Research Article

Prediction of Molar Volumes of the Sudanese Reservoir Fluids

A. A. Rabah¹ and S. A. Mohamed²

¹ Department of Chemical Engineering, University of Khartoum, P.O. Box 321, Khartoum, Sudan

² Department of Petroleum Transportation & Refining Engineering, College of Petroleum Engineering and Technology, Sudan University of Science and Technology, P.O. Box 566, Khartoum, Sudan

Correspondence should be addressed to A. A. Rabah, rabahss@hotmail.com

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This paper provided important experimental PVT data of the Sudanese reservoir fluids. It includes composition analysis of 11 mixtures and about 148 PVT data points of constant mass expansion (CME) tests at pressures below the bubble point. The datasets are compared with eight equations of state (EOS), namely, Peng Robinson (PR), Soave-Redlich-Kwong (SRK), Lawal-Lake-Silberberg (LLS), Adachi-Lu-Sugie (ALS), Schmidt-Wenzel (SW), Patel-Teja (PT), Modified-Nasrifar-Moshfeghian (MNM), and Harmens-Knapp (HK). The results of comparison reveals that, with the exception of PR and ALS EOSs, all other EOSs yield consistently a higher average absolute percent deviation (AAPD) in the prediction of molar volume; it exceeds 20% by all mixtures. The grand average AAPD of all mixtures is 17 and 16 for PR and ALS, respectively. ALS is selected to represents the mixtures. It is modified by replacing the coefficient (Ω_{b1}) of the parameter (b_1) in the dominator of repulsive term by that of PR. This procedure enhanced the accuracy of ALS by 30 to 90% for individual mixtures and the grand average AAPD is significantly reduced from 16 to about 7.

1. Introduction

In the absence of the experimental PVT study, properties such as isothermal compressibility factor, z -factor, and formation volume factor, are determined from empirically derived correlations or equations of state (EOSs). The correlations are basically developed for crude from certain geographical region with certain hydrocarbon and nonhydrocarbon contents and API. Hence such correlations may not be valid to crude oils of geographical regions other than those for which these correlations have been developed. Although EOSs are generalized correlations, their validity to different crudes varies.

Adepoju [1] has made extensive study on Texas oil and found that Peng Robinson (PR) [2], and Soave-Redlich-Kwong (SRK) [3] give a higher average absolute percent deviation (AAPD) in the prediction of the total volume of reservoir fluids. He obtained a good result when PR and SRK are modified by replacing the repulsion and attraction terms by that of Lawal-Lake-Silberberg (LLS) EOS

[4]. Akberzadeh et al. [5] have investigated the Modified-Nasrifar-Moshfeghian (MNM) EOSs, PR, and SRK for Western Canadian heavy oils. They have shown that MNM without any volume correction predicted the densities with accuracy similar to SRK EOS with volume correction.

Jensen [6] found that Adachi-Lu-Sugie (ALS) EOS [7] is the most accurate for prediction of the phase behavior of well-defined hydrocarbon mixtures with and without a considerable content of CO₂ or N₂. The ALS EOS seems to be well suited for calculation of the phase equilibrium of reservoir fluids but often proves to give inaccurate predictions of the densities of hydrocarbon mixtures [8]. By incorporating the volume translation principle of Peneloux et al. [9], ALS equation was found to give good results for hydrocarbon mixtures with and without a considerable content of CO₂ or N₂ [10].

Pedersen et al. [10] developed a characterization procedure for SRK coupled with the volume correction term of Peneloux et al. [9]. This procedure does not need experimental data and generally gives good prediction of saturation

TABLE 1: Mixtures composition analysis and reservoir conditions.

