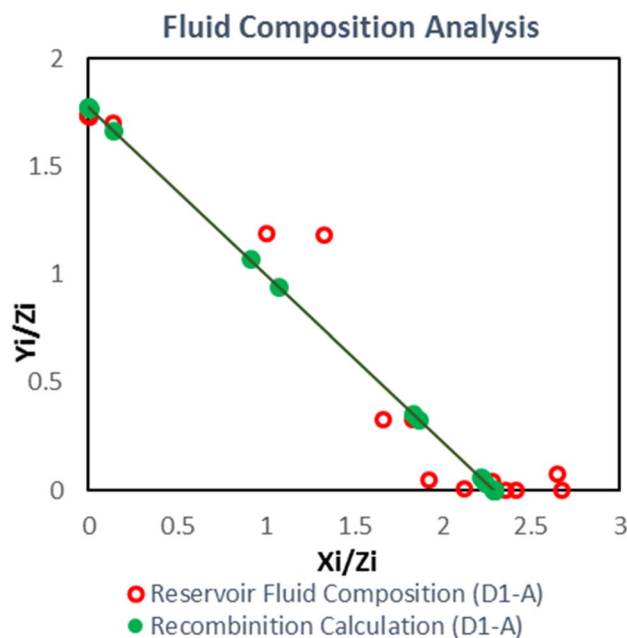


Fig. 16 Unreliable fluid sample compositions—recombination test

Table 2 Observed preliminary problems

Sample nos.	GOR (DL)	GOR (flash composition test)
B1-S	569	581
C1-I	288	206

Among whole gathered samples, compositional behavior of samples B1-A and D1-A deviates from straight line which was obtained by recombination and material balance equations. For an example, Fig. 16 shows the behavior of unreliable fluid composition for the sample of D1-A. The plot of a valid sample, C1-I, is shown in Fig. 15 to represent the expected trend for valid samples.

Moreover, reported GOR of each sample has been compared with calculated GOR by material balance equations. GORs of samples A3-S, A1-F, A3-F, and B3-S have deviated more than 5% which concluded that molecular weight or density of residual liquid of these samples is not accurate enough. Table 2 shows the calculated and reported GOR of these samples.

Thermodynamic consistency check of composition

Pressure depletion in the oil reservoir or pressure and temperature changes in the upstream and downstream facilities causes live oil liberating some gases. Composition of the liberated gases and flashed liquids highly dependent on the equilibrium ratio is known as K value. Therefore, as far as the reservoir compositional simulation is the concern of the reservoir engineers, K value has an essential rule in accuracy verification of their calculations. K value directly denotes the ratio of the molar composition of a component in the vapor phase to liquid phase of a mixture which has been reached to equilibrium. K value could be expressed by:

$$K_i = y_i/x_i \quad (4)$$

Based on the values of the equilibrium ratio, some of the thermodynamic consistency techniques have been developed to check the accuracy of the fluid composition. Hoffman plot, Buckley plot and modified Wilson plot are examples of these kinds of methods which uses the concepts of the equilibrium ratio. In addition to methods which use K value, there are some other thermodynamic methods like Watson characterization factor for checking the consistency of the reservoir fluids composition. This method uses the properties of the heptane plus fraction of fluid components instead of K value to compare composition of different samples of a black oil reservoir. These three mentioned methods have been discussed below:

Hoffman et al. (1953) have developed a method based on the earlier technique which was introduced at 1930 by S.E. Buckley of Humble Oil and Refining Company, to analyze the relationship of equilibrium ratio and fluid properties. They have shown that K value has been related to a component factor called F_i exponentially. F_i is calculated as follows:

$$F_i = \frac{\log\left(\frac{P_{ci}}{P_{sc}}\right)}{\frac{1}{T_{bi}} - \frac{1}{T_{ci}}} \left(\frac{1}{T_{bi}} - \frac{1}{T_{sp}} \right) \quad (5)$$

where T_{bi} , T_{ci} and T_{sp} are the components normal boiling point, critical temperature and separator temperature all in $^{\circ}\text{R}$, respectively. In addition, P_{ci} and P_{sc} are critical pressure standard condition test pressure in Psia , respectively.

Based on the Hoffman et al. method, a plot of $\log(K_i)$ versus F_i for light to intermediate components (C1–C6) of an equilibrated mixture should follow a linear trend. As long as the flashing pressure is high enough, this linearity behavior could also be observed for heavier components of mixture, but a deviation from straight line could be expected in lower flashing pressures for heavier components.

The logical result which could be attained from Hoffman et al. method is that if the components of the analyzed sample do not follow the expected linear trend, their reported compositions could not belong to an equilibrated mixture. Therefore, considering the Hoffman et al. method, compositions consistency of each reported sample is checked by calculating the F_i and drawing the semilogarithmic graph of the K value versus F_i as follows.

