Modified Gas Condensate Down-hole PVT Property Correlations

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ABSTRACT

In this investigation some widely used correlations for gas-condensate PVT properties were subjected to validation test, and were found to be inadequate for prediction of condensate down-hole PVT properties below the saturation pressure. The error margins associated with the use of some of these correlations for predicting condensate compressibility factor, density and viscosity were at levels unacceptable for engineering calculations. The new correlations include Eqs. (1), (4) and (22) for condensate compressibility factor, density and viscosity respectively. The modified correlations were tested and validated against large experimental measured database. The results showed a superior performance of the modified to the existing correlations in comparison with measured database. The novelty of this investigation is the demystification of the perplexing fluid PVT properties phase behaviour which is a barrier to accurate well deliverability modelling in gas condensate reservoirs.

1. INTRODUCTION

Accurate well deliverability prediction depends largely on accurate estimation of fluid PVT properties used as they govern reservoir productivity especially in gas condensate reservoir where compositional variations and phase changes arising from retrograde behaviour complicates fluid property modelling. The scarcity of measured PVT properties for reservoir simulation, production system design, analysis and optimisation accounts for recent popularity of use of correlations. More so, laboratory method and Equation of state (EOS) are tedious, expensive, time consuming and sometimes it is impossible to recreate exact reservoir conditions in the laboratory, making the use of correlations more attractive. The new correlations developed will serve as an alternative tool for designers, operators and service providers as a fit for purpose correlations for accurate well deliverability forecast below the saturation pressure in gas-condensate reservoirs. PVT correlations in-spite of its generic limitation as empirical model adds value to experimental data. This is because the experimental data required are only the test, development and the validation data. Accurate correlations developed and validated are capable of predicting the required down-hole properties at other desired reservoir conditions where experimental measurements may be difficult or impossible, thereby reducing the number of experiments and the associated costs.

The difference between compositional and black oil modelling in reservoir simulation is the PVT properties. The black oil model assumption is not usually valid for production of gas-condensate reservoir below the dew point pressure. The preference for use of black oil model approach in modelling well deliverability in gas-condensate reservoir instead of use of cumbersome and time consuming fine grid numerical simulation was the motivation for this investigation. The methods used for development of the modified correlations were specifically chosen to correct for compositional variation in black oil model approach to make it valid for condensate well deliverability prediction, which conceptually requires compositional approach. Several scholars [1][2][3][4] involved in the use of black oil approach in modelling well performance in gas–condensate reservoir is an indication of the popularity this approach.

When representative condensate sample properties are not available, the use of correlations is imperative, [5]. The ranges of PVT data currently encountered in the industry at higher depths were not used in development of existing correlations for the three key gas-condensate properties considered in this work. This may be part of the reasons for poor performance of the available correlations and the current effort has attempted to bridge the gap by proposing modified correlations that have been validated.

The new correlations were based on a wide data-base of measured experimental results whose maximum compositions are given in appendix B for compressibility factor, density and viscosity sourced from Sutton, [6, 7], Elsharkawy, [8, 9, 10, 11], and other published data bases. These sources are fully credited in this report. The new correlations were derived from existing models and it is important to briefly review these previous work to date.

2. MILESTONES IN PREDICTION OF HYDROCARBON PVT PROPERTIES

The main approaches in predicting fluid properties include;

(i) Compositional or Gas Gravity based

(ii) Corresponding States

(iii) Equations of State Method:

These methods have been employed as a single approach or combination for prediction of PVT properties. The present study combined the compositional, gas gravity with corresponding state approach. These approaches are highlighted by the contributions of many Scholars as briefly discussed below.