Comp.	1	2	3	4	5	6	7	8	9	10	11
N ₂	0.350	0.590	0.250	0.227	0.210	1.124	0.330	0.424	0.434	0.092	0.077
CO ₂	0.943	0.576	8.700	6.944	4.520	5.428	5.040	0.258	0.311	0.398	0.675
C1	21.048	41.840	1.750	1.445	1.310	0.926	1.330	25.373	12.893	14.666	29.035
C2	4.440	11.471	0.160	0.388	0.060	0.104	0.140	2.317	2.508	1.771	10.001
C3	4.525	7.631	0.110	0.664	0.050	0.444	0.110	0.700	1.176	0.145	7.747
iC4	3.173	1.384	0.020	0.252	0.020	0.195	0.030	1.524	2.180	0.43	1.229
nC4	3.287	1.885	0.040	0.392	0.030	0.199	0.060	0.239	0.234	0.03	4.102
iC5	2.704	1.320	0.010	0.306	0.010	0.169	0.020	2.550	1.497	0.441	1.177
nC5	2.233	1.687	0.020	0.381	0.020	0.397	0.030	0.119	0.257	0.06	2.249
C6	3.572	1.903	0.020	0.970	0.030	0.761	0.050	2.623	3.169	1.244	2.736
C7 ⁺	53.725	29.713	88.920	88.031	93.740	90.253	92.860	63.873	75.341	80.723	40.972
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
MWC7 ⁺	180.6	204.4	336.50	220.59	320.93	232.61	310.70	151.80	140.82	143.22	275.3
gC7 ⁺	0.816	0.835	0.895	0.845	0.896	0.852	0.896	0.788	0.775	0.778	0.843
T _R (°F)	172	223	234.0	236.0	231.0	235.0	247.0	179.3	165.0	165	244.0
P _B (Psig)	1804	3366	295.0	344.0	172.0	276.0	196.0	2362.0	1500.0	1571	1970.3
γ _{sat}	0.704	0.588	0.806	0.784	0.806	0.758	0.805	0.869	0.785	0.8021	0.672

points and vapor-liquid equilibrium. However, the model frequently calculates a too large liquid precipitation for gas condensate when simulating constant composition expansion experiments. In addition, prediction of liquid density is sometimes inaccurate, they added.

Almehaideb et al. [11] tested crude and gas samples from 17 UAE reservoirs and found that PR EOS predicted the density and bubble point pressure of UAE petroleum reservoir with an error of 9.28%. Yu and Chen [12] have evaluated PR and PT for binary and tertiary nonpolar and polar mixtures. For binary mixtures, the grand average AAPD for PR and RT is 9.69 and 10.39, respectively. For tertiary mixtures AAPD of PR and PT is 17.20 and 17.04, respectively. Kumer [13] has used 3100 data points of reservoir fluids mainly sweet and sour dry gases from various sources to evaluate the compressibility factor using eight EOSs, namely LLS, VDW, PR, RK, SRK, SW, PT, and Trebble-Bishnoi (TB). He concluded that LLS is superior to other EOSs in the prediction of z -factor.

Sudanese crude oil has come to surface on a commercial scale in the mid of 1990s, and there is little known in open literature about its PVT properties. Therefore the purpose of this work is to select an EOS that best represents the PVT data of the Sudanese reservoir fluids. The candidate EOSs includes PR, SRK, LLS, ALS, SW, PT, MNM, and HK.

2. PVT Study

Experimental PVT data were supplied by the *Ministry of Energy and Mining, Sudan*, for a number of wells representing different reservoirs. The data include compositional analysis of single carbon numbers of up to Eicosanes plus (C20⁺) and Hexatriacontanes plus (C36⁺) and PVT of CME of bottomhole samples. Table 1 shows the composition analysis of eleven reservoir fluids lumped up to C7⁺. Samples

1 and 2 are taken from [14], samples 3 to 11 are presented for the first time. The data also include bubble point pressure, reservoir temperature and molecular weight, and specific gravity of C7⁺. In some PVT reports, the molecular weight of C7⁺ is not available; under such condition it is obtained using the material balance as

$$M_{C_{n+}} = \frac{M_a - \sum_1^{C_{n+}-1} z_i M_i}{z_{C_{n+}}}, \quad (1)$$

where M_i and M_a are the component molecular weight and the apparent molecular weight, respectively, and z is the mole fraction. The plus fraction specific gravity is calculated as

$$\gamma_{C_{n+}} = \frac{1.008 M_{C_{n+}}}{42.43 + M_{C_{n+}}}. \quad (2)$$

The experimental error in pressure is ± 5 psi, temperature is $\pm 0.5^\circ\text{F}$, and cell volume is ± 0.3 cc as reported in PVT studies.

3. Flash Algorithm

Although flash calculation procedure is well documented, Figure 1 shows the Flash algorithm used in this work. The input data include the reservoir pressure (P), bubble point pressure (P_b), reservoir temperature (T), reservoir fluid composition (z_i), and the density and the molecular weight of C7⁺. For pure hydrocarbon and nonhydrocarbon, the critical properties (T_c, P_c, z_c), the molecular weight (MW), and the acentric factor (ω) are obtained from the generalized properties tables [15]. For C7⁺ the critical properties and the acentric factor are estimated for a given molecular weight and a specific gravity from Lawal-Tododo-Heinze [16] correlations. Binary interaction parameters (BIPs) for hydrocarbon-hydrocarbon, nonhydrocarbon-hydrocarbon, and nonhydrocarbon-nonhydrocarbon systems are taken as

Table 2 shows a calculation sample of mixture number 9. The rest of the results are given in Tables 6, 7, 8, and 9. Table 3

To compare EOSs to experimental data, numerous quality measurements based on statistical error analysis are computed. These include the percent deviation (PD), the average

TABLE 2: Calculation sample of mixture number 9.

