Performance Evaluation of Experimental and Simulated Constant Volume Depletion Tests on Gas Condensate Reservoir Fluid

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Abstract

The performance evaluation of Peng-Robinson Equation of State to satisfactorily simulate constant volume depletion experimental data of gas condensate reservoir fluid system has been presented. Constant volume depletion experiment was performed on a representative gas condensate reservoir fluid sample and the experimental data simulated using tuned Peng-Robinson equation of state on ECLIPSE PVT PRO simulator. Both experimental and simulated results were compared in terms of dew-point pressure, gas density, gas viscosity, gas compressibility factor, and gas formation volume factor. The results show that the simulation results exhibited similar trends as the experimental results. The dew-point pressure from the laboratory data is 4724 psia, while that of the simulation result is 4726.61 psia. This gave an average absolute deviation of 0.2092 %, a satisfactory match to the experimental data. The results presents a quantitative measure of the comparison of simulated and experimental constant volume depletion test, which quantitatively illustrates the capability of equations of state to satisfactorily simulate the constant volume depletion experimental test data – a somewhat contribution to existing body of knowledge.

Introduction

A hydrocarbon reservoir is classified as a gas condensate (retrograde gas condensate) reservoir if the reservoir temperature lies between the critical temperature and the cricondentherm of the reservoir fluids [1]. Due to the exceptional type of hydrocarbon accumulation in this type of reservoir, a unique thermodynamic behaviour of the contained fluid controls the development and productivity of the reservoir [1]. At initial reservoir conditions of pressure and temperature, and above the upper dewpoint curve, the contained fluid exist as a single phase (gas or vapour phase). As reservoir pressure declines at constatnt temperature due to depletion, from the initial reservoir pressure to the upper dew-point pressure, liquid starts to condense. This retrograde condensation behaviour continues as pressure decreases until liquid dropout approaches its maximum volume. Pressure reduction beyond the point of maximum liquid dropout initiates the typical vaporization process, which continues until all the condensed liquid has vaporized as the reservoir pressure approaches the lower dew-point pressure where the reservoir system reverts to single phase (vapour) [1-3].

Representative fluid samples of a given reservoir obtained from a reference depth in the reservoir (bottom hole sample) or at the surface from a separator (recombined oil and gas surface sample) is usually subjected to some standard Pressure-Volume-Temperature (PVT) laboratory tests. These standard experiments provide suitable PVT fluid properties (data) needed to study and understand the behaviour of the fluids in the reservoir, within the wells, in the piping system, and at surface conditions [1-3]. PVT fluid properties are also needed to estimate: well stream composition as a function of time, completion design, possible miscibility effects due to gas injection, surface facility specification, contaminants (Hydrogen Sulfide, Carbondioxide and Nitrogen) concentration in produced fluids [1-3]. Such PVT fluid properties include the oil and gas formation volume factor, fluid compressibility factor, solution gas-oil ratio, fluid density and specific gravity, fluid viscosity and API gravity, saturation pressures, mole percent and molecular weight of components [1-3].

Constant Volume Depletion (CVD) test, generally called depletion study, is one of the standard PVT experiments performed by PVT laboratories to study the phase behaviour of gas condensate samples and volatile oils [1-4]. This standard laboratory test is conducted to simulate reservoir depletion process and compositional variations. Gas condensate PVT properties generated from CVD experiment include vapour density, gas compressibility factor, gas viscosity, and gas formation volume factor (FVF) [1-3].

Evaluation of exploratory wells and the design of production equipments often requires estimate of fluid behaviour prior to obtaining a representative reservoir sample. Also, experimental PVT data are seldom available or in some cases not provided in detail due to the high cost of obtaining representative bottom hole samples, the relatively high cost of performing experimental PVT tests (CVD test), and the uncertainties in experimental PVT data [1,5]. Traditionally, petroleum engineers have used equations of state (EOSs) based PVT models to predict the volumetric and phase behaviour of a wide variety of reservoir fluids (oil and gas) in the absence of experimental PVT data, or as substitute to eliminate the relatively high cost of performing experimental PVT tests (CVD) and the uncertainty in the accuracy of such laboratory results [1,3,6-11]. Igwe and Ujile [5], recommended the use of EOSs as an attractive approach for generating these very important data, and when adequately 'tuned' EOS are capable of simulating the PVT properties of reservoir fluids, and consequently, save significant time and expenses by eliminating the need to perform a complete set of experimental PVT type tests on each and every new reservoir fluid sample.

