



EOS'S CALCULATIONS OF VOLUMETRIC AND TRANSPORT PROPERTIES OF SOUR GASES AND GAS CONDENSATES

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ABSTRACT

Compressibility, density and viscosity of natural gases are necessary in most petroleum engineering calculations. Some of these calculations are gas metering, gas compression, design of processing units, and design of pipeline and surface facilities. Properties of natural gases are also important in calculation of gas flow rate through reservoir rock, material balance calculations and evaluation of gas reserves. Usually the gas properties are measured in laboratory. Occasionally, experimental data become unavailable and estimated from equations of state or empirical correlations.

This paper presents the results of using various equations of state, corresponding state methods, and correlations to predict the volumetric and transport properties of sour gases and gas condensates. Capabilities of PR-EOS, SRK-EOS, and PT-EOS to predict gas compressibility and density of 2100 gas samples under various schemes of binary interaction number are thoroughly investigated. This study also reports a comparison between modified PR-EOS and other methods to estimate the viscosity of highly sour gases and rich gas condensates.

Keywords: EOS, Correlations, PVT, Reservoir Fluids, Density, Viscosity.

الملخص

يقدم هذا البحث نتائج استخدام معادلة الحالة والطرق الأخرى لحساب الخواص المرتبطة بحجم وحركة الغازات المكثفة والغازات المحتوية على مركبات لكبريت، كما تم استخدام القياسات المتوفرة للعديد من الغازات في معرفة تأثير عناصر التجاذب بين مكونات الغاز على حسابات انضغاطية ولزوجة الغازات المختلفة مع مقارنة معادلات الحالة المعدلة في صورها المتعددة.

1. INTRODUCTION

Natural gas compressibility, density, and viscosity are important properties in the calculations of gas flow through reservoir rocks, material balance calculations, and design of pipelines and production facilities. In the past three decades a number of natural gases and gas condensates fields have been discovered around the world. The major impurities of these natural gases and condensates sources consist of hydrogen sulfide and carbon dioxide. Several methods are now available in literatures for the calculation of natural gas properties. These methods can be

classified into three groups [Erdogumus et al. 1997]. The first group uses gas composition or gas gravity to calculate pseudo-critical properties of gases and predict gas properties from empirical correlations. In this group, often gas density is used to predict viscosity. Hence prediction of viscosity is dependent on the choice of the method of estimating the density. The second group uses gas composition to estimate gas properties via the method of corresponding states. The third category, the most recent ones, is based on equations of state (EOS) approach. The last category has the advantage of using single equation to calculate k -values, compressibility, density, and viscosity [Lawal, 1986; Guo et al, 1977&2001]. It also secures stable convergence in the vicinity of the critical point. In EOS-based viscosity models the density calculation is not required for viscosity. Li and Guo (1991) studied the accuracy of Peng-Robison EOS to predict phase equilibria of sour gases. Because PR-EOS was not accurate, they modified the original PR-EOS by introducing 33 constant. However, this modification makes the equation not convenient for engineering calculations. Mohsen-Nia et al (1994) introduced a two constant EOS, based on theoretical background of statistical mechanics, designed specially to predict properties of sours natural gases. The equation has several constants (α, β) for each of the pure components forming the gas mixture. Mohsen-Nia et al. did not explain how to calculate the constants for the plus fraction. They tested their equation for several binary systems and light gases without accounting for the effect of binary interaction numbers (BIN). Huron et al.(1978) and Evelein and Moore (1979) used Soave-Redlich-Kwong, SRK-EOS to study the hydrocarbon system containing hydrogen sulfide and carbon dioxide. They reported phase equilibria calculations but did not report thermodynamic and transport property calculations. Consequently, most of these methods have limited use specially when dealing with sour gases and gas condensates [Huron et al., 1978].

In this paper we report the effect of incorporating the BIN on the accuracy of EOS(s) prediction of the properties of sour gases and gas condensate systems. The capabilities of several EOS(s) and several correlations as well as corresponding state methods are thoroughly investigated.

2. EOS CALCULATIONS OF VOLUMETRIC PROPERTIES

Several forms of the equations of state have been presented to the petroleum industry to calculate hydrocarbon reservoir fluid properties [Ahmed et al., 1986 &1988; Danesh, 1998; Whitson and Brule, 2000]. These equations of state (EOS) can be written in general form as:

$$p = \frac{RT}{v-b} - \frac{a}{v^2 + uv - w^2} \quad (1)$$

In the above equation p is the pressure, R is the gas constant, T is the absolute temperature, v is the molar volume, and u and w are constants. The parameters a and b are constants characterizing the molecular properties of the individual component. a is a measure of the

intermolecular attraction and b represent the molecular size. In two-parameter EOS, u and w are related to b whereas in a three-parameter EOS u and w are related to a third parameter c . The two-parameter EOS are the most popular ones, where a and b are expressed as a function of critical properties as:

$$a = \frac{\Omega_a R^2 T_c^2}{P_c} \quad (2)$$

$$b = \frac{\Omega_b R T_c}{P_c} \quad (3)$$

Where Ω_a and Ω_b are constants having different values for each of the EOS.

2.1 Two-parameter EOS

Van der Waals presented the first form of the two-parameter EOS. The two-parameter EOS assumes that the parameter a to be temperature independent. In this study, two of the mostly used two-parameter equations of state are considered. The first is the one presented by Soave-Redlich-Kwong (1972) (SRK-EOS) and the other presented by Peng-Robinson (1976), PR-EOS. The SRK-EOS has the following form

$$p = \frac{RT}{v-b} - \frac{a\alpha}{v(v+b)} \quad (4)$$

In SRK-EOS Ω_a and Ω_b are constants and equal to 0.42748 and 0.08664 respectively. Zudkevitch and Joffe¹⁶, and Joffe¹⁷ showed that if Ω_a and Ω_b were treated as temperature dependent, SRK-EOS results would improve. Yarborough (1979) showed the variation of Ω_a and Ω_b with reduced temperature (T_r) and correlated them with the accentric factor, ω . The dimensionless factor α is calculated from the following equation.

$$\alpha = [1 + m(1 - T_r^{0.5})]^2 \quad (5)$$

Where T_r is the reduced temperature (T/T_c) and m is defined as:

$$m = 0.48 + 1.574\omega - 0.176\omega^2 \quad (6)$$

Soave (1972) and Graboski and Daubert (1978) to improve pure component vapor pressure prediction have proposed several modification of m . SRK-EOS can be derived from the general form of the EOS by setting u equal b and w equal zero. The gas compressibility factor (Z) is obtained from solving the following equation:

$$Z^3 - Z^2 + (A - B - B^2)Z - AB = 0 \quad (7)$$

Where A and B are calculated from the following equations.

$$A = \frac{ap}{R^2 T^2} \quad (8)$$

$$B = \frac{bp}{RT} \quad (9)$$

PR-EOS is obtained from the general form of the EOS by substituting u and w by $2b$ and b , respectively. PR-EOS has the following form:

$$p = \frac{RT}{v-b} - \frac{a\alpha}{[v(v+b)+b(v-b)]} \quad (10)$$

In PR-EOS Ω_a and Ω_b are constants and equal 0.457235 and 0.077796 respectively. Peng and Robinson used the same equations (2 and 3) to calculate a and b but a different correlation to calculate m .

$$m = 0.37464 + 1.5422\omega - 0.26992\omega^2 \quad (11)$$

This correlation was later modified to improve prediction for heavier components [Robinson and Peng, 1978].

$$m = 0.3796 + 1.485\omega - 0.1644\omega^2 + 0.01667\omega^3 \quad (12)$$

PR-EOS in term of gas compressibility factor (Z) is:

$$Z^3 - (1-B)Z^2 + (A-2B-3B^2)Z - (AB-B^2-B^3) = 0 \quad (13)$$

2.1.1 Volume shift

Comparison of SRK-EOS prediction and experimental liquid molar volume of pure components shows systematic deviation. For this reason, Peneloux et al.(1982) introduced a volume shift to improve liquid density prediction of SRK-EOS. The volume shift has minimal effect on vapor density at low and moderate pressure. But, it is advisable to adjust the gas volume by a third parameter to maintain consistency, particularly near the critical point. The corrected molar volume V^{corr} is;

$$V^{corr} = V - \sum x_i c_i \quad (14)$$

Where x_i is the mole fraction of the component and c_i is a pure component correction factor. Similar to Peneloux, Jhareni and Youngren (1984) applied the volume shift concept to PR-EOS.