P (Psia)	V_{exp} (lb/lbmole)	SRK	PR	ALS	LLS	HK	MNM	PT	SW
1514.7	2.348	5.05	34.15	8.25	30.72	17.53	21.05	21.54	21.37
1491.7	2.354	5.29	34.14	8.27	30.82	17.68	21.19	21.70	21.51
1480.7	2.357	5.40	34.14	8.12	30.87	17.75	21.25	21.76	21.59
1470.7	2.361	5.13	33.40	8.07	30.85	17.76	21.23	21.76	21.59
1449.7	2.367	5.37	33.41	8.09	30.95	17.90	21.34	21.89	21.72
1439.7	2.370	5.49	33.42	8.09	31.00	17.97	21.38	21.96	21.79
1430.7	2.373	5.61	33.43	8.08	31.02	18.02	21.41	22.00	21.83
1411.7	2.379	5.84	33.45	8.09	31.10	18.15	21.53	22.11	21.95
1401.7	2.382	5.95	33.45	8.10	31.16	18.23	21.60	22.20	22.03
1383.7	2.388	6.17	33.47	8.11	31.24	18.35	21.68	22.31	22.14
1374.7	2.392	6.32	33.50	8.07	31.23	18.36	21.68	22.31	22.15
1365.7	2.395	6.42	33.51	8.07	31.28	18.43	21.73	22.38	22.23
1341.7	2.404	6.74	33.54	8.06	31.37	18.58	21.83	22.52	22.36
1332.7	2.407	6.84	33.54	8.08	31.43	18.67	21.93	22.59	22.45
1309.7	2.417	7.18	33.60	8.03	31.48	18.77	21.99	22.68	22.53
1301.7	2.420	7.27	33.61	8.04	31.53	18.84	22.04	22.74	22.60
1286.7	2.426	7.46	33.63	8.05	31.61	18.95	22.12	22.85	22.71
1272.7	2.432	7.62	33.65	8.04	31.67	19.05	22.22	22.93	22.79
1251.7	2.442	7.92	33.72	8.00	31.72	19.17	22.28	23.02	22.90
1230.7	2.451	8.22	33.75	8.03	31.85	19.35	22.43	23.20	23.06
1217.7	2.458	8.43	33.80	7.99	31.87	19.41	22.46	23.24	23.12
1199.7	2.467	8.68	33.85	7.98	31.95	19.54	22.57	23.35	23.24
1169.7	2.483	9.13	33.93	7.93	32.07	19.74	22.71	23.53	23.43
1163.7	2.486	9.21	33.94	7.94	32.11	19.80	22.76	23.58	23.52
1141.7	2.499	9.51	34.01	7.90	32.18	19.94	22.86	23.69	23.63
1114.7	2.515	10.00	34.15	7.89	32.31	20.14	23.03	23.86	23.83
1066.7	2.546	10.84	34.41	7.85	32.54	20.52	23.31	24.18	24.18
948.7	2.641	3.98	23.41	7.62	32.84	21.42	24.00	24.87	24.96
709.7	2.960	6.88	23.13	6.61	33.58	23.18	25.30	26.02	26.43
574.7	3.279	7.79	21.75	5.40	33.86	24.26	26.09	26.54	27.24
487.7	3.599	8.28	20.53	4.62	33.68	24.68	26.33	26.49	27.46
424.7	3.919	8.41	19.36	3.46	33.50	25.04	26.54	26.48	27.63
376.7	4.240	8.39	18.27	2.82	33.33	25.34	26.78	26.41	27.78
338.7	4.557	7.77	16.76	2.40	33.34	25.77	27.11	26.51	28.07
	AAPD	7.19	31.00	7.36	31.88	19.89	22.82	23.39	23.47
	APD _{min}	3.98	16.76	2.40	30.72	17.53	21.05	21.54	21.37
	APD _{max}	7.19	31.00	7.36	31.88	19.89	22.82	23.39	23.47

shows the summary of statistical parameters for all mixtures. It is also shown in Table 3 the reservoir temperature, bubble point pressure, and C1 and C7⁺ content of each mixture. It should be noted that none of the mixtures at hand contains H₂S and they contain a little amount of CO₂ and N₂. The result of comparison reveals that none of EOSs has a grand average AAPD of less than 16. EOSs such as LLS, HK, MNM, PT and SW yield consistently high AAPD of all mixtures irrespective to their bubble point pressures and C1 and C7⁺ contents. The rest of EOSs (SRK, PR, and ALS) perform better for mixtures with a higher

