Measurement and correlation of compressibility factor of high CO_2-content natural gas

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ABSTRACT

The JEFRI-PVT apparatus made in Canada by the Schlumberger company has been used to obtain accurate compressibility factor measurements on high CO_2-content natural gasses so as to study the effect of different CO_2 content on gas compressibility factor (range covered: temperature, 263.15 K to 313.15 K; pressure, 3 MPa to 15 MPa; CO_2 content, 9.84, 28.86 and 50.99 mol%). The results showed that gas compressibility factors reduce with increasing CO_2 content in natural gasses and increase with increasing temperature. In addition, a non-integral power polynomial correlation was proposed without an iterative procedure whose coefficients were determined by fitting experimental data. The mixing rules used include: Kay's mixing rule combined with Wichert-Aziz correlations (Kay) and Stewart-Burkhardt-Voo mixing rule with Wichert-Aziz (SBV). Comparison of the DAK-SBV, DAK-Kay, and proposed correlations showed that the presented model yielded the most accurate predictions with the lowest average absolute deviation (0.42%) among them.

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1. Introduction

In recent years, more and more high CO_2-content gas reservoirs in the world have been discovered (Jokhio et al., 2001). Different CO_2 content leads to different gas compressibility factor which is involved in calculating gas properties such as formation volume factor, density, compressibility, and viscosity (Shokir, 2008).

Prediction of gas compressibility factor commonly contains three methods: experiment (Adisoemarta et al., 2004), equation of state (Li and Guo, 1991), and empirical formula (Heidaryan et al., 2010). Experimental measurement of gas compressibility factor is the most accurate among all methods. Several correlations fitting the Standing and Katz chart (Standing and Katz, 1942) can be used to calculate the gas compressibility factor (Dranchuk and Abou-Kasem, 1975; Dranchuk et al., 1974; Hall and Yaborough, 1973). But Dranchuk-Abou-Kassem (DAK) correlation is the most accurate. In addition, among the mixing rules (Bahadori et al., 2007; Elsharkawy and Elkamel, 2001; Sutton, 2007), Kay (1936) and Stewart et al. (1959) mixing rules are the most widely used. Kay's mixing rule is simple. SBV mixing rule provided the most satisfactory results (Satter and Campbell, 1963).

Since the presence of CO_2 gas, prediction of the compressibility factor is much more difficult than that of sweet gasses. Wichert and Aziz (1972) presented corrections for the presence of hydrogen sulfide (H_2S) and/or CO_2 for determining compressibility factor of sour gasses. Fortunately, in the present study, due to the absence of C_{7+} fraction, the critical properties of the C_{7+} fraction are not calculated from correlations (Pedersen et al., 1989).

This study has two objectives. The first objective is to measure gas compressibility factor for different CO_2-content natural gasses (CO_2 content is about 10%, 30% and 50%, respectively) by applying JEFRI-PVT experimental equipments which were made in Canada by the Schlumberger company. The second objective is to develop a non-iterative empirical correlation to estimate gas compressibility factor based on the experimental results, and to make a comparison among the proposed model, DAK-SBV and DAK-Kay correlation.

2. Experiment

2.1. Experimental material

CO_2 was purchased from Southwest Oil and Gas Field Company, Chengdu, China, with a purity of 99.99 mol%, and natural gas was directly taken from surface separator in Xusheng gas field, Daqing, China. All the samples were used without further purification.

Strictly speaking, this is a synthetic gas prepared in the lab. As a result, CO_2 and natural gas was mixed as follows:

Firstly, natural gas from surface separator was introduced into the equilibrium cell.
Secondly, CO_2 was added to the equilibrium cell.
Finally, stir the gas mixture well and control the cell to the desired temperature and pressure.

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2.2. Measured principles

For dry gasses, compressibility factor can be calculated using the following equation:

$$Z = \frac{P \cdot \Delta V \cdot T_s}{P_s \cdot V_s \cdot T} \tag{1}$$

In the above equation, it is of great significance to control the ambient temperature (T_s). For this experiment, the ambient temperature was about $20\,°C \pm 0.5\,°C$. When the gas was released from PVT cell, the released gas passed through a flash separator which was soaked in a constant temperature water bath whose temperature was controlled to $20\,°C$. During this period, we ensured that the gas flow rate was very slow so that the released gas temperature became the ambient temperature.