2.2 Three-parameter EOS

The two-parameter EOS (s) predict the same critical compressibility factor, Z_c , for all substances. SRK-EOS predicts Z_c of 0.333 and PR-EOS predicts Z_c of 0.307 for all pure substances, whereas Z_c varies within a range of 0.2 to 0.3 for all hydrocarbons. Several forms of the three-parameter EOS are known in the oil and gas industry. In this study, the equation of state introduced by Patel-Teja (1982) is considered as it is widely used. Patel-Teja equation of state (PT-EOS) is expressed as:

$$p = \frac{RT}{v-b} - \frac{a_c \alpha}{[v(v+b) + c(v-b)]} \quad (15)$$

In this equation, Patel-Teja modified the attraction term of PR-EOS by including a more flexible third parameter (c), as a function of accentric factor.

$$c = \Omega_c \frac{RT_c}{P_c} \quad (16)$$

$$\Omega_c = 1 - 3\zeta \quad (17)$$

$$\zeta = 0.329032 - 0.076799 \omega - 0.0211947 \omega^2 \quad (18)$$

PT-EOS can be reduced to PR-EOS or SRK-EOS by substituting the value of 0.307 or 0.333 for ζ , respectively. The general form of the EOS can be reduced to PT-EOS by substituting $u = b + c$ and $w^2 = cb$. Valderrama and Cristernas (1986) modified PT-EOS using critical compressibility, Z_c , to correlate its parameters.

$$\Omega_a = 0.66121 - 0.76105Z_c \quad (19)$$

$$\Omega_b = 0.02207 + 0.2086Z_c \quad (20)$$

$$\Omega_c = 0.57765 - 1.870807Z_c \quad (21)$$

Patel and Teja used the correlation to calculate m .

$$m = 0.46283 + 3.58230\omega Z_c - 0.819417(\omega Z_c)^2 \quad (22)$$

The gas compressibility factor (Z) is calculated from PT-EOS as:

$$Z^3 - (C-1)Z^2 + (A-2BC-C-B^2)Z - (BC-B^2C-AB) = 0 \quad (23)$$

2.3 Mixing rules

When EOS(s) are applied to multi-components hydrocarbon mixtures certain mixing rules are applied to determine their parameters. The parameters of the EOS (a , b , c) are considered to represent the attractive and repulsive forces between molecules of different substances forming the hydrocarbon mixture. These mixing rules are given by:

$$a = \sum \sum x_i x_j (a_i a_j)^{0.5} (1 - k_{i,j}) \quad (23)$$

$$b = \sum x_i b_i \quad (24)$$

$$c = \sum x_i c_i \quad (25)$$

The mixing rules, known as Van der Waals mixing rules, treat all components similarly, hence referred to as the random mixing rules. The binary interaction numbers ($K_{i,j}$) account for the attraction forces between pair of non-similar molecules. They are dependent on the difference in molecular size of the components in a binary system.

2.4 Binary interaction number (BIN)

Correlations to estimate the BIN for specific EOS such as SRK-EOS and PR-EOS as well as general ones have been suggested (Whitson and Brule, 2000). The inclusion of BIN in the EOS mixing rules provides more flexibility and in most cases reliability in EOS results. Making the BIN to be temperature dependant (Varotsis et al., 1986), pressure dependant (Voros et al., 1985), and composition dependent (Bjorkk and Firoozabadi, 1992) could enhance this flexibility in EOS calculations. However, it is well known that making BIN composition dependent causes additional complexity in EOS calculation, especially in compositional reservoir simulation. Groboski and Daubert (1978) and Soave (1972) suggest that no BIN(s) are required for hydrocarbon mixture. On the other hand, Slot-Petersen (1987) and Vidal and Dauber (1978) presented theoretical back ground for the meaning and importance of the BIN. Elliot and Daubert (1985) presented a BIN for non-hydrocarbons such as N_2 , CO_2 , and H_2S to be used with SRK-EOS.

$$\text{For } N_2, K_{i,j} = 0.107089 + 2.9776 K_{i,j}^* \quad (26)$$

$$\text{For } CO_2, K_{i,j} = 0.08058 - 0.77215 K_{i,j}^* - 1.8407 (K_{i,j}^*)^2 \quad (27)$$

$$\text{For } H_2S, K_{i,j} = 0.07654 + 0.01792 K_{i,j}^* \quad (28)$$

Where

$$K_{i,j}^* = [-(e_i - e_j)^2] / (2e_i e_j) \quad (29)$$

And

$$\epsilon_i = [a_i \ln(2)]^{0.5}/b_i \quad (30)$$

Vatrosits et al. (1986) proposed a generalized correlation for evaluating the BIN for PR-EOS as a function of pressure, temperature and accentric factors of the hydrocarbon. The generalized correlation is expressed as:

$$K_{i,j} = \delta_2 T_{ij}^2 + \delta_1 T_{ij} + \delta_0 \quad (31)$$

Where i refer to principle components N₂, CO₂, or CH₄ and j refers to the other hydrocarbon component of the binary. The coefficients δ_0 , δ_1 , are δ_2 are determined for each set of binaries from the following equations:

For N₂-HC

$$\delta_0 = 0.1751787 - 0.7043 \log(\omega_j) - 0.0862066 [\log(\omega_j)]^2 \quad (32)$$

$$\delta_1 = -0.584474 + 1.328 \log(\omega_j) + 2.035757 [\log(\omega_j)]^2 \quad (33)$$

$$\delta_2 = 2.257079 + 7.869765 \log(\omega_j) + 13.50466 [\log(\omega_j)]^2 + 8.3864 [\log(\omega_j)]^3 \quad (33)$$

The effect of the pressure on N₂-HC BIN is considered in the following equation:

$$K_{i,j} = K_{i,j} (1.04 - 4.2 \times 10^{-5} P) \quad (34)$$

For CO₂-HC

$$\delta_0 = 0.4025636 + 0.1748927 \log(\omega_j) \quad (35)$$

$$\delta_1 = -0.941812 - 0.6009864 \log(\omega_j) \quad (36)$$

$$\delta_2 = 0.741843368 + 0.441775 \log(\omega_j) \quad (37)$$

The effect of the pressure on CO₂-HC is considered in the following equation:

$$K_{i,j} = K_{i,j} (1.044269 - 4.375 \times 10^{-5} P) \quad (38)$$

3. WORK PLAN

3.1 Methods

One of the objectives of this study is to investigate the effect of various schemes of binary interaction numbers (BIN) on the accuracy of equations of state in predicting properties of natural gases. SRK-EOS, PR-EOS and PT-EOS are used to calculate the compressibility factor (Z-factor) and gas density under the following cases:

- 1- Neglect the BIN for all the components comprising the natural gases.
- 2- Consider the BIN as constant only for non-hydrocarbons with hydrocarbons, Elliot and Daubert.
- 3- Consider the BIN as a function of temperature, pressure and composition for hydrocarbons with non-hydrocarbons, Vatrotsis et al.
- 4- Consider the BIN for all components of natural gas, Danesh, Whitson and Brule, Nagy and Shirkovski (1982), Knapp and Doring (1986), William and Teja (1986), and Pedersen (1989).

Results of EOS predictions of natural gases are compared to predictions by different correlations and corresponding state. Calculations of the equation of state constants a , b , and c require critical properties of all components. Critical pressure (P_c), critical temperature (T_c), critical compressibility factor (Z_c), and acentric factor (ω) for pure components are well documents. The critical properties and acentric factor for the plus fraction are estimated from correlation. In this study Whitson (1989) correlation is used to estimate the boiling point and Kesler-lee (1976) correlation to estimate critical pressure and temperature given the molecular weight and the specific gravity of the plus fraction. The acentric factor of the plus fraction is calculated from Edminster (1958) correlation. Critical compressibility factor (Z_c) of the undefined plus fraction is calculated from Pitzer (1955) correlation.