C1 content than that of a lower C1 however, with few exceptions (e.g., mixture no. 2). In the overall evaluation ALS has the least grand average AAPD (=16) among all tested EOSs.

The reported inaccuracy is not peculiar to Sudanese reservoir fluids but it is rather a known problem associated with EOSs. Many investigators such as Coats and Smart [19] and Ahmed [20], to mention a few, have reported the inaccuracy of EOSs to reservoir fluids. The inaccuracy can be attributed to the following EOSs limitations and plus fraction properties.

TABLE 3: Summary of statistical parameters.

Mixture no.	SRK	PR	ALS	LLS	HK	MNM	PT	SW	Data points	C1 Mol%	C7+ Mol%	T °F	Pb Psig
1	11.09	9.84	9.45	30.77	23.77	26.08	27.89	26.72	10	21.05	53.73	172	1804.0
2	35.53	12.83	28.84	40.18	34.56	33.63	37.54	37.62	9	41.84	29.71	223	3366.0
3	43.01	30.02	19.10	39.46	30.85	38.33	31.02	29.73	9	1.75	88.92	234	295.0
4	33.27	20.79	19.36	50.10	37.99	42.04	39.76	40.29	15	1.45	88.03	236	344.0
5	41.73	29.03	19.67	41.29	31.32	38.20	32.04	30.83	9	1.31	93.74	231	172.0
6	25.42	13.94	11.50	42.04	29.97	33.88	31.33	31.76	14	0.93	90.25	235	266.0
7	22.27	7.76	11.56	46.09	33.69	40.33	33.72	33.31	8	1.33	92.86	247	196.0
8	22.55	3.15	27.56	47.70	37.31	38.95	40.66	40.85	11	25.37	63.87	179.3	2364.0
9	7.19	31.00	7.36	31.88	19.89	22.82	23.39	23.47	34	12.89	75.34	165	1485.3
10	5.04	25.72	8.55	26.73	15.47	18.03	18.28	18.61	23	14.67	80.72	165	1571.0
11	34.38	0.76	13.94	27.81	18.70	23.22	22.22	21.23	6	29.04	40.97	244	1970.3
Grand avr. AAPD	25.59	16.80	16.08	38.55	28.50	32.32	30.71	30.40					
APD _{min}	5.04	0.76	7.36	26.73	15.47	18.03	18.28	18.61	148*				
APD _{max}	43.01	31.00	28.84	50.10	37.99	42.04	40.66	40.85					

*Total number of data points.

TABLE 4: Calculation samples of mixtures numbers 1 and 6 with ALS in its original and modified forms.

Mixture no. 1				Mixture no. 6			
P	V _{exp}	AAPD		P	V _{exp}	AAPD	
Psia	lb/lb mole	Original	Modified	Psia	lb/lb mole	Original	Modified
1818.7	2.548	-13.08	-0.18	280.7	4.532	-16.76	-3.17
1765.7	2.573	-13.02	-0.24	279.7	4.538	-16.76	-3.19
1750.7	2.579	-13.06	-0.31	278.7	4.545	-16.73	-3.19
1473.7	2.763	-12.07	-0.17	276.7	4.556	-16.77	-3.25
1177.7	3.086	-10.41	0.25	271.7	4.592	-16.66	-3.25
993.7	3.411	-8.90	0.74	267.7	4.621	-16.59	-3.26
865.7	3.736	-7.56	1.24	233.7	4.918	-15.13	-2.61
769.7	4.062	-6.41	1.69	209.7	5.215	-13.90	-2.09
694.7	4.388	-5.42	2.08	175.7	5.810	-11.42	-0.82
634.7	4.711	-4.57	2.41	153.7	6.404	-8.60	1.01
				136.7	6.999	-6.16	2.64
				123.7	7.593	-3.82	4.29
				113.7	8.188	-1.50	6.02
				104.7	8.784	0.26	7.27
	AAPD	9.45	0.93	207.63	5.81	11.50	3.29
	APD _{min}	4.57	0.17	104.70	4.53	0.26	0.82
	APD _{max}	13.08	2.41	280.70	8.78	16.77	7.27

TABLE 5: AAPD of ALS after modification.