Figures 17 and 18 show the Hoffman plot of two different samples of our gathered data set. Samples, which behave linearity as like as sample A1-S, are valid samples, while other samples such as C2-S are not valid samples which do not follow the straight line. To describe a reliability criterion for Hoffman plot, we use the correlation coefficient (R^2) of best linear line which crosses the observed point of each

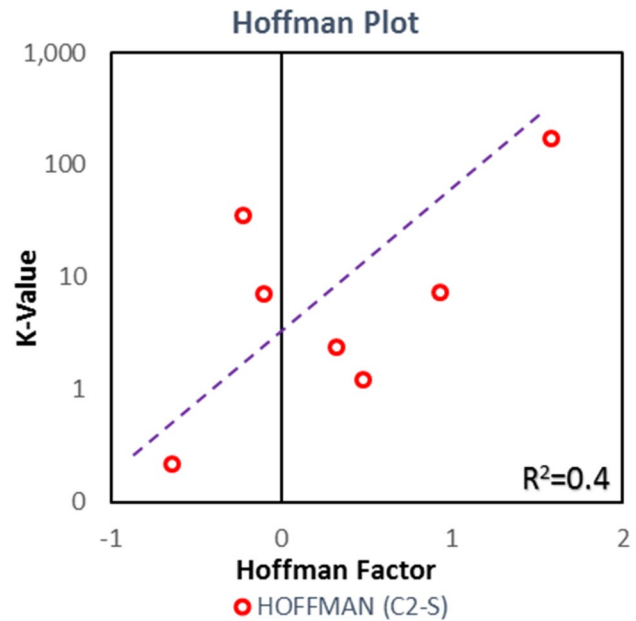


Fig. 18 Invalid Hoffman plot—recombination test

sample. Considering this, samples A5-F, C2-S, C8-S, C2-I and C3-I do not pass the reliability criterion.

Buckley plot is another thermodynamic method which has been developed to consistency check of the equilibrated mixtures. As like as the Hoffman et al. method, Buckley plot is a semilogarithmic graph of K_i versus a component critical property-dependent parameter. Buckley parameter is the square of the critical temperature of hydrocarbon components. Buckley has shown that $\log(K_i)$ versus T_c^2 yields

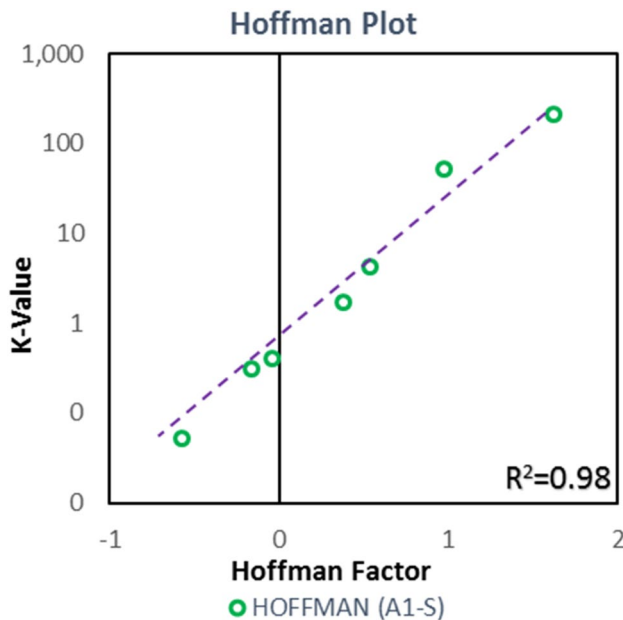


Fig. 17 Valid Hoffman plot—recombination test

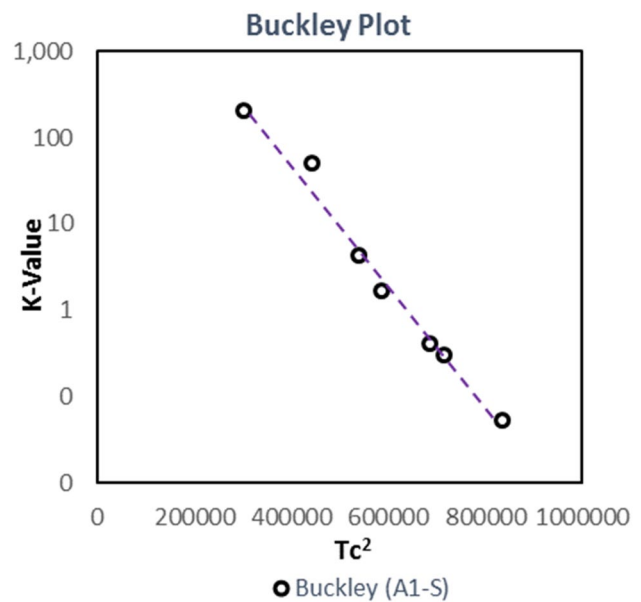


Fig. 19 Valid Buckley plot—recombination test

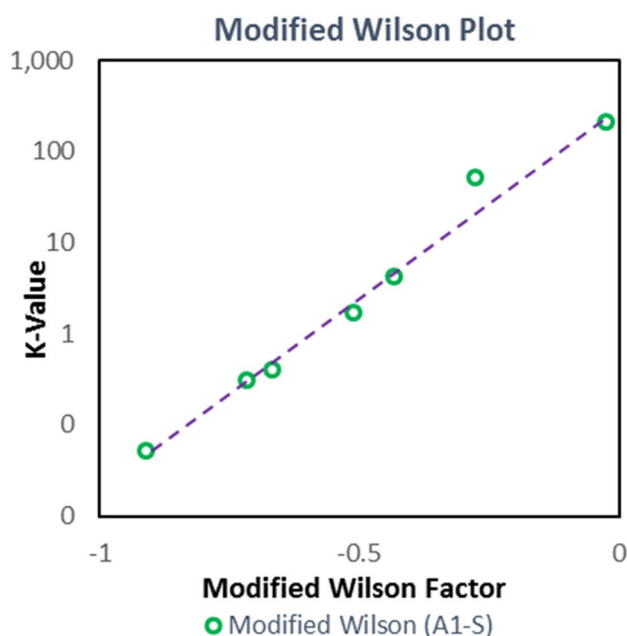


Fig. 20 Valid modified Wilson plot—recombination test

a straight line with negative slope. Therefore, any observed deviations from the straight line in the Buckley plot illustrate existing of the composition measuring errors (Whitson and Brulé 2000; Akpabio et al. 2014, 2015).