3.2 Data Bank

In order to carry out the work plan explained in this study, a large data bank of a variety of natural gases has been used. This data bank contains properties of 2200 gases collected from various regions worldwide. Some of these gases are collected from literature (Lawal, 1986; Simon et al., 1964; Robinson et al., 1965; Buxton and Campbell, 1967; Mcleod, 1968; Wichert, 1970; and Elsharkawy and Foda, 1998). Measurements of gas compressibility factor (Z -factor), gas density, and gas viscosity over a pressure range from 100 to 12,000 psia and a temperature range of 40 to 327 °F have been used in this study. These gases have molecular weights ranges from 16.4 to 55 (gas gravity from 0.566 to 1.895). Most of these gases are highly sour and has a very high content of hydrogen sulfide. Miner amount of these gases are condensate having as high as 17% heptane plus. These properties of natural gases used in this study are reported in Table (1).

4. CALCULATIONS OF VOLUMETRIC PROPERTIES

4.1 Results and Discussion

Table (2) shows result of density calculations of all natural gases using SRK-EOS, PR-EOS, and PT-EOS. Although PR-EOS predicts compressibility factors at critical point more accurate than SRK-EOS, the latter has an overall better accuracy. Calculation of density by

SRK-EOS is improved when volume shift proposed by Peneloux 1989 is considered (SRK-Peneloux). The best accuracy of SRK-P is obtained when the binary interaction parameters of Nagy and Skirkosvski (1982) are used. Improvement in PR-EOS calculations of gas density is accomplished when the intermolecular effect of non-hydrocarbon components to hydrocarbon is considered using BIN proposed by Varotsis et al (1986). Ahmed (1989) reported that the inadequacy of the predictive capability of PR-EOS lies with the improper procedure for calculating the parameters a , b , and α for the C7+. He devised a approach for optimizing these parameters from readily measured physical parameters for the heptane plus fraction. In this study, Ahmed's optimization for a , b , and α for PR-EOS was used to calculate the properties of natural gases. Results shown in table (2) shows that this optimization did not improve PR-EOS calculations. Table (2) also shows accuracy of PT-EOS. Best results are obtained from PT-EOS when effect of non-hydrocarbon components is accounted for using BIN proposed by William and Teja (1986). Valderrama and Cisternas (1986) used experimental critical compressibility factor in calculating the parameters of PT-EOS. These modifications have been used in this study to calculate gas properties by PT-EOS. The results reported in table (2), shows that this modification did not improve PT-EOS capability to predict gas density. This is in agreement with Danesh (1990) who indicated that PT-EOS as modified by Valderrama without BIN was more successful in modeling phase behavior of reservoir fluids than with accounting for the BIN. Probably, improvement in EOS or a more thorough characterization of the plus fraction might reduce the need to use BIN for hydrocarbon fluids. Table (2) also shows that BIN has little effect on all the density calculations using the equation of states.

Figure (1) and (2) show error distribution in density calculation using SRK-EOS as a function of the hydrogen sulfide and heptane plus content, respectively. These figures illustrate an average absolute deviation in the order of about 2% for either highly sour gas or rich gas condensate. They also indicate that the accuracy of gas density calculations is independent of the amount of hydrogen sulfide in the natural gas or amount of the heptane plus. Typical behavior have been noticed for PR-EOS and PT-EOS regardless the BIN that has been used.

Comparison of Z-factor predictions using the equations of state (SRK, PR, and PT) as well as other correlations for different gases with various amount of hydrogen sulfide, heptane plus, and carbon dioxide are presented in Table (3). The other correlations used for estimating gas compressibility factors are explained in elsewhere (Elsharkawy and Elkamel, 2001; Elsharkawy et al, 2001). Some of the gas samples have as high as 70% hydrogen sulfide (sample 2076) and other has 63% carbon dioxide (sample 926). The superiority of PT-EOS with BIN presented by William (1986) is clearly indicated for all samples except one sample (sample 504). For this particular sample whose composition is reported in Table (3), PT-EOS has predicted negative compressibility factor. This erratic behavior could not be explained. The other equations of state have less accuracy as compared to correlations but did not show this erratic behavior for this gas.

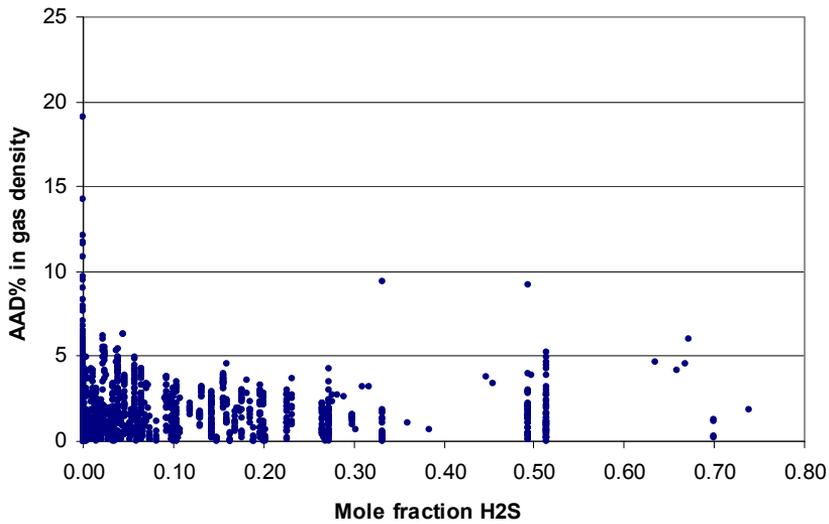


Figure 1. Error distribuiton from EOS as function of H2S content

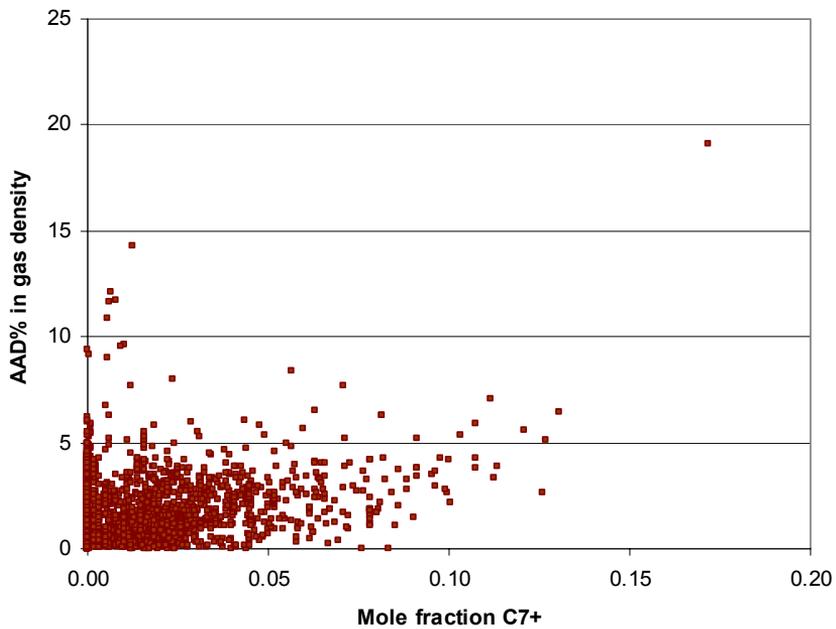


Figure 2. Error distribuiton from EOS as function of C7+ content

Comparison between the experimental and predicted compressibility data for highly sour gas (sample 1866 in table 3) is shown in Figure (3). The predicted compressibility factors include three equations of states (SRK, PR, and PT), two methods based on calculations of Z-factor from composition (Piper et al, 1993; Wichert-Aziz, 1972) and two methods using gas gravity (Sutton; 1985; Elsharkawy et al, 2001). Figure (3) indicates excessively high prediction of gas compressibility from the methods that use gas gravity. All the prediction made by the equations of state and correlations matches the experimental data with PT-EOS has the superiority.