Statistical parameters	Mixtures										
	1	2	3	4	5	6	7	8	9	10	11
AAPD	0.93	19.68	7.51	7.53	6.14	3.29	6.50	15.54	5.16	5.53	1.55
APD _{min}	0.17	17.50	1.18	1.22	4.87	0.82	0.46	14.34	4.30	3.29	0.04
APD _{max}	2.41	20.85	10.81	9.29	8.23	7.27	13.44	16.54	5.60	13.24	3.00
Enhancement %	90.17	31.75	60.66	61.08	68.81	71.39	43.80	43.61	29.95	35.32	88.91

TABLE 6: PD of mixtures numbers 2 and 3.

P (psia)	V_{exp} (ft ³ /lbmole))	SRK	PR	ALS	LLS	HK	MNM	PT	SW
Mixture no. 2									
3380.7	1.787	-50.38	-8.17	-30.91	-43.78	-32.05	-34.19	-36.03	-35.68
3181.7	1.807	-49.59	-10.00	-32.37	-45.13	-33.58	-35.52	-37.68	-37.31
2234.7	2.129	-40.75	-12.61	-32.11	-43.41	-34.80	-34.63	-38.65	-38.24
1801.7	2.446	-36.05	-13.29	-30.54	-41.34	-35.00	-33.75	-38.29	-38.26
1531.7	2.765	-32.73	-13.73	-28.98	-39.54	-34.92	-33.07	-37.86	-38.01
1339.7	3.085	-30.21	-13.74	-27.63	-38.23	-34.88	-32.70	-37.51	-37.81
1194.7	3.405	-28.27	-13.79	-26.52	-37.23	-34.82	-32.48	-37.19	-37.59
1079.7	3.725	-26.86	-13.93	-25.66	-36.53	-34.81	-32.40	-36.95	-37.43
764.7	5.078	-24.96	-16.16	-24.81	-36.41	-36.16	-33.88	-37.65	-38.26
Mixture no. 3									
309.7	6.119	-51.65	-35.61	-22.17	-46.35	-36.18	-45.00	-36.33	-34.81
299.7	6.164	-51.82	-36.00	-22.70	-46.72	-36.23	-45.38	-36.77	-35.27
290.7	6.209	-52.07	-36.32	-23.13	-47.03	-36.68	-45.70	-37.15	-35.28
272.7	6.317	-52.14	-36.84	-23.95	-47.48	-37.30	-46.16	-37.36	-35.94
233.7	6.666	-51.10	-36.97	-24.94	-47.32	-37.68	-45.65	-37.74	-36.39
197.7	7.228	-47.75	-34.92	-23.99	-44.24	-35.92	-43.28	-35.99	-34.74
159.7	8.344	-39.27	-28.45	-19.20	-36.86	-29.63	-36.01	-29.70	-28.62
130.7	10.009	-27.17	-18.27	-10.70	-25.63	-19.55	-24.89	-19.63	-18.72
109.7	12.144	-14.08	-6.82	-1.12	-13.50	-8.48	-12.88	-8.54	-7.80

(1) High level of uncertainty in the prediction of the critical properties and the acentric factor of plus fraction which are not measured in the laboratory. Bearing in mind that plus fraction is the main constituent of mixtures. It constitutes more than 75% in most of the mixtures at hand (mixtures no. 3 to no. 7 and mixture no. 9). The inaccuracy in prediction of critical properties and acentric factor is due to the fact that the plus fraction lumps millions of compounds that only few of them (C7 to C36) are known by measurement. Hence it is expected that as the content of the plus fraction in the mixture increases the inaccuracy of EOS increases. This may justify the relatively good performance of SRK, PR and ALS for mixtures of a lower percentage of plus fraction.

(2) The parameters of the attraction term a , $\alpha(T)$ and covolume b of EOS are determined based on van der Waal critical point assumption while the reservoirs temperatures in this work (cf. Table 1) are higher than the critical temperatures of N₂, CO₂, C1, and C2. For mixtures numbers 1, 2, 8, and 11, these components together constitute more than 20% of the said mixture. This means that the applicability limit of EOS is violated and hence the inaccuracy of EOSs is not a surprise.