The main objective of this research work is to present a laboratory CVD test data, simulate the laboratory CVD test data using Peng-Robinson (PR); and then compare the performance of the simulated result with the experimental results in order to determine the performance of EOS when applied to CVD experimental data, in predicting the hydrocarbon phase behaviour in gas condensate reservoirs. In achieving the objective of this study, the following fluid properties are evaluated: dew point pressure, gas density, gas viscosity, gas formation volume factor (FVF) and gas compressibility factor (Z-Factor), respectively, at the reservoir temperature.

This research work employed ECLIPSE PVT PRO computer software and a cubic equation of state (PR 1976). Cubic equations of state are equations, which has the volume term raised to the first, second and third power. Most commonly encountered phase equilibrium calculations, such as vapour-liquid equilibrium, involve only two phases for which a cubic equation is suitable [1].

The PR EOS is one of the most used EOS in the petroleum industry. Peng and Robinson [12] gave examples of the use of the Peng-Robinson (PR) EOS for predicting vapour pressure and volumetric behaviour of pure component and binary mixtures. Harstad et al. [13] reported that the PR equation of state was superior to other equations of state, for predicting vapour-liquid equilibrium in hydrogen and nitrogen containing mixtures. They asserted that it is easy to use and provide accurate relationship between temperature, pressure and phase composition in binary multi-component systems. However, it only requires critical properties, acentric factor and little computer resources to give a good phase equilibrium correlation.

In analysing the effect of equations of state on compositional grading models, Igwe et al. [14] observed that the PR 1976 EOS is the most suitable and performed better than other equations of state when applied to isothermal model, zero thermal diffusion model and the Kemper's model; whereas the PR 1978 EOS simulated the most accurate compositional grading with respect to experimental values when applied to the Haase's thermal diffusion model. Zhao and Olesik [15] reported that the PR EOS is capable of representing the experimental data with an average relative deviation within 6%. More so, Igwe and Ujile [5] simulated laboratory Differential Liberation (DL) test data on HYSYS simulation package using the PR EOS and obtained a satisfactory match to the experimental results evaluated, with an absolute deviation of <1% (0.774%) for the bubble point pressure. They concluded that equations of state, when sufficiently tuned, can simulate the PVT properties of reservoir fluids.

According to Ahmed [2], collecting a representative sample of a gas condensate reservoir, especially a representative bottom hole sample is significantly more knotty than for a conventional black oil reservoir. The main reason for this difficulty is that liquid may dropout from the reservoir fluid during the sampling process, which will result to erroneous composition in the recovered sample due to irregular proportions of both liquid and gas [2]. Surface sampling methods has been recommended as a solution to the subsurface sampling difficulties of gas condensate reservoir systems. However, the long stabilization flow periods required to obtain a representative surface sample is a major concern. Hence, the need to simulate the CVD experiment of gas condensate reservoir fluid using PR equation of state, and consequently, save significant time and expenses by eliminating the need to performing a complete set of experimental PVT tests on each and every new reservoir fluid sample.

Materials and Methods

Materials

  i.   Gas condensate fluid sample
 ii.   PVT cell
iii.   Computer (ECLIPSE PVT PRO Software)

Methods

This research work involved both experimental CVD test of a gas condensate resevoir fluid sample obtained from a well drilled in a sandstone reservoir and simulation of the CVD experimental data based on PR 1976 EOS using ECLIPSE PVT PRO, which is capable of predicting equilibrium constant and performing flash calculation, as well as simulating the required CVD test data. The reservoir characteristics, sampling conditions, and the composition of the recombined separator fluid samples (representative reservoir fluid sample) are presented in tables 1, 2, and 3, respectively.