Figure (4) shows comparison between experimental and predicted compressibility from various equations of state and correlations for a CO₂-rich gas sample whose composition is given in table (3), sample 926. Again the methods based on gas gravity (Sutton; 1985; Elsharkawy et al, 2001) depict a large deviation from experimental data and correlations based on Wichert-Aziz (1972) method show deviation at high pressure. EOS predictions, however, closely match the experimental data. Prediction of compressibility and density made by PT-EOS considering the binary interaction parameter presented by Varotsis has the best accuracy among the other methods.

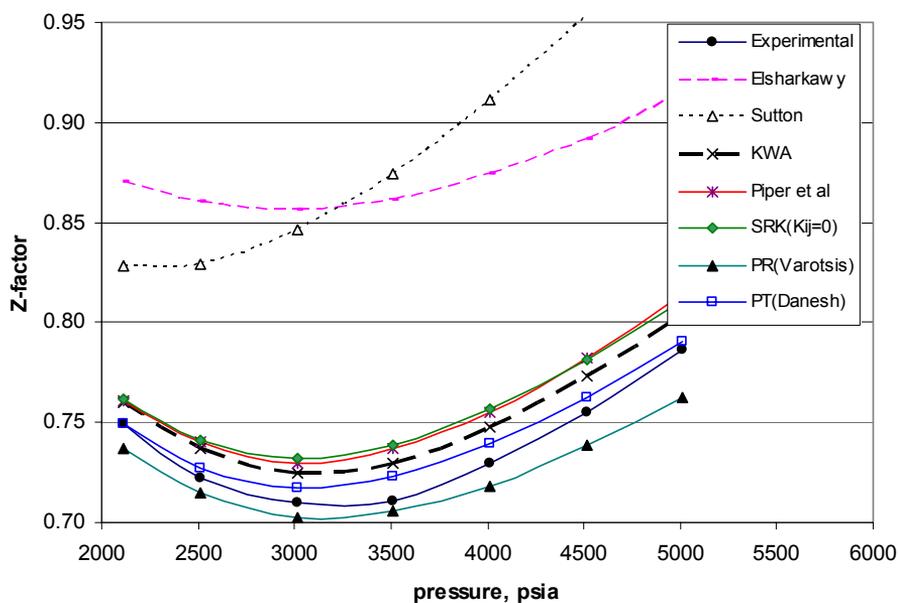


Figure 3. plot of gas compressibility of highly sour gas (sample 1866) @ 230 F

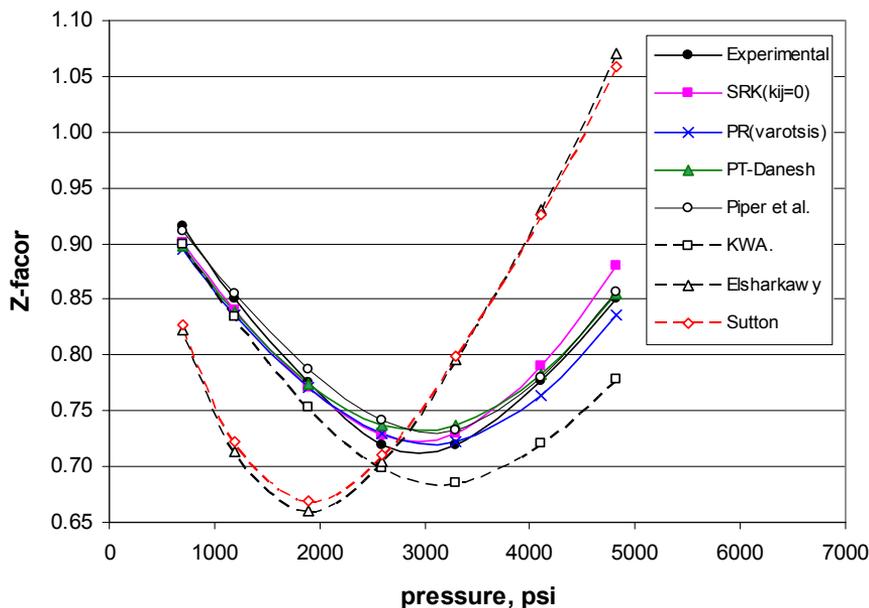


Figure 4 experimental and predicted z-factor for gas sample 926

5. TRANSPORT PROPERTIES

5.1 Method of Calculations

Although numerous viscosity correlations and semi-empirical correlation are available in the literature, there have been many drawbacks in their applications. Among these drawbacks are:

- 1) Their range of application is limited;
- 2) A smooth transition near critical point can not be achieved;
- 3) Calculation of viscosity is involving density, hence accuracy of viscosity calculation is dependent on density correlation.

Guo et al. (1997) presented two viscosity models based on PR-EOS and PT-EOS. They found that their EOS based viscosity model is capable of satisfactorily describing pure component hydrocarbon viscosity but poorly predict viscosity of reservoir fluids. Later, Guo et al. (2001) modified PR-EOS viscosity model (MPR-VISC) to predict viscosity behavior of hydrocarbon mixtures. They tested their model to predict viscosity of sweet and light gases. Therefore it is important to study the capability of the EOS- based viscosity model to predict viscosity of sour gases and rich condensates. Guo et. al. ignored the effect of the binary interaction

numbers on the prediction of viscosity. Hence, this study is extended to investigate the effect of various sets of BIN on calculations of viscosity. The modified PR-EOS viscosity model (MPR-Viscosity) is given below:

$$T = \frac{rP}{u-b} - \frac{a}{u(u+b) + b(u-b)} \quad (39)$$

Where

$$a = 0.45724 \frac{r_c^2 P_c^2}{T_c} \quad (40)$$

$$b = 0.07780 \frac{r_c P_c}{T_c} \quad (41)$$

$$r = r_c \tau(T_r, P_r) \quad (42)$$

$$r_c = \frac{u_c T_c}{P_c Z_c} \quad (43)$$

The critical pure component viscosity is calculated from Uyehara and Watson⁵² correlation.

$$u_c = 7.7 T_c^{-1/6} M^{1/2} P_c^{2/3} \quad (44)$$

In this correlation the critical temperature is in degree K, critical pressure in atm, and viscosity in micro poise.

$$\tau(T_r, P_r) = [1 + Q_1((P_r T_r)^{0.5} - 1)]^{-2} \quad (45)$$

$$b^* = b\Phi(T_r, P_r) \quad (46)$$

$$\Phi(T_r, P_r) = \exp[Q_2(\sqrt{T_r} - 1)] + Q_3(\sqrt{P_r} - 1)^2 \quad (47)$$

The coefficients Q_1 , Q_2 , and Q_3 for light hydrocarbons and non-hydrocarbons are calculated from accentric factor ω , when $\omega < 0.3$, as follows:

$$Q_1 = 0.829599 + 0.350857 \omega - 0.747680 \omega^2 \quad (48)$$

$$Q_2 = 1.94546 - 3.197770 \omega + 2.80193 \omega^2 \quad (49)$$

$$Q_3 = 0.299757 - 2.20855 \omega + 6.64959 \omega^2 \quad (50)$$

For heavy hydrocarbons and plus fraction, when $\omega > 0.3$, the coefficients are calculated from the following equations:

$$Q_1 = 0.956763 + 0.192829 \omega - 0.303189 \omega^2 \quad (51)$$

$$Q_2 = -0.258789 - 37.1071 \omega + 20.5510 \omega^2 \quad (52)$$

$$Q_3 = 5.163070 - 12.8207 \omega + 11.0109 \omega^2 \quad (53)$$

For a complex mixture, the parameters a_m , b_m , b'_m and r_m are calculated from the following mixing rules:

$$a_m = \sum x_i a_i \quad (54)$$

$$b_m = \sum x_i b_i \quad (55)$$

$$b'_m = \sum \sum x_i x_j \sqrt{b_i b_j} (1 - k_{i,j}) \quad (55)$$

$$r_m = \sum x_i r_i \quad (56)$$

When calculating properties of reservoir fluids, the hydrocarbon plus fraction is usually divided into number of pseudo-components to improve calculation accuracy. Guo et al. (2001) found the calculated viscosity from MPR-VISC is not sensitive to the subfraction of $c7+$ fraction and treated the heptane plus as single pseudo-component. In this study, the plus fraction is not split into sub-fractions for the purpose of comparing with other empirical correlations (Carr-Kobayashi-Burrows, 1959; Dempsey, 1965; Lee-Gonzalez-Eakin, 1966; Dean-Stiel, 1965; Lucas, 1981), semi-empirical (Lohrenz et al., 1964) and corresponding state method (Pedersen et al., 1989).