(3) Lack of information on BIPs of N₂-CO₂, N₂-hydrocarbon, and CO₂-hydrocarbon, However, the

presence of the nonhydrocarbon components (N₂ and CO₂) is small in the investigated mixtures.

(4) All EOSs used in this work contain three $[a, b, \alpha(T)]$ and four $[a, \alpha(T), b_1 \text{ and } b_2 \text{ or } c]$ parameters, hence besides the van der Waal critical point conditions, the parameters were determined by regressing experimental data for pure components. The commonly used experimental data for such a purpose include vapor pressure, normal boiling point and density at standard conditions ($T = 15^\circ\text{C}$ and $P = 1 \text{ atm}$). These data are generally for lower molecular weight components. Hence an EOS that developed on these data unlikely will suffice for reservoir fluid which contains a higher molecular weight plus fraction.

Because the inaccuracy of EOSs rests on the four reasons outlined above, a number of methods have been proposed over years to enhance the capability of EOS yet maintaining its original characteristics. These accuracy enhancement methods include the following.

- (1) Development of accurate models for the prediction of critical properties and acentric factor of plus fraction.
- (2) Application of a volume-translation technique such as Peneloux shift factor to the EOS.
- (3) Tuning EOS to experimental data. However, Pedersen [21] warned that “*using equation of state parameters “tuned” to one specific property yields unreliable predictions of other thermodynamic properties.*”

TABLE 7: PD of mixtures numbers 4 and 5.

P (psia)	V_{exp} (ft ³ /lbmole))	SRK	PR	ALS	LLS	HK	MNM	PT	SW
Mixture no. 4									
359.7	4.082	-40.11	-25.08	-23.04	-54.75	-41.00	-45.76	-43.22	-43.62
357.7	4.092	-40.00	-25.03	-23.00	-54.70	-40.97	-45.72	-43.19	-43.59
357.7	4.092	-40.00	-25.03	-23.00	-54.70	-40.97	-45.72	-43.19	-43.59
355.7	4.102	-39.90	-24.98	-22.96	-54.66	-40.96	-45.69	-43.17	-43.56
352.7	4.113	-39.89	-25.03	-23.03	-54.75	-41.07	-45.80	-43.27	-43.68
350.7	4.124	-39.76	-24.95	-22.97	-54.67	-41.03	-45.74	-43.22	-43.63
344.7	4.152	-39.66	-24.88	-22.96	-54.68	-41.09	-45.77	-43.26	-43.68
334.7	4.206	-39.16	-24.65	-22.79	-54.48	-41.03	-45.65	-43.16	-43.60
291.7	4.479	-36.95	-23.63	-21.70	-54.06	-40.82	-45.18	-42.77	-43.28
235.7	5.026	-32.82	-21.14	-19.77	-51.48	-38.94	-42.77	-40.56	-41.16
200.7	5.574	-28.75	-18.35	-17.40	-47.58	-36.80	-40.27	-38.19	-38.85
175.7	6.122	-25.13	-15.82	-15.22	-44.58	-34.64	-37.81	-35.85	-36.54
156.7	6.669	-22.10	-13.60	-13.20	-41.91	-32.67	-35.60	-33.74	-34.44
142.7	7.218	-18.94	-11.11	-10.85	-38.83	-30.21	-32.92	-31.16	-31.87
131.7	7.766	-15.87	-8.65	-8.54	-35.72	-27.65	-30.18	-28.51	-29.21
Mixture no. 5									
186.7	6.026	-46.53	-31.69	-20.37	-45.12	-33.43	-41.69	-34.61	-33.20
184.7	6.044	-46.49	-31.72	-20.45	-45.13	-33.48	-41.72	-34.65	-33.25
180.7	6.081	-46.43	-31.79	-20.61	-45.16	-33.58	-41.77	-34.75	-33.35
175.7	6.131	-46.32	-31.85	-20.80	-45.17	-33.68	-41.80	-34.84	-33.46
166.7	6.232	-46.13	-31.87	-21.01	-45.12	-33.94	-41.14	-34.36	-33.06
144.7	6.551	-44.98	-31.62	-21.47	-44.52	-33.87	-40.72	-34.27	-33.03
106.7	7.527	-40.44	-29.13	-20.64	-40.14	-31.64	-37.63	-32.01	-30.93
77.7	9.086	-32.75	-23.45	-17.51	-34.16	-27.01	-32.00	-27.34	-26.43
57.7	11.223	-25.52	-18.14	-14.21	-27.06	-21.25	-25.30	-21.52	-20.79

TABLE 8: PD of mixtures numbers 7 and 8.