2.3. Experimental apparatus and procedure

In this study, mercury free DBR-PVT vessels were used to measure gas compressibility factors. A schematic diagram of the apparatus is shown in Fig. 1.

The experimental apparatus used consisted of PVT vessel of approximately 135 ml capacity, automatic pump, gas chromatography, dry gasometer, constant temperature air bath, flash separator and ground separator.

Experimental procedure:

(1) Clean PVT vessel and cells, then connect the PVT vessel to the cells and evacuate the cells;
(2) Control and maintain the desired temperature using the constant-temperature air bath;
(3) Introduce a test gas (about 100 ml) into PVT vessel at the specified temperature and pressures in the oven and keep 5 h, then hold up half an hour and measure the gas volumes of the PVT vessel;
(4) Slightly open the valve between the cells and bleed gas from the PVT vessel into the flash separators, at the same time, keep the pressures of the PVT vessel constant using automatic pump;
(5) Record the bled gas volumes and remaining gas volumes of PVT vessel;
(6) Use Eq. (1) to determine Z-factors;

Table 1
Composition of gas mixtures and critical properties of defined component.

Component	Sample 1	Sample 2	Sample 3	P_c/MPa	T_c/K	Mw/g·mol^{-1}
	Mole fraction					
CO_2	0.0984	0.2886	0.5099	7.38	304.1	44.01
N_2	0.0205	0.0124	0.0083	3.39	126.20	28.013
C_1	0.8602	0.6773	0.4654	4.60	190.4	16.043
C_2	0.0167	0.0159	0.0116	4.88	305.4	30.07
C_3	0.0031	0.0042	0.0033	4.25	369.8	44.094
iC_4	0.0004	0.0006	0.0005	3.65	408.2	58.124
nC_4	0.0005	0.0007	0.0006	3.80	425.2	58.124
iC_5	0.0001	0.0003	0.0002	3.39	460.4	72.151
nC_5	–	0.0001	0.0001	3.37	469.7	72.151
C_6	0.0001	–	–	3.01	507.5	86.178

Repeat procedures (4)–(6), and ensure that tested Z-factors are about the same at least three times. For more detailed descriptions see SY/T 6434-2000 and Varotsis and Pasadakis (1996)

2.4. Experimental results

The gas samples used were analyzed using a HP-6890 Gas Chromatograph. The results of analysis were shown in Table 1. The critical pressure and temperature for the pure components normally present in natural gasses are also provided in Table 1 (Reid et al., 1987).

Experimental compressibility factors for different CO_2-content natural gasses were listed in Table 2. Table 2 indicated that compressibility factors reduce with increasing CO_2 content in natural gasses and pressures, but increase with increasing temperature.

3. Methods

3.1. Existing methods

When gas composition is available, pseudo critical properties are calculated using a given mixing rule. In the present work, Kay and SBV mixing rules are considered. Kay's mixing rule, based on molar weighted average critical properties, has the following form:
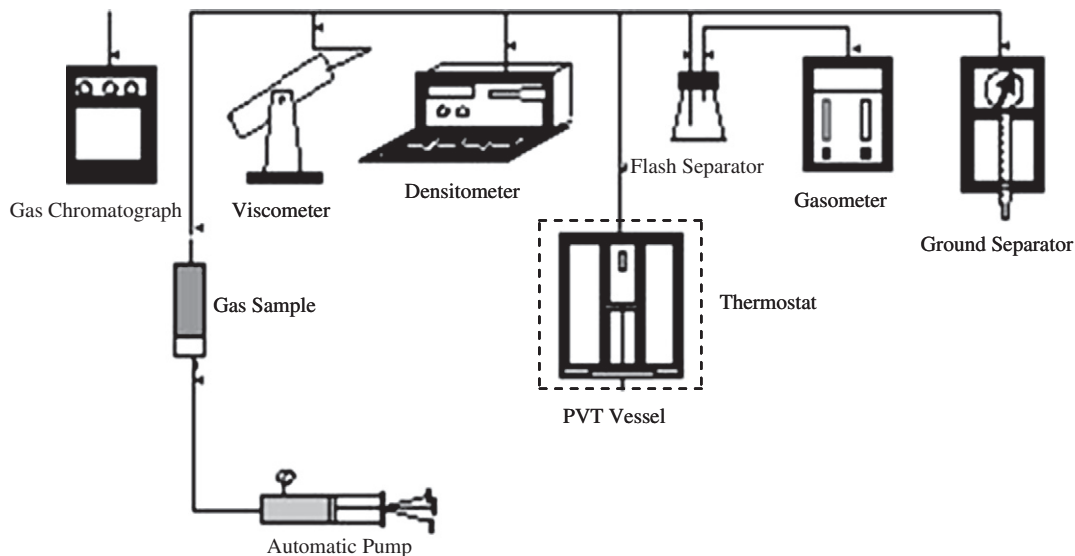
$$P_{pc} = \sum_{i=1}^{n_c} y_i P_{ci} \tag{2}$$