5.2 Results and Discussion of EOS Calculations of Transport Properties

Results of EOS prediction for viscosity of sour gases and condensates are show in Table (4) for various schemes of binary interaction numbers (BIN). This table indicates that the various schemes of BIN(s) have little effect on the accuracy of MPR-EOS to predict the viscosity of natural gases. MPR-EOS was able at best to predict the viscosity of sour and gas condensates

with an overall average absolute deviation (AAD) of 16.37% when BIN(s) were set to zero for all the components forming the natural gas. When the binary interaction numbers proposed by Whitson and Brule (2000), is used viscosity prediction from MPR-EOS is improved as the AAD was reduced to 16.06%. Probably research effort might be directed to a better characterization of the plus fraction or splitting the heptane plus rather than finding the optimum set of $K_{i,j}$.

Guo et al. (2001) showed comparison of MPR-EOS and Lohrenz-Bray-Clark (LBK) correlation for viscosity prediction for nine natural gas mixtures. Their results indicated the superiority of MPR-EOS to LBK. All of the viscosity calculations reported by Guo et al. (2001) for these nine natural gas mixture were very high, AAD of several hundred percent, and these results are questionable. Using a very large database, our results indicate that LBK has nearly the same level of accuracy as the MPR-EOS. However, LBK correlation requires independent correlation to calculate the fluid viscosity. In this study, gas density was calculated using Alani-Kennedy (1960) correlation for LBK to predict gas viscosity. MPR-EOS has the advantage of not requiring calculating of fluid density.

The gas viscosity correlation presented by Carr-Kobayashi- Burrows correlation, which was later, presented in mathematical form by Dempsey, Lee-Gonzalez-Eakin (LGE), Dean-Stiel (DS) correlation, and Lacus correlation, and Corresponding state method (Pedersen et al), were all used to predict the viscosity of the gases considered in this study. Table (4) illustrates that Pedersen, LGE, Lacus, and DS has comparable accuracy of predicting gas viscosity. CKB-D correlation, however, has the lowest accuracy. Because most laboratories rarely measure gas viscosity, it is frequently calculated from LGE correlation or CKB-D. Given the wide applicability of Lucas method, Whitson and Brule (2000) recommended its use to estimate gas viscosity. Results reported in Table (4) do not agree with Whitson and Brule recommendation. Our results agree with Awuy et al (1997) that CKB correlation is not recommended for sour gases and gas condensate or for use at elevated temperatures and pressures.

The accuracy of MPR-EOS, as the most accurate method, to predict viscosity of sour natural gas and gas condensate was studied for different gases having different amount of hydrogen sulfide and heptane plus content, respectively. Figure (5) indicates that amount of hydrogen sulfide has an effected on calculated gas viscosity from MPR-EOS. Figure (6) indicates that heptane plus content of natural gas has a great effect on accuracy of MPR-EOS. The different binary interaction numbers (BIN) used in this study could not properly account for the interaction between hydrocarbon and non-hydrocarbon or pure component hydrocarbon and plus fraction.

Table (5) reports comparison of predicted viscosity from various methods for four different groups of gases. The first group comprises sweet and dry gases, having no hydrogen sulfide

and heptane plus fraction of less than 1%. For this particular group, CKB-D, LGE, and DS correlations show better prediction of viscosity than MPR-EOS and LBK. The second group includes sweet-gas condensates having from 3% to 12% heptane plus. MPR-EOS and LBK, respectively, show equal superiority over the other methods in predicting the viscosity of rich gas condensates. However both MPR-EOS and LBK unsatisfactorily predict the gas condensate viscosity. The other correlations (CKB-D, LGE, and DS) poorly predict the gas viscosity and show error as high as 100% for rich gas condensate having heptane plus content of 5% or more. The third group consists of sour dry gases of varying amount of H₂S and CO₂. All the methods reported in table (5) have similar accuracy of predicting gas viscosity except for gas number 9. For this particular gas, MPR-EOS predicts unreasonably high gas viscosity. The fourth group includes sour gas condensates. MPR-EOS satisfactorily predicts the gas viscosity and show superiority than the other methods. Figure (7) and (8) show viscosity plots for sour gas (gas No. 13) and gas condensate (gas No. 2) whose compositions are shown in Table (5). It is clear from figure (7) that all the methods considered in this study could not match the measured viscosity for this highly sour gas. Composition and measured viscosity of gas No. 2 are reported by Ahrabi et al. (1989). Figure (8) shows that all the methods do not satisfactorily predict the measured viscosity except at 5000 psia.