P (psia)	V_{exp} (ft ³ /lbmole))	SRK	PR	ALS	LLS	HK	MNM	PT	SW
Mixture no. 7									
210.7	5.73	-23.11	-5.38	-7.24	-45.58	-31.02	-39.24	-31.09	-30.53
196.7	5.839	-22.64	-5.35	-7.90	-46.00	-31.75	-39.23	-31.81	-31.29
190.7	5.893	-22.25	-5.11	-8.18	-46.13	-32.03	-39.46	-32.08	-31.58
179.7	6.001	-22.05	-5.43	-8.76	-46.39	-32.53	-39.85	-32.58	-32.10
153.7	6.325	-21.36	-5.93	-9.71	-46.28	-33.78	-40.78	-33.81	-33.39
115.7	7.098	-21.24	-8.03	-12.93	-46.94	-35.47	-41.76	-35.47	-35.14
86.7	8.185	-21.36	-10.37	-16.35	-46.62	-36.55	-42.01	-36.53	-36.27
52.7	11.076	-24.15	-16.47	-21.43	-44.79	-36.42	-40.32	-36.43	-36.18
Mixture no. 8									
2310.7	1.995	-31.27	3.74	-29.60	-49.18	-34.73	-38.06	-39.07	-38.90
2251.7	2.007	-30.73	3.94	-29.57	-49.19	-34.90	-38.15	-39.23	-39.05
2036.7	2.058	-28.73	4.38	-29.50	-49.24	-35.58	-38.49	-39.88	-39.66
1867.7	2.11	-27.01	4.51	-29.34	-49.16	-36.06	-38.68	-40.31	-40.10
1563.7	2.24	-23.89	4.05	-28.81	-48.85	-36.95	-39.00	-41.01	-40.88
1202.7	2.502	-20.34	2.43	-27.94	-48.09	-37.93	-39.24	-41.53	-41.57
988.7	2.764	-18.56	0.67	-27.09	-47.21	-38.43	-39.33	-41.58	-41.83
842.7	3.028	-17.58	-0.91	-26.35	-46.66	-38.76	-39.40	-41.49	-41.93
737.7	3.292	-16.89	-2.17	-25.59	-46.06	-38.84	-39.30	-41.19	-41.80
655.7	3.556	-16.67	-3.44	-25.10	-45.77	-39.09	-39.42	-41.10	-41.87
593.7	3.812	-16.39	-4.38	-24.30	-45.33	-39.09	-39.36	-40.84	-41.73

TABLE 9: PD of mixtures numbers 10 and 11.

P (psia)	V_{exp} (ft ³ /lbmole))	SRK	PR	ALS	LLS	HK	MNM	PT	SW
Mixture no. 10									
1585.7	2.406	-1.38	27.91	-10.65	-33.03	-18.90	-22.33	-22.57	-22.78
1565.7	2.41	-1.24	27.85	-10.71	-33.15	-19.05	-22.47	-22.72	-22.93
1552.7	2.415	-1.05	27.88	-10.64	-33.11	-19.04	-22.44	-22.71	-22.93
1540.7	2.42	-0.86	27.91	-10.43	-33.05	-19.01	-22.40	-22.67	-22.89
1528.7	2.424	-0.73	27.91	-10.41	-33.04	-19.04	-22.41	-22.69	-22.91
1499.7	2.435	-0.35	27.94	-10.31	-32.98	-19.05	-22.39	-22.69	-22.91
1471.7	2.446	0.02	27.97	-10.21	-32.92	-19.07	-22.38	-22.70	-22.92
1445.7	2.457	0.38	28.00	-10.10	-32.85	-19.07	-22.35	-22.69	-22.91
1369.7	2.492	1.42	28.10	-9.78	-32.62	-19.03	-22.24	-22.62	-22.84
1326.7	2.514	2.05	28.17	-9.58	-32.45	-19.00	-22.15	-22.58	-22.79
1247.7	2.558	3.23	28.36	-9.25	-32.17	-18.98	-22.04	-22.50	-22.64
1275.7	2.542	2.79	28.27	-9.35	-32.26	-18.98	-22.07	-22.52	-22.73
1270.7	2.545	2.94	28.35	-9.33	-32.23	-18.97	-22.05	-22.51	-22.72
1246.7	2.559	3.24	28.38	-9.23	-32.14	-18.96	-22.02	-22.50	-22.70
1211.7	2.582	3.80	28.49	-9.02	-31.95	-18.88	-21.89	-22.38	-22.60
1176.7	2.605	4.36	28.62	-8.86	-31.81	-18.87	-21.83	-22.33	-22.55
777.7	3.063	7.56	24.79	-5.72	-27.78	-17.10	-19.43	-20.03	-20.31
439.7	4.218	11.15	21.87	-0.67	-20.27	-12.44	-13.85	-14.17	-14.58
311.7	5.379	12.00	19.81	2.66	-15.37	-8.99	-9.87	-9.99	-10.53
243.7	6.536	12.81	18.99	4.86	-11.33	-6.34	-7.14	-7.03	-7.69
201.7	7.695	13.70	18.82	6.87	-8.23	-3.95	-4.66	-4.38	-5.13
171.7	8.854	14.04	18.42	8.13	-6.17	-2.44	-3.07	-2.65	-3.49
150.7	10.012	14.78	18.63	9.87	-3.97	-0.68	-1.25	-0.71	-1.62
Mixture no. 11									
1985	3.137	-39.42	0.28	-13.20	-27.27	-18.19	-22.30	-20.55	-19.42
1860	3.210	-37.26	-0.04	-13.54	-27.45	-18.80	-22.58	-21.13	-20.04
1728	3.304	-34.90	-0.69	-13.83	-27.63	-18.80	-22.92	-21.81	-20.78
1617	3.398	-33.02	-0.93	-14.09	-27.86	-18.80	-23.33	-22.52	-21.57
1523	3.489	-31.54	-1.22	-14.39	-28.19	-18.80	-23.86	-23.30	-22.42
1441	3.583	-30.15	-1.43	-14.59	-28.44	-18.80	-24.32	-23.98	-23.17