Modified Wilson plot is another thermodynamic method which could be applied for checking the fluid compositions reliability. Modified Wilson method is a graph of $\log(K_i)$ versus a composition factor which is calculated as follows (Danesh 1998):

$$\text{Modified Wilson Factor} = (1 + \omega)(1 - 1/T_r) \quad (6)$$

where ω and T_r are the acentric factor and dimensionless reduced temperature. It should be noted that the Buckley and modified Wilson and Hoffman plot follow the same concept and behave as same as each other. Therefore, applying one of them is adequate to check the accuracy of fluid sample compositions. Figures 19 and 20 show Buckley and modified Wilson plot of sample A1-S. Hoffman plot of this sample is also shown in Fig. 17. Comparing these two figures confirms that all Buckley and modified Wilson plot behave as same as the Hoffman plot.

Generally, deviation of Hoffman, Buckley and modified Wilson plot is due to flashed fluid compositional errors. Instability of flashing condition and/or inaccuracy of measuring fluid compositions is the main reason for any observed deviation in these plots. Therefore, deviations illustrate the unreliability of fluid samples due to un-equilibration of the flashed mixture.

Watson characterization factor

Hoffman et al. and Buckley methods are not very useful to check the quality and accuracy of the heavy component compositions. Then, it is better to analyze the heptane plus fractions by Watson characterization factor, K_w . This factor has been introduced by Watson to qualitatively represent the relative paraffinicity of hydrocarbon fluid. K_w depends on normal boiling point and specific gravity of the hydrocarbon fluid, but for the stock tank oils and flashed liquids of black oil reservoir fluids, K_w could be estimated by specific gravity and molecular weight of heptane plus fraction (Watson et al. 1935).

Regarding the K_w , Austad et al. have stated that K_w of heptane plus fraction (K_{w7+}) of a specified reservoir fluid is constant during the whole depletion periods of the reservoir. Considering this statement, different samples of a reservoir should have the same K_{w7+} and a graph of the specific gravity of heptane plus fraction versus molecular weight of the heptane plus fraction should have laid on the straight line of the constant average K_{w7+} of the reservoir. To check the validity of the samples of a specific reservoir K_{w7+} method could be applied. Fluctuation around the straight line of constant K_{w7+} up to the ± 0.03 units is acceptable, but more deviations are questionable. This deviation could be caused by inaccuracy in the measurement of the heavy components molecular weight. This inaccuracy may also form some errors in molar composition of the plus fraction component (Whitson 1983, 1988). However, specific gravity and molecular weight of heptane plus component of whole available samples were not reported; then, Watson plot analysis is not applicable for the available fluid samples.

Y-function of CCE test

The total cell volume of the CCE test just below the bubble point pressure is an essential parameter to calculate the bubble point pressure, accurately. Usually, because of the laboratory errors, measured total volume below the bubble point should be corrected and smoothed by a correction factor called Y-function (Ahmadi et al. 2014; Hosein et al. 2014; Nnabuo et al. 2014). The Y-function is calculated as:

$$Y = \frac{V_b(P_b - P)}{P(V_t - V_b)} \quad (7)$$

where P_b is bubble pressure (psi), P is pressure values lower than bubble pressure, V_t is the total cell volume at pressure P , and V_b is cell volume at pressure P_b .

In addition to smoothing the total volume of CCE test, Y-function could also be used as a method to check the quality of the CCE test (Amyx et al. 1960; Whitson and Brulé 2000). It has been proved that Y-function should have