Numerous studies on prediction of natural gas condensate PVT properties exist in the literature. A major milestone in prediction of natural gas PVT properties includes the Katz and Standing, [12] Charts for determination of compressibility factors of reservoir fluid. The chart is still the basis for the prediction of compressibility factor by many correlations presently in the Oil and Gas industry though in digital forms. The digital forms of the Katz Chart were facilitated by several scholars, (Hall and Yarborough [13]; Dranchuk Abou Kisser, (DAK) [14][15]. These were followed by evaluation work to determine the accuracy of the developed digital correlation for Katz Chart. The magnitude of errors associated with the use of correlations for prediction compressibility factor were highlighted in Abd-el Fattah’s work in which he provide guidelines for range of applicability of correlations for prediction of compressibility factor. Most of the correlations involved the use of some form of equation of state (EOS) involving trial and error method of solution and the accuracy of these methods is within 0.5%, but for region where reduced temperature, Tr=1 and reduced pressure, Pr>1 very large errors have been reported (Kumar, 1987Further developments on improving the performance of compressibility factor correlations followed. Witchet and Aziz, [16] proposed a correlation factor to extend the applicability of the Standing and Katz compressibility factor chart to sour gases. The inaccurate prediction of PVT properties of reservoir fluids arising from non-hydrocarbon components stimulated further investigation into ways of improving the performance prediction of down-hole PVT properties, Sutton, [6, 7] Elsharkawy, [8, 9, 10, 11].

The problems with most of the available correlations applied for natural gas- condensate PVT properties prediction were developed for sweet and dry gases. The applications of these correlations to natural gas-condensate reservoir fluid property predictions are not only limited by geographical locations of the reservoir as a general problem with empirical correlations, but also to a range of reservoir temperatures and pressures. Though some of the available correlations for natural gases have been modified, further modifications are still needed to cater for liquid condensate flow below the saturation pressure. Available correlations are mostly for flow of condensate above the dew/saturation pressure. Accurate PVT properties for flow of condensate below the saturation pressure which is the main subject of this work may provide insight to the much needed technology towards remediation of condensate banking and production of the lost condensate to the formation. The compressibility factor correlation developed by Standing and Katz up to the digitized versions by Dranchuk and Abou Kassem and others have all been specific to sweet and dry gases. This led Londono [17] to suggest that the attempts for prediction of compressibility factors should be extended to gas-condensate systems.

The major focus of numerous works has been on the improvement of the prediction of the pseudo critical properties of gas mixtures including heptanes plus fractions using different mixing rules and accounting for the non-hydrocarbon contents as critical input parameters in forecasting the compressibility factors. For a soft-ware driven industry such as Oil and Gas, there is no better time for reviewing and updating outdated correlations in most of our widely used simulators than now.

3. COMPRESSIBILITY FACTOR PROPOSED

Compressibility factor is one of the critical parameters in inflow performance relationship in both vertical and horizontal well, therefore a compulsory variable in prediction of well deliverability. On testing the performance of available compressibility factor correlations, Elsharkawy's had a lower error margin though followed closely by Sutton. The lowest absolute average error margin and the compact method of calculation of compressibility factor were the main criteria used for selection of Elsharkawy's correlation for modification. The various mixing rule correlations available in literature represents the various efforts by different scholars to extend the validity of Standing-Katz chart, developed for sweet dry gas to heavier natural gas-mixture including gas-condensate. The modification was to specifically account for condensate PVT properties below the dew-point pressure. To get a better fit of digitised standing-Katz chart to measured condensate compressibility factor using modified Elsharkwy mixing rule, a multiple non-linear regression of Elsharkawy parameter was done using statistical software, MINITAB on large database of published gas-condensate measured compressibility factor. This resulted in the following new modified expressions for condensate compressibility factor given by Eq. 1;

$$Z_m = \frac{Z_{DAK}}{2} + 0.36015 \qquad (1)$$

Where;

$$Z_{DAK} = \left[A_1 + \frac{A_2}{T_{pr}} + \frac{A_3}{T_{pr}^3} + \frac{A_4}{T_{pr}^4} + \frac{A_5}{T_{pr}^5}\right]\rho r + \left[A_6 + \frac{A_7}{T_{pr}} + \frac{A_8}{T_{pr}^2}\right]\rho_r^2$$