Table 1 Reservoir Characteristics

Production Zone	Pressure (psia)	Temperature(ºF)
Sandstone	4,832	184

Table 2 Surface Sampling Conditions

Parameter	Value
Choke size	36/64''
Tubing head pressure	3141 psia
Tubing head temperature	85.5ºF
Separator temperature	51.4ºF
Separator CGR	44 bbl/mmscf

Table 3 Composition of Recombined Surface Sample (Gas Condensate)

Component	Mol %
Nitrogen	0.11
Carbon Dioxide	0.30
Hydrogen Sulfide	0.00
Methane	90.72
Ethane	5.61
Propane	2.03
i-Butane	0.36
n-Butane	0.44
i-Pentane	0.14
n-Pentane	0.09
Hexanes	0.11
Heptanes	0.05
Octanes	0.02
Nonanes plus	0.02
Total	**100.00**
Nonanes plus MW (g/mol)	124.9
Nonanes plus Specific gravity (Air = 1)	0.63

Experimental Procedure

In accordance with the experimental procedure for CVD test presented by Ahmed [1], a measured amount of the representative reservoir fluid sample, with known overall initial composition of initial compressibility (Z_i), was charged into a visual PVT cell at dewpoint pressure (4724 psia) and constant reservoir temperature (184ºF). The initial volume of the fluid sample in the cell, at saturation pressure (dewpoint pressure) was taken as the reference volume (V_i). The cell pressure was then reduced to below dewpoint by withdrawing mercury from the cell. This is critical to simulating the hydrocarbon phase behaviour and the reservoir depletion performance. The resulting retrograde liquid volume (V_L) and gas (vapour phase) volume (V_g), at equilibrium cell condition, were then measured and recorded. Mercury is subsequently reinjected into the PVT cell at constant pressure, resulting to simultaneous removal of an equal volume of gas untill the initial volume (V_i) is reached. The mercury reinjection process simulates a reservoir producing only gas with immobile retrograde liquid [1]. The volume and composition of the discharged gas is measured and determined, respectively. The compressiblity factor of the discharged gas is determined from relevant correlation. The two-phase comprssiblity factor is also calculated. The volume of produced gas as a percentage of gas initially in-place is also determined. The laboratory test procedure is repeated severally until a minimum test pressure is reached. Thereafter, the remaining quantity and

composition of the gas and retrograde liquid in the PVT cell are determined.

Simulation Approach and Model Equations

Figure 1 illustrates the flow diagram and steps followed in simulating experimental CVD data. The CVD experimental data was simulated based on PR 1976 EOS using ECLIPSE PVT PRO computer simulator to estimate the volumetric properties and phase behaviour description of the reservoir fluid sample. According to Ahmed [1], it is imperative to apply an EOS that is able to attain an adequate match between EOS result and all experimental PVT laboratory data.

The two-constant equation of state proposed by Peng and Robinson [16] is thus:

$$P = \frac{RT}{v-b} - \frac{a\alpha}{v(v+b)+b(v-b)} \tag{1}$$

Where
P = Pressure
V = Volume
a = Molecular attractive force parameter
b = effective molecular volume
α = Temperature-dependent parameter
R = Universal gas constant

Peng and Robinson adopted Soave's approach for calculating temperature dependent parameter, as:

$$\alpha = [1 + m(1 - \sqrt{T_r})]^2 \tag{2}$$
$$T_r = \frac{T}{T_c}$$
$$m = 0.37646 + 1.54227\omega - 0.26992\omega^2$$

Where;
T_r = Pseudo-reduced temperature
ω = Acentric factor
For ω greater than 0.49,
$m = 0.37646 + 1.48503\omega - 0.1644\omega^2 + 0.016666\omega^3$.

At critical point:

$$a(T_c) = 0.45724\frac{R^2 T_c^2}{P_c} = a(T) \tag{3}$$
$$b(T_c) = 0.07780\frac{RT_c}{P_c} = b(T) \tag{4}$$

And,

$$Z_c = 0.307.$$

However, at temperatures other than the critical temperature, the expression for the temperature-dependent parameter is generalized as:

$$a(T) = a(T_c).\alpha(T_r,\omega)$$

Equation (1) can be rewritten in terms of compressibility factor as:

$$Z^3 - (1-B)Z^2 + (A - 3B^2 - 2B)Z - (AB - B^2 - B^3) = 0 \tag{5}$$

Where
$Z = \frac{pv}{RT}$ = Compressibility factor.
$A = \frac{aP}{R^2 T^2}$
And,
$B = \frac{bP}{RT}$