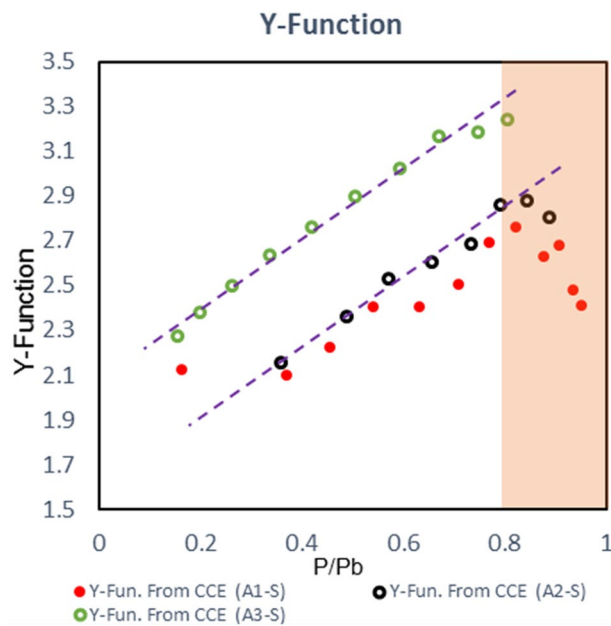


Fig. 21 Different Y-function of reservoir S—CCE test

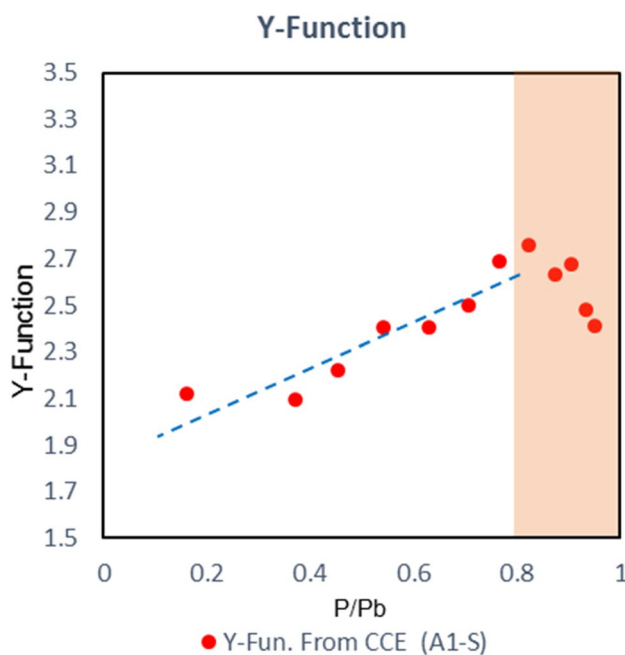


Fig. 22 Invalid Y-function—CCE test

a linear trend below the bubble point pressure (especially when the oil samples have low concentration of nonhydrocarbon compounds) (Hosein et al. 2014; Nnabuo et al. 2014). Therefore, a graph of the Y-function versus pressure is drawn for CCE tests data and for samples which the linear trend has not been observed in low test pressure up to 0.8 bubble point pressure, and the CCE test would be rejected.

Checking the Y-function of whole samples, two samples, A1-S and C4-I, have not a valid Y-function. Figure 21 shows the Y-function of three samples which belong to the same reservoir. One of these samples, A1-S, does not follow the expected straight line of Y-functions (Fig. 22); therefore, the CCE test of this sample is rejected.

Y-function of DL test

Y-function has been developed to smooth the measured total volume and check the consistency of the CCE test data. But Potsch et al. (2017) were suggested to use the Y-function concept, verifying the accuracy of the DL test. They proved that Y-function of DL test theoretically does not behave linearly, especially for low-density fluids, but, in reality, lies almost on the straight line. By the following equation the Y-function for each step would be calculated:

$$Y - \text{function}_{DL} = \frac{\frac{P_b}{P} - 1}{\frac{B_o + B_g R_s}{B_{ob}} - 1} \quad (8)$$

The plot of the Y-function versus pressure for CCE and DL tests is compared to check the linearity behavior and the differences between them. A deviation less than one unit between Y-functions is acceptable, but higher deviation concludes the existence of the error in reported properties of the DL test (Potsch et al. 2017). It is noted that in order to check the Y-function of DL test, accuracy of CCE test must be approved, subsequently.

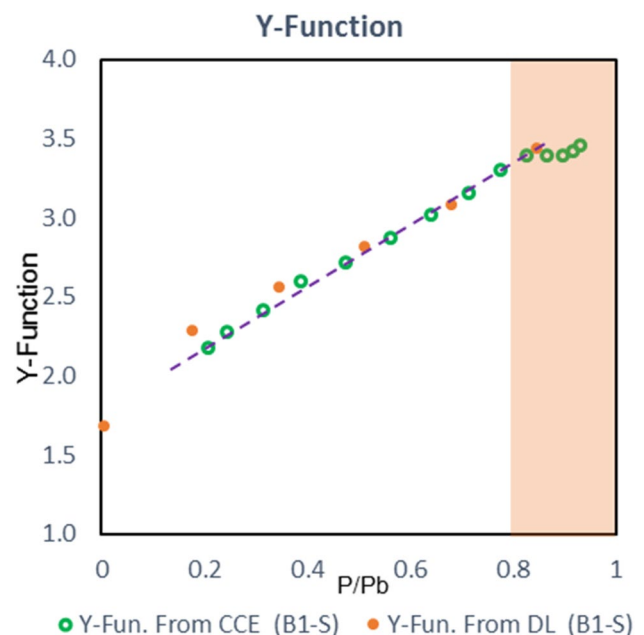


Fig. 23 Valid trend of Y-function of DL test—(B1-S)

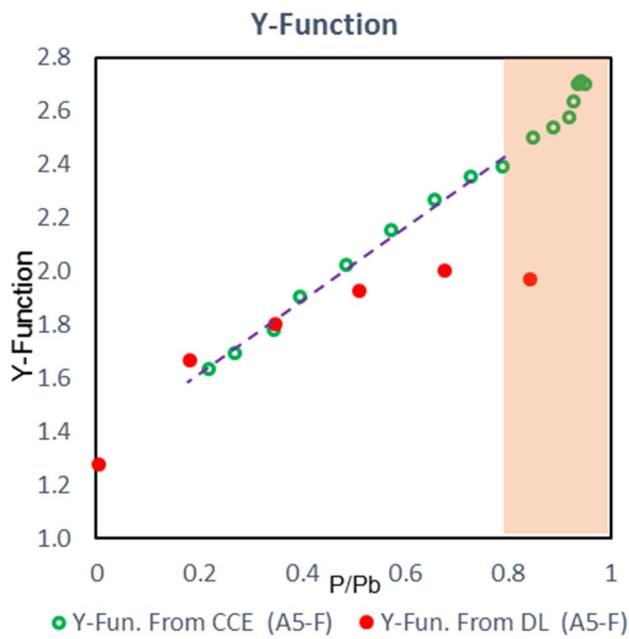


Fig. 24 Invalid trend of Y-function of DL test—(A5-F)