$$-A_9\left[\frac{A_7}{T_{pr}} + \frac{A_8}{T_{pr}^2}\right]\rho_{pr}^5 + A_{10}\left(1 + A_{11}\rho_r^2\right)\frac{\rho_r^2}{T_{pr}^3} 3\exp\left[-A_{11}\rho_r^2\right] + 1 \qquad (2)$$

$$\rho_r = \frac{0.27P_{pr}}{ZT_{pr}} \qquad (3)$$

Where $\boldsymbol{A}_1 = 0.3265$, $\boldsymbol{A}_2 = -1.0700$, $\boldsymbol{A}_3 = -0.5339$, $\boldsymbol{A}_4 = 0.01569$, $\boldsymbol{A}_5 = -0.05165$, $\boldsymbol{A}_6 = 0.5475$, $\boldsymbol{A}_7 = -0.7361$, $\boldsymbol{A}_8 = 0.1844$, $\boldsymbol{A}_9 = 0.1056$, $\boldsymbol{A}_{10} = 0.6134$, $\boldsymbol{A}_{11} = 0.7210$.

Calculation steps for Eq. (1) to(4) are defined in appendix A.

The modified Z- factor, Zm was used to predict condensate density from the equation (4);

$$\rho_c = \frac{PM_a}{Z_m RT} \qquad (4)$$

The model was validated with published measured database. It gave superior performance on comparison with some widely used correlation in the industry as shown in figures 1 and 2, tables 1 and 2

4. EVALUATION OF VISCOSITY CORRELATIONS;

The most widely used correlations for viscosity prediction in gas and gas-condensate reservoirs were reviewed with view to evaluate performance as first step to developing more accurate methods for condensate viscosity prediction for application to modelling well deliverability below dew point pressure in gas-condensate reservoirs. The correlations evaluated in the study include;

(i) Lee-Gonzalez-Eakin (LGE) [19]
(ii) Sutton, [20]
(iii) Elsharkawy, [11]
(iv) Carr-Kobayashi-Burrows (1959) as modified by Dempsey (CKB-D) (1965)

4.1 Lee-Gonzalez-Eakin [19] (LGE)

The theoretical concept of this model can be mathematically expressed as follows;

$$\mu_g = 10^{-4} K \times \exp\left[X\left(\frac{\rho_g}{62.4}\right)^Y\right] \qquad (5)$$

Where,

$$K = \frac{(9.379 + 0.016M_a)T^{1.5}}{209.2 + 19.26M_a + T} \quad (6)$$

$$X = 3.448 + \frac{986.4}{T} + 0.01009M_a \quad (7)$$

$$Y = 2.4 - 0.2X \quad (8)$$

Many viscosity correlations in petroleum reservoir engineering are derived from Lee-Gonzalez's model and have always been acknowledged for this significant contribution.

4.2 Sutton, (2007) viscosity correlation

A modified LGE correlation expressed as follows;

$$\mu_{gsc}\xi = 10^{-4}\begin{bmatrix} 0.807T_{pr}^{\;0.618} \\ -0.357\exp(-0.449T_{pr}) \\ +0.34\exp(-4.058T_{pr}) + 0.018 \end{bmatrix} \quad (9)$$

Where, viscosity parameter

$$\xi = 0.9490\left(\frac{T_{pc}}{M^3 P_{pc}^{\;4}}\right)^{1/6} \quad (10)$$

$$\mu_g = \mu_{gsc} \times \exp\left[X\left(\frac{\rho_g}{62.4}\right)^Y\right] \quad (11)$$

Where,

$$X = 3.47 + \frac{1588}{T} + 0.0009M_a \quad (12)$$

$$Y = 1.66378 - 0.04679X \quad (13)$$

4.3. Elsharkawy, (2006) viscosity correlation

This is an extension of the LGE viscosity correlation to correct for the presence of non-hydrocarbons and the C_{7+} content present in heavy reservoir gases and condensates.