Fig. 1. Schematic diagram of the experimental apparatus.

Table 2
Experimental compressibility factors for high CO_2 natural gasses.

Pressure (MPa)	Sample 1					
	313.15 K	303.15 K	293.15 K	283.15 K	273.15 K	263.15 K
3.00	0.9423	0.9307	0.9196	0.9028	0.8959	0.8833
5.00	0.9128	0.8992	0.8803	0.8608	0.8483	0.8337
7.00	0.8901	0.8721	0.8518	0.8252	0.8037	0.7829
9.00	0.8711	0.8563	0.8280	0.7981	0.7719	0.7410
11.00	0.8607	0.8369	0.8079	0.7809	0.7495	0.7054
13.00	0.8500	0.8309	0.8013	0.7714	0.7324	0.6901
15.00	0.8452	0.8286	0.8001	0.7691	0.7303	0.6860
	Sample 2					
	313.15 K	303.15 K	293.15 K	283.15 K	273.15 K	265.65 K
4.21	–	–	–	0.8892	–	–
4.50	–	–	0.8891	–	0.8505	–
5.00	0.9025	0.8941	0.8718	0.8595	0.8297	0.8066
6.00	0.8745	0.8605	0.8452	0.8344	0.7998	0.7600
7.00	0.8576	0.8358	0.8161	0.8087	0.7710	0.7202
9.00	0.8277	0.8010	0.7809	0.7524	0.7109	0.6589
11.00	0.7957	0.7661	0.7406	0.7075	0.6719	0.6137
13.00	0.7644	0.7429	0.7136	0.6743	0.6395	0.5854
15.00	0.7513	0.7290	0.6882	0.6594	0.6431	0.5877
	Sample 3					
	313.15 K	303.15 K	293.15 K	283.15 K	275.85 K	
4.00	–	–	0.8859	0.8574	0.8386	
4.50	0.9118	0.8927	–	–	–	
5.00	0.9002	0.8710	0.8353	0.8099	0.7674	
6.00	0.8627	0.8247	0.7961	0.7710	0.6992	
7.00	0.8246	0.7893	0.7683	0.7335	0.6470	
9.00	0.7630	0.7423	0.7017	0.6402	0.5576	
11.00	0.7158	0.7052	0.6483	0.5653	0.4915	
13.00	0.6787	0.6735	0.6117	0.5211	0.4771	
15.00	0.6565	0.6507	0.5890	0.5246	0.4937	

$$T_{pc} = \sum_{i=1}^{n_c} y_i T_{ci} \tag{3}$$

SBV mixing rule can be expressed as below:

$$J = \frac{1}{3}\sum_{i=1}^{n_c}\left(\frac{yT_c}{p_c}\right)_i + \frac{2}{3}\left[\sum_{i=1}^{n_c}\left(y\sqrt{\frac{T_c}{p_c}}\right)_i\right]^2 \tag{4}$$