- (4) Modification of the expression used in the denominator of the attractive term Yu et al. [22]. This method as mentioned earlier is employed by Adepoju [1]. He has made a significant improvement in the accuracy of PR and SRK by replacing their parameters by those of LLS.

In this work ALS EOS which produced the least grand average AAPD (=16) of all mixtures is considered as the candidate to predict PVT data of the Sudanese reservoir fluids. Enhancement procedure, using the technique number 4 listed above, is considered.

Prior to the employment of the modification, ALS is described as

$$\begin{aligned}
 P &= \frac{RT}{v - b_1} - \frac{a(T)}{(v - b_2)(v + b_3)}, \\
 b_i &= \frac{\Omega_{bi}RT_c}{P_c}, \quad i = 1, 2, 3, \\
 a(T) &= \frac{\Omega_a(RT_c)^2\alpha(T)}{P_c},
 \end{aligned} \quad (5)$$

$$\Omega_a = 0.44869 + 0.04024\omega + 0.01111\omega^2 - 0.00576\omega^3, \quad (6a)$$

$$\Omega_{b1} = 0.08974 - 0.03452\omega + 0.00330\omega^2, \quad (6b)$$

$$\Omega_{b2} = 0.5 \left[2(1 + \Omega_{b1}) - 3\Omega_a^{1/3} + (4\Omega_a - 3\Omega_a^{2/3})^{1/2} \right], \quad (6c)$$

$$\Omega_{b3} = 0.5 \left[-2(1 + \Omega_{b1}) + 3\Omega_a^{1/3} + (4\Omega_a - 3\Omega_a^{2/3})^{1/2} \right]. \quad (6d)$$

The modification includes the replacement of the first term of the coefficient Ω_{b1} (cf. (6b)) by that of PR EOS ($\Omega_b = 0.07780$). Hence the modified form of Ω_{b1} is

$$\Omega_{b1} = \underbrace{0.07780}_{\text{PR}} - 0.03452\omega + 0.00330\omega^2. \quad (7)$$

Remember that the modification of Ω_{b1} will automatically modify the coefficients Ω_{b2} and Ω_{b3} .

Table 4 shows calculation samples of mixtures numbers 1 and 6. Table 5 shows the summary of AAPD for all mixtures after the modification of the ALS parameters. It can be seen

that the accuracy of ALS enhanced by a factor of 30 to 90%. The grand average AAPD is reduced significantly from 16 to 7.

5. Conclusion

The work provided important information on PVT data on Sudanese reservoir fluids. It includes composition analysis of fraction plus up to C7+ and about 148 data points of CME test (pressure-volume data) at pressures below the bubble point. The paper presents also a modified form of ALS that describes the Sudanese reservoir fluids with a good level of accuracy.

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