The original form of Elsharkawy model is

$$\mu_g = 10^{-4}K \times \exp\left[X\left(\frac{\rho_g}{62.4}\right)^Y\right] \quad (14)$$

Where,

$$K = \frac{(9.379 + 0.016M_a)T^{1.5}}{209.2 + 19.26M_a + T} \quad (15)$$

$$X = 3.448 + \frac{986.4}{T} + 0.01009M_a \quad (16)$$

$$Y = 2.4 - 0.2X \quad (17)$$

And corrected for non-hydrocarbon and the heptanes plus fraction as follows;

$$\Delta\mu_{H2S} = y_{H2S}\left(-3.2268\times10^{-3}\log\gamma_g + 2.1479\times10^{-3}\right) \quad (18)$$

$$\Delta\mu_{CO2} = y_{CO2}\left(6.4366\times10^{-3}\log\gamma_g + 6.7255\times10^{-3}\right) \quad (19)$$

$$\Delta\mu_{C7+} = y_{C7+}\left(-3.2875\times10^{-1}\log\gamma_g + 1.2885\times10^{-1}\right) \quad (20)$$

Giving the corrected viscosity correlation as;

$$(\mu_c)_{corrected} = \mu_c + \Delta\mu_{H2S} + \Delta\mu_{CO2} + \Delta\mu_{C7+} \quad (21)$$

Where $\mu_g = \mu_c$

4.4 New viscosity correlation (study)

The margin of errors associated with the use of existing gas-condensate viscosity correlations were found to be high on performance evaluation and needed upgrading for meaningful engineering calculations.

Elsharkawy [11] Viscosity correlation gave the least average absolute error compared to other widely used viscosity correlations and had a better versatility of application to non hydrocarbon impurities and heptanes plus fraction. Based on the above criteria was selected for further modification to improve on the accuracy of prediction of gas-condensate viscosity which was the main objective of this part of the study. Viscosity is very significant parameter in predicting the productivity of any class of petroleum reservoir. The sensitivity of this parameter to temperature, composition and pressure is high, and any error in prediction could lead to misleading production forecast.

The method applied for developing the new prediction procedure for gas condensate viscosity below the saturation pressure included the following steps;

(i) Created a compositional database for published measured gas condensate viscosity at different reservoir pressure and temperature condition of world-wide sample representation.

(ii) Compiled and evaluated performance of different available viscosity correlations against the created database.

(iii) Used average absolute error criteria for model selection for further development for lack of good match of any of the tested to measured values in the database.

(iv) Modification of the Elsharkawy [11] Viscosity model that gave the least absolute average error margin on evaluation using part of the database as development and validation data, ensuring that development data was different from validation data to eliminate the likely error.

(v) Validated the modified model and compared the performance with the best available correlation based on the evaluated performance of the existing models as shown in figure 3 below.

Measured condensate viscosity database from CVD test was used to derive new coefficient for the original Elsharkawy viscosity model using non-linear regression statistical techniques. The above technique resulted in the following new modified Elsharkawy, (Study) viscosity correlation;

$$\mu_c = K^{-2.5}\exp(176 + 0.062\rho Y - 15.5X) \quad (22)$$

Where K, Y and X are same as in equations (15 – 17) and the corrections for the non hydrocarbon contents and heptanes plus fraction remains same as defined in equations (18 – 21).