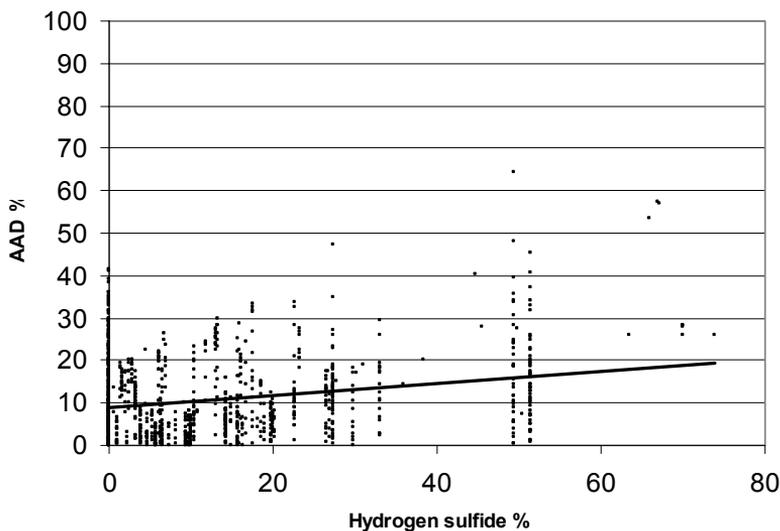


Figure 5. Accuracy of Viscosity prediction using MPR-EOS

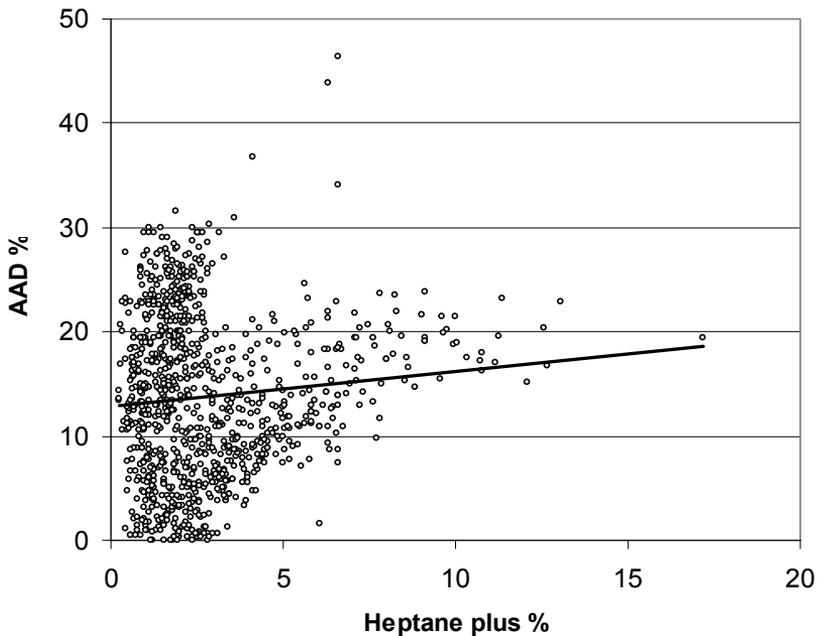


Figure 6 Accuracy of Viscosity prediction using MPR-EOS

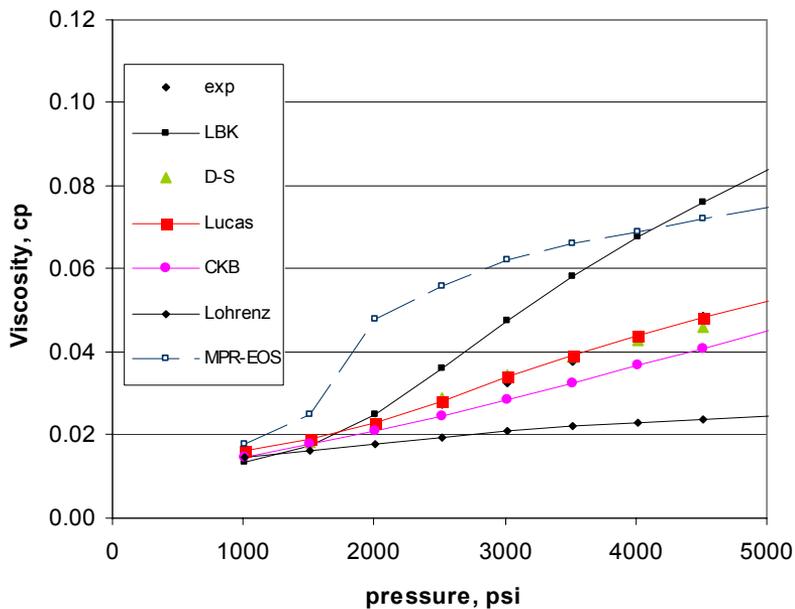


Figure 7 Viscosity of sour gas # 13 @ 120F

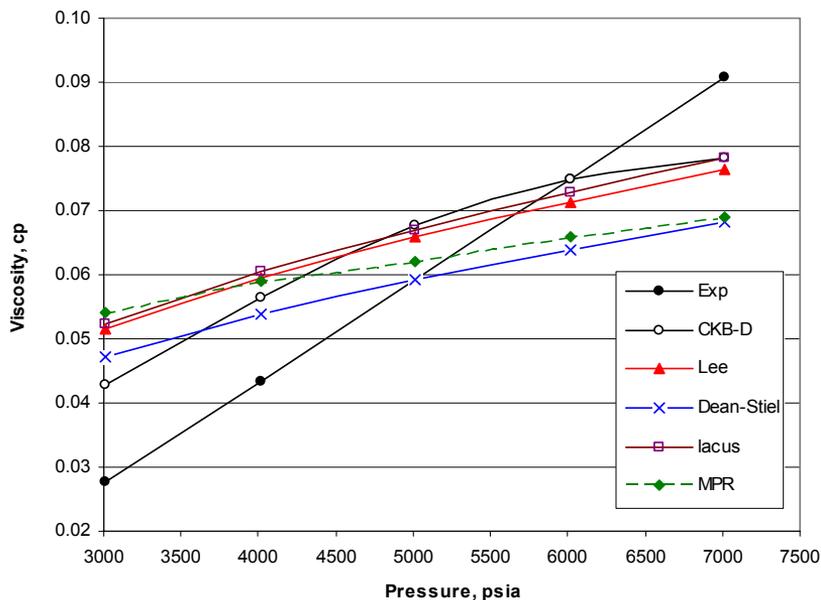


Figure 8 Viscosity of NGL #2 @ 215 F

6. CONCLUSIONS

- (1) Although PR-EOS has better prediction of Z-factor near critical region than SRK-EOS, the later shows better accuracy at different pressures and temperatures for various sour gases and gas condensates.
- (2) Best prediction of compressibility and density for various gases was obtained from PT-EOS, especially when the effect of non-hydrocarbon components are considered by incorporating the BIN proposed by William and Teja.
- (3) Accuracy of EOS(s) in predicting the volumetric properties of sour gases and gas condensates is independent of the amount of non-hydrocarbon components or the heptane plus content.
- (4) Calculation of compressibility and gas density using gas gravity is not recommended as it produces large error especially for highly sour gases and rich gas condensates.
- (5) Viscosity correlations presented by Lee-Gonzalez-Eakin, Carr-Kobayashi- Burrows, Dean-Stiel, and Lacus are recommended for use to predict viscosity of sweet and dry gases.

- (6) MPR-EOS viscosity model and Lohrenz correlation are recommended for viscosity prediction of sour gas condensates. However, their accuracy is limited especially at high pressures and temperature.
- (7) Capability of MPR-EOS to predict viscosity of gas condensates deteriorates as the amount of heptane plus increases.
- (8) For all the EOS(s) considered in this study, BIN has little effect on the EOS prediction of volumetric and transport properties. It is therefore recommended to properly describe the hydrocarbon plus fraction rather than to find the optimum BIN set.

List of Symbols

| | |
|-----------|------------------------------------|
| a | EOS constant in eq 2 |
| b | EOS constant in eq 3 |
| c | EOS constant in eq 15 |
| $K_{i,j}$ | Binary interaction number (BIN) |
| m | Correlating parameter in eq 6 |
| M | Molecular weight |
| P | Pressure |
| P_c | Critical pressure |
| P_r | Reduced pressure = (P/P_c) |
| Q_i | Constant for MPR-EOS ($i=1,2,3$) |
| R | Universal gas constant |
| r_c | Constant for MPR-EOS |
| T | Absolute temperature |
| T_c | Critical temperature |
| Tr | Reduced temperature = (T/T_c) |
| u | EOS constant in eq 1 |
| V | molar volume |
| w | EOS constant in eq 1 |
| x | Component mole fraction |
| Z | compressibility factor |
| Z_c | critical compressibility |

Greek

| | |
|------------|---|
| α | Dimensionless factor for eq 5. |
| η | Correlating parameter |
| μ | Gas viscosity |
| μ_c | Critical gas viscosity |
| σ_i | coefficient for $K_{i,j}$ ($i=0,1,2$) |
| ω | Accentric factor |
| Ω_a | EOS constant |
| Ω_b | EOS constant |
| Ω_c | EOS constant |

Abbreviations

| | |
|-----|----------------------------|
| BIN | Binary interaction number |
| EOS | Equation of state |
| PR | Peng-Robinson |
| SRK | Soave-Redlich-Kwong |
| PT | Patel-Teja |
| AAD | Average absolute deviation |
| LBK | Lohrenz-Bray-Clark |
| LGE | Lee-Gonzalez-Eakin |
| CKB | Carr-Kobayashi-Burrows |
| DS | Dan-Stiel |

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Table (1) Properties of natural gases used in this study

| | Min. | Max. | Ave. |
|--------------------------|-------|--------|-------|
| Composition mole % | | | |
| Hydrogen sulfide | 0 | 73.85 | 7.45 |
| Carbon dioxide | 0 | 67.16 | 4.04 |
| Nitrogen | 0 | 25.15 | 1.72 |
| Methane | 12.7 | 97.40 | 74.14 |
| Ethane | 0 | 28.67 | 6.00 |
| Propane | 0 | 13.16 | 2.56 |
| Iso-Butane | 0 | 2.61 | 0.50 |
| N-Butane | 0 | 5.20 | 0.84 |
| Iso-Pentane | 0 | 2.85 | 0.35 |
| N-Pentane | 0 | 2.09 | 0.32 |
| Hexane | 0 | 5.300 | 0.44 |
| Heptane plus | 0 | 17.20 | 1.64 |
| Mw C ₇₊ | 98.0 | 253 | 127 |
| γ C ₇₊ | 0.72 | 0.85 | 0.77 |
| Reservoir pressure, psi | 100 | 12,000 | 2900 |
| Reservoir temperature, F | 40 | 327 | 190 |
| Z-factor | 0.402 | 1.775 | 0.900 |

Table 2- Results of EOS(s) prediction of density of natural gases.