$$K = \sum_{i=1}^{n_c}\left(\frac{yT_c}{\sqrt{p_c}}\right)_i \tag{5}$$

$$T_{pc} = K^2/J \tag{6}$$

$$P_{pc} = T_{pc}/J \tag{7}$$

Eqs. (2) and (3) or Eqs. (4)–(7) provide critical properties for sweet natural gas systems. For high CO_2 natural gasses, these equations must be corrected for the presence of non-hydrocarbon components. The method proposed by Wichert and Aziz (1972) (WA) is used to correct the pseudo critical properties of natural gasses to H_2S and/or CO_2 components. The WA correlation is given as follows:

$$\xi = \frac{5}{9}\left[120\left(A^{0.9} - A^{1.6}\right) + 15\left(B^{0.5} - B^4\right)\right] \tag{8}$$

$$T'_{pc} = T_{pc} - \xi \tag{9}$$

$$P'_{pc} = \frac{p_{pc}T'_{pc}}{T_{pc} + B(1-B)\xi} \tag{10}$$

Reduced pressure and temperature for the system are calculated as follows:

$$P_r = \frac{P}{P'_{pc}} \tag{11}$$

$$T_r = \frac{T}{T'_{pc}} \tag{12}$$

DAK correlation is extensively used to calculate the gas compressibility factor using reduced pressure and reduced temperature as below:

$$Z = 1 + \left(A_1 + \frac{A_2}{T_r} + \frac{A_3}{T_r^3} + \frac{A_4}{T_r^4} + \frac{A_5}{T_r^5}\right)\rho_r + \left(A_6 + \frac{A_7}{T_r} + \frac{A_8}{T_r^2}\right)\rho_r^2$$
$$- A_9\left(\frac{A_7}{T_r} + \frac{A_8}{T_r^2}\right)\rho_r^5 + A_{10}\left(1 + A_{11}\rho_r^2\right)\left(\frac{\rho_r^2}{T_r^3}\right)\exp\left(-A_{11}\rho_r^2\right) \tag{13}$$

$$\rho_r = 0.27\frac{P_r}{ZT_r} \tag{14}$$

Where $A_1 = 0.3265$, $A_2 = 1.07$, $A_3 = 0.5339$, $A_4 = 0.01569$, $A_5 = 0.05165$, $A_6 = 0.5475$, $A_7 = 0.7361$, $A_8 = 0.1844$, $A_9 = 0.1056$, $A_{10} = 0.6134$, $A_{11} = 0.721$.

Because the gas compressibility factor appears on both sides of DAK's correlation (Eq. (13)), a Newton–Raphson iteration method is used.

3.2. Proposed method

According to Maclaurin's expansion, the following equation can be obtained:

$$f(x) \approx f(0) + f'(0)x + \frac{f''(0)}{2!}x^2 + \cdots + \frac{f^{(n)}(0)}{n!}x^n \tag{15}$$

Eq. (15) is an integral polynomial. Independent variable x is transformed to the power function x^a, which can improve the fitting accuracy greatly under the condition of the same number of terms (Sheng et al., 2004). That is, continuous function can be approximate to the following non-integral power polynomial:

$$g(x) \approx a_0 + a_1 x^b + a_2 x^{2b} + \cdots + a_n x^{nb} \tag{16}$$

Where b in Eq. (16) is an undetermined parameter and a_0 is equal to $g(0)$. If $b = 1$, Eq. (16) reduces to Eq. (15).

In order to illustrate the rationality of Eq. (16), suppose $b > 0$. Then differentiation of Eq. (16) with respect to x and letting $x = 1$ yield:

$$\begin{cases} g'(1) = ba_1 + 2ba_2 + 3ba_3 + \cdots + nba_n \\ g''(1) = b(b-1)a_1 + 2b(2b-1)a_2 + \cdots + nb(nb-1)a_n \\ \vdots \\ g^{(n)}(1) = b(b-1)\cdots[b-(n-1)]a_1 + 2b(2b-1)\cdots[2b-(n-1)]a_2 \\ \qquad\qquad + \cdots + nb(nb-1)\cdots[nb-(n-1)]a_n \end{cases} \tag{17}$$