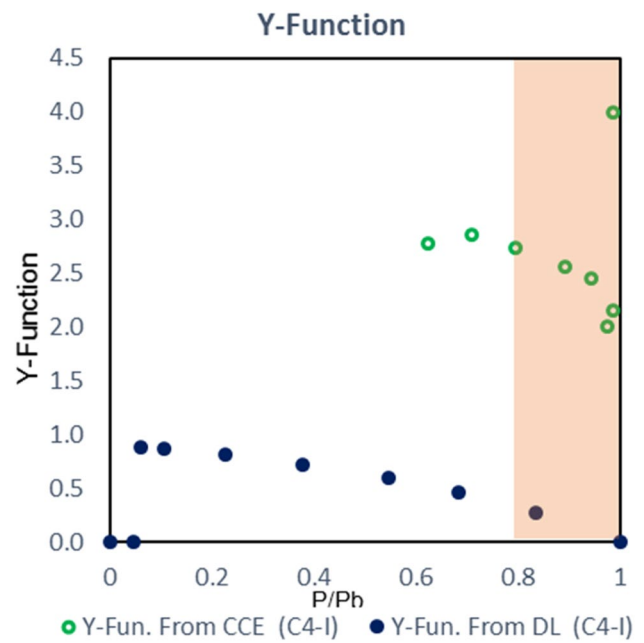


Fig. 26 Invalid trend of Y-function of DL test—(C4-I)

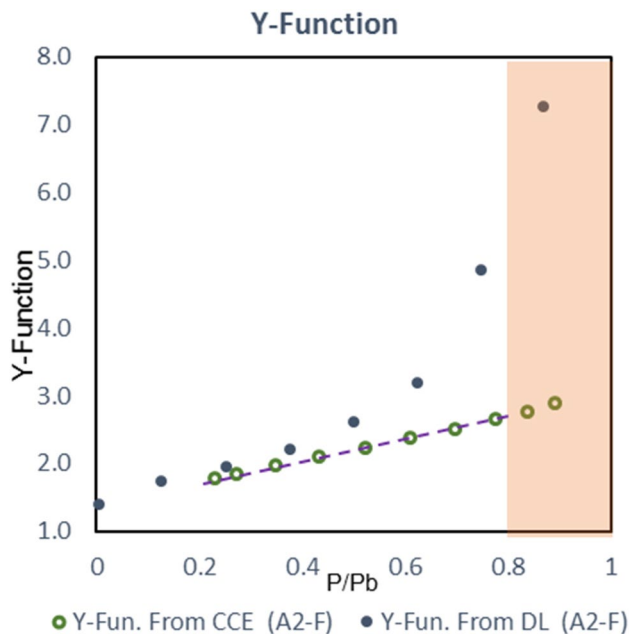


Fig. 25 Invalid trend of Y-function of DL test—(A2-F)

Figure 23 shows an acceptable Y-function for both DL and CCE test. However, Figs. 24, 25 and 26 show non-acceptable Y-functions for DL test. In Figs. 24 and 25, Y-function trend of CCE test is valid, but the Y-function of DL test deviates from Y-function of CCE test which illustrate that these two samples, A2-F and A5-F, are influenced by errors during measuring the properties of DL

test. In addition, as shown in Fig. 26, sample C4-I has also a nonacceptable CCE and DL Y-functions.

Compositional material balance of DL test

As it is discussed in material balance check of the composition consistency section, the material balance test is the most accurate technique to analyze compositional consistency of flashed fluid compositions. In the DL test, for each step, liquid of the previous step flashed into the liquid and liberated gas. Therefore, material balance could also be used for DL test to check the composition consistency of flashed fluids. The fundamental step to perform the material balance check on the DL test is the calculation of the liquid compositions at each step. Liquid composition of each step is calculated as follows:

Basis = 1 STB Residual Oil

$$\text{Mass of residual oil} : m_{or} = V_{or}\rho_{or} \quad (9)$$

$$\text{Mole of Liberated Gas} : M_{gi} = 0.00255(R_{s_{i-1}} - R_{s_i}) \quad (10)$$

$$\text{Mass of Liberated Gas} : m_{gi} = M_{gi}M_{w_{gi}} \quad (11)$$

$$\text{Mass of Feed Oil at Bubble Point} : m_f = m_{or} + \sum_{i=1}^n m_{gi} \quad (12)$$

$$\text{Mole of Feed Oil at Bubble Point : } M_f = mf/M_{wf} \quad (13)$$

For the first step:

$$M_f z_{i_1} = M_{g_1} y_{i_1} + (M_f - M_{g_1}) x_{i_1} \quad (14)$$

Then

$$x_{i_1} = \frac{M_f z_{i_1} - M_{g_1} y_{i_1}}{(M_f - M_{g_1})} \quad (15)$$

For the second step:

$$x_{i_2} = \frac{(M_f - M_{g_1}) x_{i_1} - M_{g_2} y_{i_2}}{(M_f - M_{g_1} - M_{g_2})} \quad (16)$$