For pure component,

$A = \frac{a\alpha P}{R^2 T^2}$

$B = \frac{bP}{RT}$

For mixtures,

$A = \frac{(a\alpha)_m P}{R^2 T^2}$

And,

$B = \frac{b_m P}{RT}$

Where

$(a\alpha)_m = \sum_i . \sum_j [x_i x_j \sqrt{a_i a_j \alpha_i \alpha_j} (1 - k_i)]^2$

$b_m = \sum_i [x_i b_i]$

K_i = Binary interaction coefficient (for hydrocarbon systems, $K_i = 0$)

The performances of the experimental and simulated CVD test results were evaluated statistically based on percentage average absolute deviation (% AAD) using (6) The lower the calculated % AAD, the more suitable the PR EOS simulation results.

$$\% AAD = 100 * ABS \left[\frac{\sum_{i=1}^{N} \left((Sim - Exp)/Exp \right)}{N} \right]$$

(6)

Where; Sim is the simulated value of CVD property with respect to pressure, Exp is the experimental value of CVD Property with respect to pressure, and N is the number of sample points (observations).
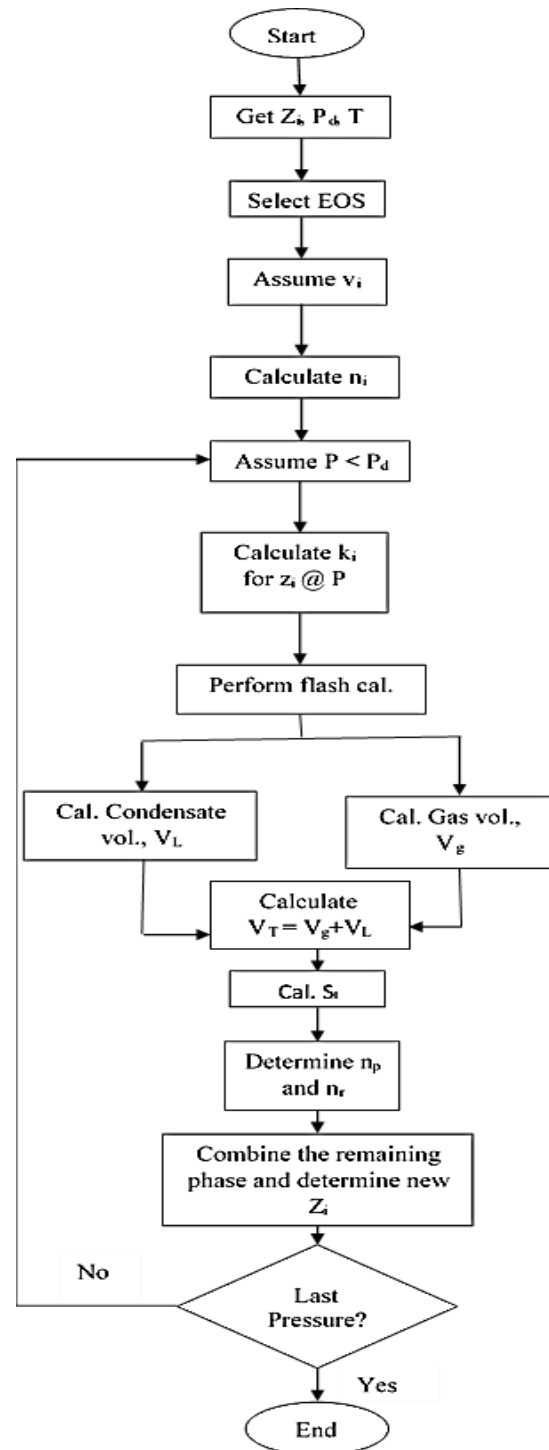

Figure 1 CVD Simulation Flow Chart (Modified from Ahmed [1])

From figure 1:

$Z_i = \frac{P_d V_i}{n_i RT}$ (7)

And,

$n_i = \frac{V_i P_d}{Z_d RT}$ (8)

Also,

$V_g = \frac{(n_v)_i Z_v RT}{P}$ (9)