| EOS | Binary interaction | AAD% |
|---------------|-------------------------|------|
| SRK | $K_{ij}=0$ | 1.71 |
| | Elliot-Daubert (1985) | 2.23 |
| | Nagy-Shirkosvski (1982) | 1.88 |
| | Pedersen (1989) | 2.22 |
| | Knapp-Doring (1986) | 2.09 |
| SRK-Peneloux | $K_{ij}=0$ | 1.52 |
| | Elliot-Daubert (1985) | 1.56 |
| | Nagy-Shirkosvski (1982) | 1.45 |
| | Pedersen (1989) | 1.57 |
| | Knapp-Doring 1986 | 1.52 |
| PR | $K_{ij}=0$ | 4.46 |
| | Elliot-Daubert (1985) | 3.50 |
| | Varotsis (1986) | 2.92 |
| | Whitson-Brule (2000) | 3.98 |
| | Pedersen (1989) | 3.51 |
| | Knapp-Doring 1986 | 3.82 |
| PR-Ahmed | Elliot-Daubert 1985 | 6.57 |
| | Varotsis (1986) | 5.68 |
| | Whitson-Brule (2000) | 4.56 |
| | Pedersen (1989) | 6.11 |
| | Knapp-Doring 1986 | 5.71 |
| PT | $K_{ij}=0$ | 1.64 |
| | Elliot-Daubert (1985) | 1.45 |
| | Danesh (1998) | 1.39 |
| | Pedersen (1989) | 1.41 |
| | William –Teja (1986) | 1.54 |
| PT- Valerrama | Elliot-Daubert (1985) | 1.67 |
| | Danesh (1998) | 1.74 |
| | Pedersen (1989) | 1.58 |
| | William –Teja (1986) | 1.72 |

Table (3) Comparison of z-factor prediction results of various methods for different gas samples

| IND | 1 | 84 | 416 | 439 | 504 | 752 | 817 | 926 | 1225 | 1275 | 1277 | 1280 | 1714 | 1788 | 1866 | 2073 | 2076 |
|-----------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|-------------|--------------|--------------|--------------|--------------|--------------|--------------|
| H2S | 0.0000 | 0.0708 | 0.0383 | 0.2816 | 0 | 0.1693 | 0.1047 | 0.0034 | 0.0000 | 0.0680 | 0.1078 | 0.1826 | 0.2327 | 0.2730 | 0.5137 | 0.6587 | 0.7003 |
| CO2 | 0.0017 | 0.0096 | 0.0058 | 0.0608 | 0.0097 | 0.0576 | 0.0163 | 0.6352 | 0.0061 | 0.0209 | 0.0616 | 0.0866 | 0.0287 | 0.0451 | 0.0319 | 0.0914 | 0.0865 |
| N2 | 0.0150 | 0.0064 | 0.0020 | 0.0383 | 0.0041 | 0.0011 | 0.0244 | 0.0386 | 0.0000 | 0.1019 | 0.0040 | 0.0037 | 0.0304 | 0.0061 | 0.0258 | 0.0108 | 0.0092 |
| C1 | 0.7284 | 0.6771 | 0.7564 | 0.4033 | 0.8616 | 0.6619 | 0.7352 | 0.1937 | 0.8500 | 0.6857 | 0.7414 | 0.5213 | 0.5601 | 0.6459 | 0.4241 | 0.2373 | 0.2024 |
| C2 | 0.0847 | 0.0871 | 0.0706 | 0.0448 | 0.0355 | 0.0412 | 0.0498 | 0.0303 | 0.0600 | 0.0590 | 0.0327 | 0.1165 | 0.0820 | 0.0084 | 0.0024 | 0.0018 | 0.0016 |
| C3 | 0.0418 | 0.0384 | 0.0336 | 0.0248 | 0.0154 | 0.0188 | 0.0181 | 0.0174 | 0.0332 | 0.0282 | 0.0121 | 0.0142 | 0.0345 | 0.0093 | 0.0007 | 0.0000 | 0.0000 |
| IC4 | 0.0110 | 0.0050 | 0.0104 | 0.0060 | 0.0046 | 0.0044 | 0.0059 | 0.0033 | 0.0085 | 0.0047 | 0.0022 | 0.0039 | 0.0085 | 0.0027 | 0.0002 | 0.0000 | 0.0000 |
| NC4 | 0.0171 | 0.0156 | 0.0135 | 0.0132 | 0.0046 | 0.0076 | 0.0073 | 0.0093 | 0.0129 | 0.0116 | 0.0061 | 0.0083 | 0.0110 | 0.0020 | 0.0003 | 0.0000 | 0.0000 |
| IC5 | 0.0088 | 0.0056 | 0.0072 | 0.0079 | 0.0026 | 0.0032 | 0.0040 | 0.0039 | 0.0057 | 0.0085 | 0.0057 | 0.0095 | 0.0000 | 0.0020 | 0.0002 | 0.0000 | 0.0000 |
| NC5 | 0.0084 | 0.0082 | 0.0055 | 0.0081 | 0.0020 | 0.0036 | 0.0037 | 0.0047 | 0.0066 | 0.0000 | 0.0000 | 0.0000 | 0.0071 | 0.0010 | 0.0001 | 0.0000 | 0.0000 |
| C6 | 0.0124 | 0.0083 | 0.0077 | 0.0121 | 0.0035 | 0.0052 | 0.0053 | 0.0051 | 0.0109 | 0.0035 | 0.0046 | 0.0103 | 0.0028 | 0.0012 | 0.0002 | 0.0000 | 0.0000 |
| C7+ | 0.0707 | 0.0656 | 0.0490 | 0.0991 | 0.0564 | 0.0261 | 0.0253 | 0.0551 | 0.0062 | 0.0080 | 0.0218 | 0.0431 | 0.0022 | 0.0032 | 0.0004 | 0.0000 | 0.0000 |
| MW+ | 152 | 154 | 158 | 165 | 253 | 144 | 132 | 170 | 125 | 125 | 125 | 125 | 145 | 103 | 120 | | |
| SG+ | 0.810 | 0.776 | 0.783 | 0.818 | 0.850 | 0.788 | 0.774 | 0.811 | 0.75 | 0.75 | 0.75 | 0.75 | 0.85 | 0.7 | 0.75 | | |
| Temp, F | 221 | 296 | 325 | 250 | 271 | 255 | 290 | 219 | 200 | 157 | 189 | 216 | 120 | 250 | 230 | 150 | 175 |
| press, psi | 4973 | 4669 | 5095 | 4190 | 11830 | 4050 | 4255 | 4825 | 3500 | 2347 | 5065 | 5385 | 1000 | 5014 | 3514 | 1594 | 1364 |
| Z-factor | 0.997 | 0.970 | 1.011 | 0.838 | 1.775 | 0.914 | 0.968 | 0.851 | 0.916 | 0.823 | 0.95 | 0.942 | 0.802 | 0.931 | 0.711 | 0.452 | 0.606 |
| Key-Aziz | 0.977 | 0.958 | 1.022 | 0.769 | 1.644 | 0.889 | 0.960 | 0.778 | 0.889 | 0.827 | 0.953 | 0.925 | 0.802 | 0.933 | 0.730 | 0.461 | 0.605 |
| Piper et. al | 1.006 | 0.971 | 1.031 | 0.841 | 1.783 | 0.886 | 0.963 | 0.857 | 0.900 | 0.842 | 0.955 | 0.946 | 0.797 | 0.926 | 0.737 | 0.489 | 0.615 |
| Sutton | 0.996 | 0.987 | 1.036 | 0.938 | 1.760 | 0.930 | 0.975 | 1.058 | 0.900 | 0.795 | 0.991 | 1.040 | 0.804 | 1.011 | 0.874 | 0.670 | 0.732 |
| Elsharkawy | 0.990 | 0.983 | 1.032 | 0.940 | 1.741 | 0.931 | 0.977 | 0.936 | 0.909 | 0.812 | 0.986 | 1.032 | 0.820 | 1.010 | 0.878 | 0.680 | 0.740 |
| SRK,BIN=0 | 1.025 | 1.001 | 1.064 | 0.855 | 1.923 | 0.901 | 0.981 | 0.879 | 0.923 | 0.837 | 0.968 | 0.961 | 0.774 | 0.942 | 0.739 | 0.413 | 0.588 |
| PR-Varotisis | 0.964 | 0.969 | 1.037 | 0.796 | 1.528 | 0.871 | 0.956 | 0.836 | 0.889 | 0.805 | 0.911 | 0.908 | 0.751 | 0.898 | 0.706 | 0.423 | 0.582 |
| PT-William | 0.982 | 0.968 | 1.033 | 0.812 | -1.490 | 0.888 | 0.964 | 0.838 | 0.905 | 0.829 | 0.950 | 0.934 | 0.774 | 0.931 | 0.736 | 0.451 | 0.600 |