5. RESULTS AND DISCUSSIONS

The correlations in each case in figures 1 and 2 were validated with measured experimental database to test for accuracy, physical trend consistency. Figures 1 and 2 suggest a good performance of the new correlations as the trend follows a good physical behaviour expected theoretically for compressibility factor and density as a function of pressure under isothermal reservoir conditions. The absolute average errors for the new correlations of this study as shown in tables 1 and 2 were less than that for the existing correlations, suggesting a better performance. The modified (study) correlations showed a better agreement with the measured experimental database in figures 1 and 2. The improvement in the correlation could translate to accurate well deliverability prediction in gas condensate reservoirs as the properties correlated are critical variables in both vertical and horizontal well models that predict well deliverability. The existing viscosity correlations in figure 3 show absolute average errors far in excess of the range acceptable for technical calculations. This may be as result of the data which the correlations were derived. Present reservoir production scenarios are experiencing a harsher offshore environment (deeper water, high temperature and pressure) and these are reflected on the new database for the modified correlation. Figures 4 went further to define error as under prediction of the viscosity values using the existing correlations, Elsharkawy, [11] and Sutton, [7]. These average errors in figure 4 could translate to unreliable production forecast figures that could have serious investment implications. The accuracy of fluid characterisation achieved by the modified correlation is important in production optimization, facility and field development plans.

6. CONCLUSIONS

Compressibility factor, density and viscosity correlations for prediction of Condensate PVT properties below the dew point pressure have been developed. They were developed from Elsharkawy correlations which are more applicable for condensate flow above the dew point. The new models are Eqs. (1), (4) and (22) for condensate compressibility factor, density and viscosity respectively.

On validation, the new correlations have demonstrated superior performance over the existing models. These correlations are indispensable in modelling well deliverability below the dew point pressure in gas-condensate reservoirs. Condensate below the saturation pressure has been reported to have perplexing flow behaviour resulting from great variability in composition from reservoir thermodynamics. The prediction of the key PVT properties becomes difficult and complex as result. This makes accurate prediction of well deliverability at those reservoir conditions unreliable, and optimization of such reservoir becomes impossible except with the use of fine grid numerical simulation which is expensive. Some insights have been given on how to solve the above problems in another investigation not reported here, by application of developed correlations on semi analytical horizontal well models for prediction of well deliverability. The contribution of this work is much with respect to making the use of semi analytical models for accurate well deliverability prediction, production optimisation of gas condensate reservoirs and reduced cost of experimentation as the correlations can be alternatively used.

The novelty of this investigation is the demystification of the perplexing fluid PVT properties phase behaviour which is a barrier to accurate well deliverability modelling in gas condensate reservoirs.

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8. NOMENCLATURE

E_j , E_k, F_j	SSBV Mixing Rule parameters
$\alpha_0 - \alpha_{15}$	Correlation Constants
$\beta_0 - \beta_7$	Correlation Constants
$A_1 - A_{11}$	DAK and DPR correlations constants
X ,Y	Viscosity Correlation parameter
y_{C7+}	Mole fraction of the C_{7+} plus fraction
y_i	Mole fraction of the 'i' component
Z	Gas Compressibility factor
β	Turbulence Factor
h	Reservoir Thickness (ft)
h_p	Perforated Interval (ft)
J	Mixing Rule parameters
J'	Corrected J parameter for Mixing Rules
k	Permeability (md)
K	Viscosity Correlation parameters
K'	Corrected K parameter for Mixing Rules
P_{sc}	Pressure at standard conditions (psi)
P_R	Reservoir Pressure (psi)
P_{wf}	Bottom hole flowing pressure (psi)
Q	Gas flow rate (scf/day)
r_e	Drainage Radius (ft)
r_w	Wellbore Radius (ft)
R	Universal gas constant = 10.73 psia ft^3/lb-mole °R
S	Skin Factor
V	Volume (ft^3)
ε	Wichert – Aziz Correction factor

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Table 1 Percentage average absolute error margins for different Z-factor correlations

Reservior pressure(psia)	Sutton, 2006 % Error	Elsharkawy % Error	Study % error
4190	-11.30	-19.33	-2.64
3600	-19.80	5.29	7.96
3000	-22.44	-7.47	1.19
2400	-22.83	-16.37	-2.70
1800	-20.43	-18.28	-1.91
1200	-17.20	-18.44	0.22
700	-14.36	-19.11	1.93
AAE	**18.34**	**14.90**	**2.65**

AAE - Average Absolute Error

Table 2 Predicted gas-condensate density using modified Elsharkawy's compressibility factor correlation approach and AAE