$V_l = \frac{(n_l)_i Z_l RT}{p}$ (10)

$n_p = \frac{P(V_g)_{sc}}{RT_{sc}}$ (11)

$$n_r = (n_v)_i - n_p \qquad (12)$$

$$S_l = \left(\frac{V_l}{V_i}\right) * 100 \qquad (13)$$

Where

P_d = Dew-point pressure
V_i = Initial gas volume
n_i = Initial number of moles of gas
R = Universal gas constant
T = Temperature
P = Pressure
Z_d = Compressibility factor at dew-point
V_g = Gas volume
V_l = Volume of the retrograde liquid
S_l = Retrograde liquid saturation
V_{gsc} = Volume of gas produced (measured at standard condition
n_p = Moles of gas produced
n_r = Moles of fluid remaining in the cell
Z_v, Z_l = Vapour and liquid phase compressibility
T_{sc} = Standard temperature.

Results and Discussion

The performance evaluation of the experimental and simulated CVD data using PR EOS, in terms of gas density, gas viscosity, gas Z-factor and gas FVF, are presented graphically. These graphical results illustrates the comparison of the experimental and simulated CVD test results, respectively. Figure 2 shows the comparison of the experimental and simulated gas density with respect to pressure, Figure 3 compared the experimental and simulated gas viscosity with respect to pressure. The comparison of the experimental and simulated gas Z-factor with respect to pressure is illustrated in Figure 4, and Figure 5 illustrates the similarity between the experimental and simulated gas FVF with respect to pressure. The simulated results exhibited similar trends with the experimental results. The results show that PR EOS simulated the CVD test data and closely approximated (closely matched) the experimental data in terms of the PVT properties evaluated.

By relying on existing methodology, this study has made somewhat contribution to the existing body of knowledge by presenting quantitative measure of the comparison of simulated and experimental constant volume depletion test, which quantitatively illustrates the capability of EOSs to satisfactorily simulate the constant volume depletion experimental test data.
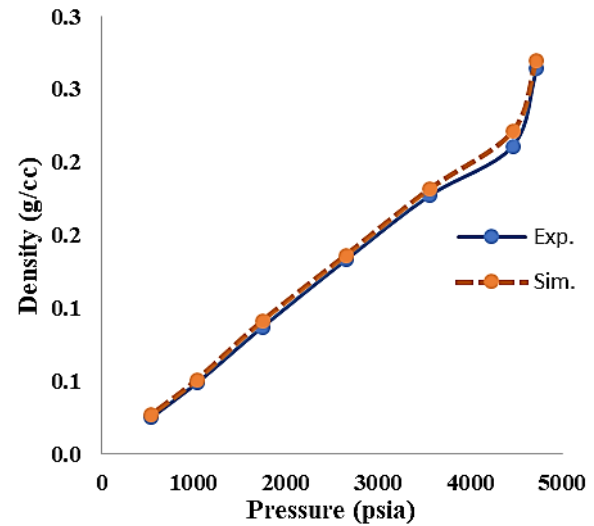

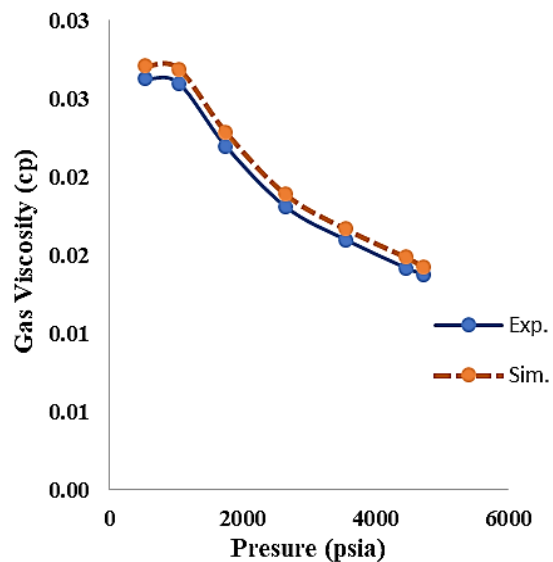**Figure 2** Graph of Gas Density against Pressure