After liquid composition calculation, two different aspects of the calculated and measured properties of the DL test should be checked. Simplest check is that calculated liquid compositions must not be negative value. Negative compositions indicate the inaccuracy of the reported gas compositions of each step. Liquid compositions of the DL test in each step are calculated by material balance. Hence, the graph of the y_i/z_i versus x_i/z_i yields an exact straight line. However, the slope of the straight line is used to check the accuracy of reported solution gas–oil ratio of each step. As it is mentioned, based on the material balance equation, slope of the observed straight line equals to negative molar ratio of the liquid phase to gas phase. Therefore, GOR could be calculated by converting the slope to the volumetric ratio of the gas phase to liquid phase of each step as follows:

$$\begin{aligned} \text{GOR} \left(\frac{\text{Scf}}{\text{Stb}} \right) &= \frac{V}{L} \left(\frac{\text{lb}_{\text{mole}}}{\text{lb}_{\text{mole}}} \right) \times \frac{1}{0.00255} \left(\frac{\text{Scf}}{\text{lb}_{\text{mole}}} \right) \\ &\times \frac{1}{M_{w_o}} \left(\frac{\text{lb}_{\text{mole}}}{\text{lb}_{\text{mass}}} \right) \times \rho_o \left(\frac{\text{lb}_{\text{mass}}}{\text{ft}^3} \right) \\ &\times 5.615 \left(\frac{\text{ft}^3}{\text{Bbl}} \right) \times B_o \left(\frac{\text{Bbl}}{\text{Stb}} \right) \end{aligned} \quad (17)$$

By calculating GOR of each step, differences between reported and calculated GOR are considered as a consistency check of the DL test. Maximum error of 5% is accepted in this manner, but higher error indicates that reported properties of the DL test are not valid anymore. As presented in Table 3 among whole available samples only three of

Table 3 Observed material balance problems

Sample nos.	Reported GOR (SCF/STB)	Calculated GOR (SCF/STB)	Error (%)
A3-S	350	370	5.2
A1-F	1575	1421	10
A3-F	1725	1190	31
B3-S	465	513	10

them are passed the criteria of validity for this method. It means that properties of liberated gas from each step were not measured accurately for most of the samples. Accuracy of compositional material balance of DL test is crucial for compositional reservoir simulation. But this method is not concern in black oil modeling.

Overall mass balance of DL test

This aims at comparing the experimental Rs (or dissolution GOR), Bo and oil density resulting from the differential liberation test with the Rs, Bo and oil density resulting from the material balance. The gas mass could be calculated between two consecutive pressures, and then, liberated masses should be converted to its respective volume to calculate the Rs of each step. To compare the oil densities, the value of density is estimated from $\rho_o = (\rho_o SC + Rs * \rho_g SC)/B_o$ and is compared with the density measured in DL. Similarly,

Table 4 Reported GOR and calculated GOR from compositional material balance of DL test

Sample nos.	Solution GOR (SCF/STB)	Calculated GOR from DL composition test (SCF/STB)	Error (%)
A1-S	293	310	6
A2-S	293	309	5
A3-S	434	458	5
A1-F	1916	—	—
A2-F	1678	—	—
A3-F	1996	—	—
A4-F	1519	—	—
A5-F	1090	1186	9
B1-S	569	605	6
B2-S	664	—	—
B3-S	535	—	—
B4-S	737	792	7
B1-A	474	497	5
B2-A	618	—	—
C1-S	480	513	7
C2-S	434	464	7
C3-S	480	516	8
C4-S	412	448	9
C5-S	514	555	8
C6-S	451	490	9
C7-S	367	399	9
C8-S	417	451	8
C1-I	288	316	10
C2-I	339	361	6
C3-I	334	348	4
C4-I	269	—	—
D1-A	720	749	4
D2-A	833	869	4

B_o is estimated from $B_o = (\rho_o SC + R_s * \rho_g SC) / \rho_o$ and is compared with the B_o measured in the DL. In the above equations, SC stands for the standard condition. It has been assumed that the test is valid when the calculated error is equal or lower than 5%.

Table 4 summarizes the errors which have been observed in available samples. The B_o of the whole samples was accurate, but the density and R_s of eight samples have some errors.

Density check for separator test

The density test has been suggested by Imo-Jack and Emelle (2013) to perform a comparison between the oil densities (ρ_o) at bubble point pressure (P_b) measured in the differential liberation test (DL) and the ρ_o at the same conditions calculated from the outputs of the separator test (ST) based on the material balance concept. The oil density of the separator test at the bubble point could be calculated as:

$$\rho_{oST} = \gamma_o \rho_w / B_{oST} + \frac{0.0763277}{B_{oST}} \left((\gamma_g R_s)_{Sep1} + (\gamma_g R_s)_{Sep2} + \dots + (\gamma_g R_s)_{Tank} \right) \quad (18)$$

where ρ_{oST} is the oil density at P_b calculated from ST output, γ_o is the oil specific gravity, γ_g is the gas specific gravity, ρ_w is the water density, B_{oST} is the oil formation volume factor from ST, and R_s is the solution gas from ST. The difference between these two densities is an indication of the possible inconsistency of the laboratory tests. It assumes that the test is fair if the density test results in an error equal to or lower

than 5%. It is important to note that the oil specific gravity is calculated from reported API in the separator test.