Reservoir Pressures (psi)	Experiment Density(lb/f	Elsharkawy Density(lb/f	Modified Mc Density(lb/f	Elsharkawy % Error	Study) % Error
4190	27.34	21.06	25.46	22.99	6.88
3600	19.52	21.03	19.04	-7.76	2.47
3000	15.06	14.33	14.5	4.86	3.74
2400	11.3	9.94	10.91	12.05	3.43
1800	7.95	6.86	7.88	13.72	0.88
1200	5.06	4.35	5.2	13.97	-2.85
700	2.91	2.49	3.1	14.3	-6.67
		Average Absolute Error		12.81	3.85

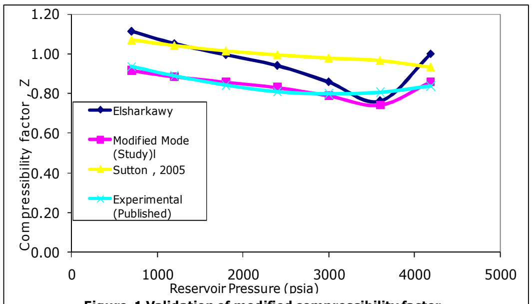

Figure 1 Validation of modified compressibility factor

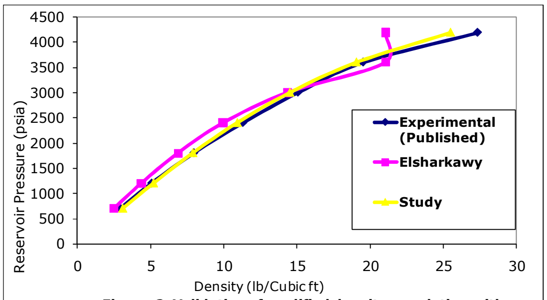

Figure 2 Validation of modified density correlation with experimental data

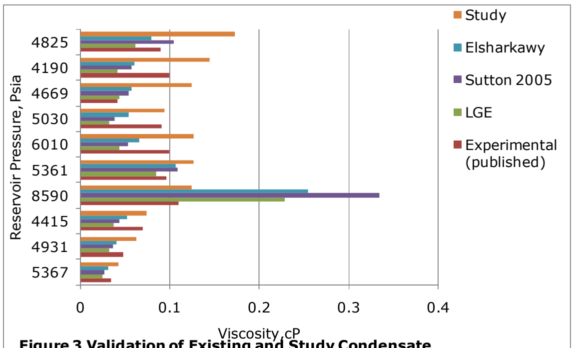

Figure 3 Validation of Existing and Study Condensate Viscosity Correlations with Published Experimental Data

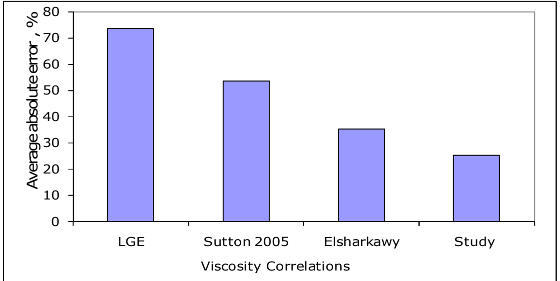

Figure 4 Absolute average error comparison for gas-condensate viscosity correlations

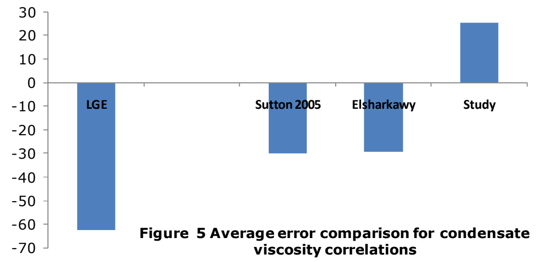

Figure 5 Average error comparison for condensate viscosity correlations

10. APPENDIX A

Summary of Calculation steps;

Compressibility factor;

The calculation steps are same with Elsharkawy, 2006 except the difference in the new coefficients got from regression analysis.