Figure 3 Graph of Gas Viscosity against Pressure

The % AAD of the simulated CVD data of the reservoir fluid (gas condensate) from the experimental results are shown in Table 4. Generally, the % AAD of the simulation results with respect to the experimental results is less than 4 % for all the PVT properties evaluated, which suggest a satisfactory match with the experimental data. The dew point pressure from the experiment and simulation are 4724 psia and 4726.61 psia, respectively, which indicated an average absolute deviation of 0.2092 %. The dewpoint pressure is critical to the prediction of phase behaviour of gas condensate reservoir system.
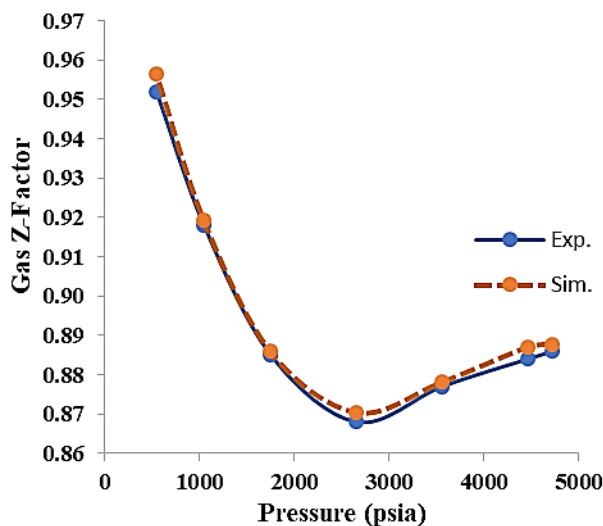
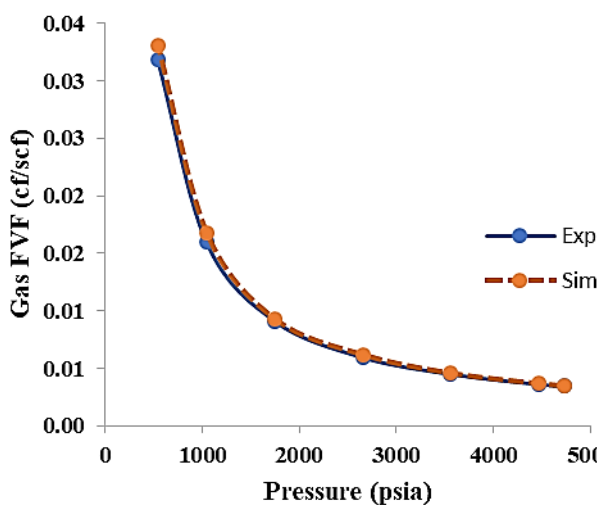**Figure 4** Graph of Z-Factor against Pressure

Figure 5 Graph of Gas FVF against Pressure

Table 4 %AAD of Simulated CVD Data

Parameter	% Abs. Deviation
Pressure	0.2092
Gas Density	3.6720
Gas Viscosity	3.9917
Z-Factor	0.2390
Gas FVF	3.2626

Conclusion

The performance of the experimental and simulated CVD data using PR EOS on ECLIPSE PVT PRO simulator, in terms of gas density, gas viscosity, gas Z-factor and gas FVF, has been evaluated. The simulation results indicated satisfactory match with experimental data. The dewpoint pressure from the experiment and simulation are 4724 psia and 4726.61 psia, respectively, which indicated a % AAD of 0.2092 %. Therefore, PR 1976 EOS on ELIPSE PVT PRO can satisfactorily simulate CVD experimental data of gas condensate reservoir fluid, thereby, minimize the need to performing rigorous and expensive experimental CVD tests on every new reservoir fluid samples. The results presents a quantitative illustration of the capability of equations of state to satisfactorily simulate the constant volume depletion experimental test data – a somewhat contribution to existing body of knowledge.

Abbreviations

CVD: Constant Volume Depletion
PVT: Pressure Volume Temperature
EOS: Equation of State
PR: Peng-Robinson
SRK: Soave-Redlich-Kwong
FVF: Formation Volume Factor
Z-Factor: Compressibility or Deviation Factor
AAD: Average Absolute Deviation
CGR: Condensate Gas Ratio
MW: Molecular Weight
API: American Petroleum Institute

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Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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