Separator test was performed for fifteen samples of our gathered data set. Density of whole fifteen samples is calculated, and then, a graph of the calculated density versus measured density is plotted for all of them (Fig. 27). Accounting this consistency check method, samples A1-F, A5-F, C4-S, C1-I and C7-S have an unreliable separator test. However, it should be noted that the validity of fluid samples could not be rejected by the unreliability of the separator test.

Results and discussion

After implementing the proposed checking procedure (Fig. 5), only 9 out of 28 PVT samples are satisfied all the preliminary and complementary check methods. Twelve samples were rejected and assigned invalid due to the

Table 5 The error of DL material balance

Sample nos.	Avg. error density (%)	Avg. error B_o (%)	Avg. error R_s (%)
A1-S	0.62	1.48	0.38
A2-S	2.69	0.28	0.04
A3-S	4.55	0.48	18.09
A1-F	5.96	2.59	0.04
A2-F	6.93	3.09	0.04
A3-F	6.92	2.91	0.04
A4-F	5.86	2.52	0.04
A5-F	6.24	2.83	0.04
B1-S	2.89	1.34	0.04
B2-S	3.09	1.36	1.53
B3-S	4.50	1.20	4.26
B4-S	3.23	1.48	0.04
B1-A	2.67	1.30	0.04
B2-A	2.97	1.44	0.04
C1-S	2.84	1.10	0.04
C2-S	2.42	0.90	0.04
C3-S	2.45	1.07	0.04
C4-S	2.70	1.24	0.10
C5-S	2.93	1.20	0.23
C6-S	2.79	1.16	0.50
C7-S	2.17	0.96	0.10
C8-S	2.25	0.79	0.74
C1-I	1.36	0.57	0.10
C2-I	1.26	1.38	0.04
C3-I	5.52	2.69	0.04
C4-I	1.14	0.15	38.81
D1-A	3.62	1.79	0.04
D2-A	3.53	1.72	0.04

Bold values are high error ones

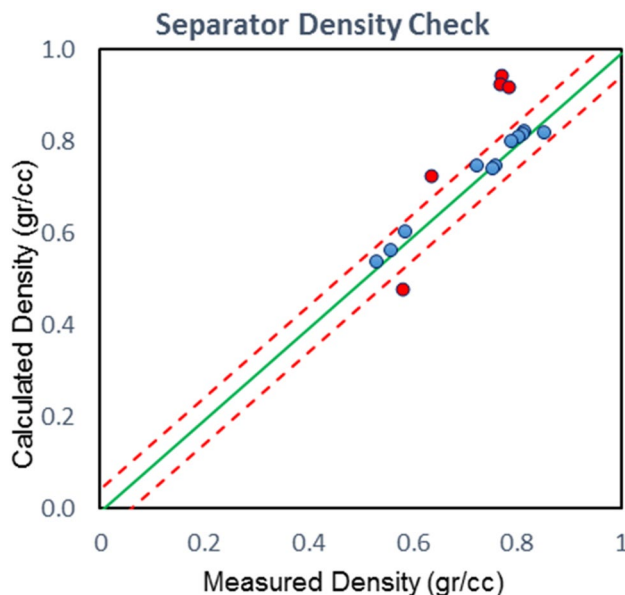


Fig. 27 Density check—separator test

inconsistency of CCE and/or DL test properties. As just one of the 12 rejected samples was detected by preliminary check, then the preliminary check is not adequate to validate whole aspects of consistency of the PVT samples. Although DL and CCE test of all other remaining samples (7 samples) behave adequately accurate, but preliminary check, well stream composition check and/or separator test check of these samples was not completely verified, it is preferred to specify them as the unreliable samples. The summary of the validity condition for PVT samples and the final conclusion of the quality and consistency check are reported in Table 5.

How to select representative fluid sample

After the investigation of the laboratory experiments to ensure accuracy, consistency and validity of the resulting PVT analysis, selecting the representative fluid sample(s) is an important step for reservoir characterization. This step is highly important because the result of PVT experiment(s) would affect initiating dynamic model. Then, acquiring proper representative reservoir fluid sample(s) (which accurately represents real reservoir fluid behavior) is a critical step for dynamic modeling to describe accurately the reservoir behavior during the field production life. Here an applicable procedure is provided for reservoir engineers to try to obtain a representative fluid sample(s). This procedure should be applied step by step as presented below:

Consistency check

As explained before many factors can affect the quality and consistency of the fluid samples. Then, the quality check must be evaluated based on the presented consistency check procedure flowchart. By following the procedure described previously, “invalid” fluid sample(s) should not be utilized as a representative fluid sample, while the selection of representative fluid sample should be continued with “valid” and “unreliable” fluid sample(s).

Well condition check

At this step, condition of well and fluid sampling is reviewed and the representative samples are required to meet all the following conditions. For the PVT samples to be representative of the reservoir fluid, the PVT sample should:

- (a) Be collected at initial stage of reservoir life because fluid composition has not changed much. Whether fluid

sample which was taken from new production wells should not be affected by drainage area of past wells.