Table 4- Results of EOS and other methods for the prediction of viscosity of sour and gas condensates.

| Method | AAD% |
|--|-------|
| Modified PR-EOS | |
| $K_{i,j}$ - Whitson-Brule (2000) | 16.06 |
| $K_{i,j}$ - Knapp-Doring (1986) | 16.21 |
| $K_{i,j} = 0$ | 16.37 |
| $K_{i,j}$ - Varotsis (1986) | 16.58 |
| Lohrenz-Bray-Clark (LBK) | 16.31 |
| Pedersen et al. | 22.78 |
| Lee-Gonzalez-Eakin (LGE) | 23.31 |
| Lcaus | 24.68 |
| Dean-Stiel (DS) | 26.94 |
| Carr-Kobayashi-Burrows-Dempsey (CKB-D) | 33.12 |

Table 5 comparison of predicted viscosity from various methods for different gases.

| Gas No | I | | | II | | | III | | | IV | | | | | | |
|---------------------|---------------|---------------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| | 1 Koc46 | 2 Ahrabi- NGL | 3 Koc59 | 4 lawal1 | 5 lawal5 | 6 lawal9 | 7 Lawal10 | 8 42 | 9 281 | 10 295 | 11 1111 | 12 1650 | 13 1881 | 14 2076 | 15 84 | 16 439 |
| H2S | 0.0057 | 0.0000 | 0.0002 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.2260 | 0.0000 | 0.4935 | 0.7003 | 0.0708 | 0.2816 | 0.0034 |
| CO2 | 0.0014 | 0.0181 | 0.0148 | 0.0000 | 0.0000 | 0.0088 | 0.0038 | 0.0081 | 0.0231 | 0.0508 | 0.0050 | 0.5446 | 0.0865 | 0.0096 | 0.0608 | 0.6352 |
| N2 | 0.0051 | 0.0053 | 0.0010 | 0.0135 | 0.0211 | 0.0053 | 0.0164 | 0.0098 | 0.0137 | 0.0058 | 0.0046 | 0.0024 | 0.0092 | 0.0064 | 0.0383 | 0.0386 |
| C1 | 0.8002 | 0.2028 | 0.7424 | 0.8740 | 0.7758 | 0.6796 | 0.7257 | 0.6514 | 0.6583 | 0.6449 | 0.7561 | 0.4460 | 0.4447 | 0.6771 | 0.4033 | 0.1937 |
| C2 | 0.0900 | 0.2145 | 0.1148 | 0.0391 | 0.0768 | 0.0621 | 0.0541 | 0.0975 | 0.0803 | 0.0731 | 0.0071 | 0.0068 | 0.0016 | 0.0871 | 0.0448 | 0.0303 |
| C3 | 0.0435 | 0.3528 | 0.0554 | 0.0172 | 0.0342 | 0.0237 | 0.0307 | 0.0517 | 0.0417 | 0.0406 | 0.0006 | 0.0000 | 0.0000 | 0.0384 | 0.0248 | 0.0174 |
| IC4 | 0.0055 | 0.0455 | 0.0059 | 0.0045 | 0.0112 | 0.0056 | 0.0066 | 0.0135 | 0.0078 | 0.0084 | 0.0002 | 0.0000 | 0.0000 | 0.0050 | 0.0060 | 0.0033 |
| NC4 | 0.0137 | 0.1145 | 0.0220 | 0.0058 | 0.0128 | 0.0151 | 0.0134 | 0.0230 | 0.0184 | 0.0183 | 0.0002 | 0.0000 | 0.0000 | 0.0156 | 0.0132 | 0.0093 |
| IC5 | 0.0040 | 0.0136 | 0.0068 | 0.0035 | 0.0083 | 0.0067 | 0.0082 | 0.0120 | 0.0075 | 0.0071 | 0.0000 | 0.0000 | 0.0000 | 0.0056 | 0.0079 | 0.0039 |
| NC5 | 0.0051 | 0.0151 | 0.0118 | 0.0037 | 0.0080 | 0.0054 | 0.0054 | 0.0102 | 0.0108 | 0.0098 | 0.0000 | 0.0000 | 0.0001 | 0.0082 | 0.0081 | 0.0047 |
| C6 | 0.0042 | 0.0083 | 0.0127 | 0.0071 | 0.0116 | 0.0147 | 0.0108 | 0.0152 | 0.0116 | 0.0153 | 0.0000 | 0.0000 | 0.0000 | 0.0083 | 0.0121 | 0.0051 |
| C7+ | 0.0016 | 0.0035 | 0.0122 | 0.0316 | 0.0426 | 0.0788 | 0.1268 | 0.1076 | 0.1268 | 0.1259 | 0 | 0 | 0 | 0.0656 | 0.0991 | 0.0551 |
| MW+ | 100.2 | 100 | 107 | 155 | 157 | 135 | 273 | 187 | 191 | 164 | | | | 154 | 165 | 170 |
| SG+ | 0.726 | 0.7 | 0.823 | 0.7927 | 0.7818 | 0.7999 | 0.8777 | 0.808 | 0.831 | 0.823 | | | | 0.776 | 0.818 | 0.811 |
| Temp. F | 168 | 215 | 240 | 244 | 262 | 217 | 282 | 251 | 313 | 290 | 175 | 100 | 120 | 296 | 250 | 219 |
| Press psi | 2100 | 5015 | 2600 | 5367 | 4931 | 4415 | 8590 | 5361 | 6010 | 5030 | 5000 | 1703 | 2500 | 4669 | 4190 | 4825 |
| Exp Vis, cp | 0.0172 | 0.0592 | 0.0191 | 0.0350 | 0.0480 | 0.0700 | 0.1100 | 0.0960 | 0.0990 | 0.0910 | 0.030 | 0.023 | 0.030 | 0.042 | 0.100 | 0.090 |
| Predicted viscosity | | | | | | | | | | | | | | | | |
| CKB-D | 0.0170 | 0.0676 | 0.0192 | 0.0250 | 0.0270 | 0.0310 | 0.0480 | 0.041 | 0.039 | 0.037 | 0.029 | 0.019 | 0.027 | 0.028 | 0.044 | 0.054 |
| LGE | 0.0171 | 0.0658 | 0.0201 | 0.0300 | 0.0330 | 0.0400 | 0.1970 | 0.070 | 0.076 | 0.062 | 0.031 | 0.021 | 0.036 | 0.036 | 0.090 | 0.197 |
| DS | 0.0168 | 0.0592 | 0.0199 | 0.0280 | 0.0300 | 0.0350 | 0.0680 | 0.048 | 0.048 | 0.043 | 0.028 | 0.022 | 0.029 | 0.031 | 0.045 | 0.053 |
| Lacus | 0.0174 | 0.0670 | 0.0206 | 0.0300 | 0.0320 | 0.0360 | 0.0760 | 0.051 | 0.051 | 0.045 | 0.029 | 0.019 | 0.028 | 0.033 | 0.047 | 0.055 |
| LBK | 0.0212 | 0.0669 | 0.0255 | 0.0330 | 0.0370 | 0.0480 | 0.0720 | 0.071 | 0.072 | 0.062 | 0.024 | 0.015 | 0.020 | 0.037 | 0.042 | 0.083 |
| Pedersen | ----- | ----- | ----- | 0.0320 | 0.0360 | 0.0280 | 0.0670 | 0.079 | 0.075 | 0.066 | | | | -- | | -- |
| MPR-EOS | 0.0200 | 0.0620 | 0.0250 | 0.0370 | 0.0410 | 0.0590 | 0.1550 | 0.086 | 0.087 | 0.078 | 0.031 | 0.025 | 0.056 | 0.048 | 0.088 | 0.077 |

CKB-D: Carr-Kobayashi-Burrows-Dempsey, LGE: Lohrenz-Bray-Clark, DS: Dean-Stiel, LBK: Lee-Gonzalez-Eakin