The governing equations for the mixing rule include;

$$J_{\inf} = \alpha_0 + \left[\alpha_1\left(y_i\frac{T_{ci}}{P_{ci}}\right)_{H2S}\right] + \left[\alpha_2\left(y_i\frac{T_{ci}}{P_{ci}}\right)_{CO2}\right] + \left[\alpha_3\left(y_i\frac{T_{ci}}{P_{ci}}\right)_{N2}\right] + \left[\alpha_4\sum\left(y_i\frac{T_{ci}}{P_{ci}}\right)_{C1-C6}\right] + \alpha_5\left(y_iM\right)_{C7+} \quad (23)$$

$$K_{\inf} = \beta_0 + \left[\beta_1\left(y_i\frac{T_{ci}}{\sqrt{P_{ci}}}\right)_{H2S}\right] + \left[\beta_2\left(y_i\frac{T_{ci}}{\sqrt{P_{ci}}}\right)_{CO2}\right] + \left[\beta_3\left(y_i\frac{T_{ci}}{\sqrt{P_{ci}}}\right)_{N2}\right] + \left[\beta_4\sum\left(y_i\frac{T_{ci}}{\sqrt{P_{ci}}}\right)_{C1-C6}\right] + \beta_5\left(y_iM\right)_{C7+} \quad (24)$$

Where;

$\alpha_0 = 0.036983$, $\alpha_1 = 1.043902$, $\alpha_2 = 0.894942$

$\alpha_3 = 0.792231$, $\alpha_4 = 0.882295$, $\alpha_5 = 0.018637$

$\beta_0 = -0.7765003$, $\beta_1 = 1.0695317$, $\beta_2 = 0.985$

$\beta_3 = 0.8617653$, $\beta_4 = 1.0127054$, $\beta_5 = 0.4014$

To properly define all the parameters required in calculating the pseudo-critical properties, the mixing rule of Stewart-Burkhardt-Voo was adopted, defining Parameter J as follows;

$$J = \left(\frac{1}{3}\right)\left[\sum yi\left(\frac{T_c}{P_c}\right)_i\right] + \left(\frac{2}{3}\right)\left[\sum yi\left(\frac{T_c}{P_c}\right)_i^{0.5}\right]^2 \quad (25)$$

$$K = \sum\left[yi\left(\frac{T_c}{P_c^{0.5}}\right)_i\right] \quad (26)$$

From a given composition, the parameters $J_{\inf}, K_{\inf}$ could be calculated from equations 23 and 24 and the pseudo-critical properties were calculated using the correlations below;

$$\boldsymbol{T_{pc}} = \frac{\boldsymbol{K_{\inf}^2}}{\boldsymbol{J}} \quad (27)$$

$$\boldsymbol{P_{pc}} = \frac{\boldsymbol{T_{pc}}}{\boldsymbol{J_{\inf}}} \quad (28)$$

The pseudo reduced properties were calculated from the two correlations below and applied to calculation of compressibility factor from DAK correlations, equation 2 for fitting Standing and Katz compressibility chart.

$$\boldsymbol{P_{pr}} = \frac{\boldsymbol{P}}{\boldsymbol{P_{pc}}} \quad (29)$$

$$\boldsymbol{T_{pr}} = \frac{\boldsymbol{T}}{\boldsymbol{T_{pc}}} \quad (30)$$

Appendix B

Table B1 Maximum value of Condensate PVT data used in study

Pressure (psia)	10000
Temperature (^{0}F)	500
Gas gravity	30
Gravity (^{o}API)	70
H2S	0.745 (mole fractions)
CO2	0.9
N2	0.25
C_1	0.98
C_2	0.30
C_3	0.13
i-C_4	0.026
n-C_4	0.052
i-C_5	0.03
n-C_5	0.02
C_6	0.05
C_{7+}	0.17