- (b) Not be collected from wells with high water cut, high cumulative oil production, high oil rate variation and high gas–oil ratio variation.
- (c) Not be sampled near the water–oil contact and gas–oil contact.
- (d) Be collected from wells with flowing pressure of the above saturation pressure around sampling date.

Comparison of fluid properties

As the last step to select the representative fluid sample, the properties behavior (such as GOR, Bo, density and viscosity) of all consistent samples should be investigated simultaneously. Properties of these samples are compared with each other, and differences between the PVT properties of all accepted samples should be meaningful. The fluid sample(s) with meaningless differentiation is disregarded from representative sample selection procedure (Table 6).

Representative fluid sample selection

Finally, samples which have passed all the above steps could be utilized as the representative of the reservoir fluids at actual reservoir conditions. It is also recommended some complementary issues would be considered to make final decision about representative sample selection as follows:

- (a) Ensuring that DLE and CCE experiments were performed at reservoir temperature (Bagoo et al. 2014).
- (b) Comparison of field GOR and separator test GOR
- (c) Sample(s) with unreliable consistency condition can only be used as the representative sample if no valid sample was available.

Conclusion

This paper suggests and applies a new comprehensive procedure to check the consistency of PVT samples. Reported results for the PVT sample experiments usually consist of some invalid information, which are not detectable without implementation of the consistency check tests. In addition, every PVT experiment is designed to investigate a specific aspect of the flow behavior in petroleum reservoirs. Therefore, it is essential to have a comprehensive algorithm to check consistency of all aspects of the PVT samples behavior. The suggested procedure integrated most previous

Table 6 Summary results of consistency check

Sample nos.	Preliminary check	Well stream composition			CCE test check	DL tests check			Separator test check	Consistency check conclusion
		Maximum error of recombination (%)	Average error of recombination (%)	Graphical trend of Xi/Zi versus Yi/Zi		Y-function	Avg. error density (%)	Avg. error Bo (%)		
A1-S	Accept	3	2	Good	98	0	0.62	1.48	0.38	Invalid
A2-S	Accept	2	1	Good	98	3	2.69	0.28	0.04	Valid
A3-S	Accept	3	2	Good	98	5	4.55	0.48	18.09	Invalid
A1-F	Accept	7	4	Good	96	10	5.96	2.59	0.04	Invalid
A2-F	Accept	3	1	Good	100	1	6.93	3.09	2.01	Invalid
A3-F	Accept	23	15	Good	92	31	6.92	2.91	0.04	Invalid
A4-F	Accept	1	1	Good	98	1	5.86	2.52	0.04	Invalid
A5-F	Accept	2	1	Good	82	3	6.24	2.83	0.04	Invalid
B1-S	Fair	1	0	Good	93	1	2.89	1.34	0.04	Unreliable
B2-S	Accept	3	1	Good	100	4	3.09	1.36	1.53	Valid
B3-S	Accept	7	4	Good	95	10	4.50	1.20	4.26	Invalid
B4-S	Accept	1	1	Good	99	2	3.23	1.48	0.04	Valid
B1-A	Accept	18	5	Good	98	5	2.67	1.30	0.04	Valid
B2-A	Accept	2	1	Good	90	3	2.97	1.44	0.04	Valid
C1-S	Accept	1	1	Good	94	3	2.84	1.10	0.04	Valid
C2-S	Accept	2	1	Good	40	3	2.42	0.90	0.04	Unreliable
C3-S	Accept	2	2	Good	96	4	2.45	1.07	0.04	Valid
C4-S	Accept	6	1	Good	90	3	2.70	1.24	0.10	Unreliable
C5-S	Accept	2	2	Good	96	4	2.93	1.20	0.23	Invalid
C6-S	Accept	1	0	Good	97	1	2.79	1.16	0.50	Valid
C7-S	Accept	1	1	Good	96	1	2.17	0.96	0.10	Invalid
C8-S	Accept	2	1	Good	86	3	2.25	0.79	0.74	Unreliable
C1-I	Fair	2	1	Good	99	4	1.36	0.57	0.10	Unreliable
C2-I	Accept	3	2	Good	82	5	1.26	1.38	0.04	Unreliable
C3-I	Accept	5	3	Good	90	8	5.52	2.69	0.04	Invalid
C4-I	Reject	2	2	Good	100	4	1.14	0.15	38.81	Invalid
D1-A	Accept	24	8	Fair	99	7	3.62	1.79	0.04	Unreliable
D2-A	Accept	3	2	Good	98	5	3.53	1.72	0.04	Valid

Bold values are high error ones

studies to offer most reliable and integrated procedure of consistency check of PVT samples.

It should also be noted the commercial fluid modeling software packages compare the experimental data with equation of state results only based on the mathematical perspectives and tune the fluid parameters to achieve a good match to observed experimental data; however, they do not consider the validity and consistency of the imported parameters (experimental data), thermodynamically. Therefore, we proposed our algorithm and the following conclusions are achieved:

- Implementing the proposed procedure (provided flow-chart) is an applicable and useful technique to detect the validity of laboratory PVT sample.
- The preliminary check is not adequate to validate whole aspects of consistency of the PVT samples.
- Y-function of CCE test behavior, comparison of Y-function of the CCE and DL tests and overall mass balance of DL test have the main role for implementing and assessing complementary consistency check of fluid sample(s).

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