The coefficients a_i ($i = 1, 2,\ldots, n$) can be determined through Eq. (17). In common, when fitting experimental data, let $n = 3$, which can be sufficient to satisfy an engineering requirement. Therefore, Eq. (16) can be rewritten as follows:

$$g(x) = g(0) + \frac{1}{2b^3}\left[\left(6b^2 - 5b + 1\right)g'(1) - (5b-3)g''(1) + g'''(1)\right]x^b$$
$$+ \frac{1}{2b^3}\left[-\left(3b^2 - 4b + 1\right)g'(1) + (4b-3)g''(1) - g'''(1)\right]x^{2b}$$
$$+ \frac{1}{6b^3}\left[\left(2b^2 - 3b + 1\right)g'(1) - 3(b-1)g''(1) + g'''(1)\right]x^{3b} \tag{18}$$

Table 3
Comparison of the precision of Eqs. (15) and (18) approximating to $y = (1+x)^{2.5}$.

x	0	0.4	0.8	1	1.2	1.6	2	2.4	3	AAD/%
y	1	2.3191	4.3469	5.6569	7.1789	10.9002	15.5885	21.3156	32.0000	/
f	1	2.3200	4.3600	5.6875	7.2400	11.0800	16.0000	22.1200	33.8125	1.718
$g(b=0.92)$	1	2.3365	4.3635	5.6734	7.1954	10.9177	15.6121	21.3585	32.1195	0.282
$g(b=0.96)$	1	2.3194	4.3457	5.6556	7.1777	10.9004	15.5976	21.3523	32.1466	0.086
$g(b=1.00)$	1	2.3046	4.3305	5.6404	7.1624	10.8854	15.5841	21.3435	32.1569	0.256

When the conditions of the same number of terms between Eqs. (15) and (16) apply, Eq. (15) becomes:

$$f(x) = f(0) + f'(0)x + \frac{f''(0)}{2}x^2 + \frac{f'''(0)}{6}x^3 \qquad (19)$$

In order to indicate the accuracy of Eqs. (18) and (19), a random function $y = (1+x)^{2.5}$ is taken for example (see Table 3). The average absolute deviations (AAD) and absolute relative deviations (ARD) in the subsequent tables are, respectively, defined as:

$$AAD(\%) = \frac{1}{n_c} \sum_{i=1}^{n_c} \left| \frac{Cal. - Exp.}{Exp.} \right|_i \times 100 \qquad (20)$$

$$ARD(\%) = \left| \frac{Cal. - Exp.}{Exp.} \right|_i \times 100 \qquad (21)$$

Table 3 showed that Eq. (18), whose AAD = 0.086% and b = 0.96, significantly improved the accuracy of the prediction of $y = (1+x)^{2.5}$ as compared with Eq. (19) (AAD = 1.718%).

Eq. (18) was extended to apply to bi-variant one as follows:

$$\begin{aligned}
g(x,t) &= a_0(t) + a_1(t)x^b + a_2(t)x^{2b} + a_3(t)x^{3b} \\
a_0(t) &= c_{0,0} + c_{1,0}t^{\beta_0} + c_{2,0}t^{2\beta_0} + c_{3,0}t^{3\beta_0} \\
a_1(t) &= c_{0,1} + c_{1,1}t^{\beta_1} + c_{2,1}t^{2\beta_1} + c_{3,1}t^{3\beta_1} \\
a_2(t) &= c_{0,2} + c_{1,2}t^{\beta_2} + c_{2,2}t^{2\beta_2} + c_{2,2}t^{3\beta_2} \\
a_3(t) &= c_{0,3} + c_{1,3}t^{\beta_3} + c_{2,3}t^{2\beta_3} + c_{3,3}t^{3\beta_3}
\end{aligned} \qquad (22)$$

Finally, a new correlation of gas compressibility factors for high CO_2-content natural gasses can be obtained:

$$\begin{aligned}
Z(P_r, T_r) &= a_0(T_r) + a_1(T_r)P_r^\alpha + a_2(T_r)P_r^{2\alpha} + a_3(T_r)P_r^{3\alpha} \\
a_0(T_r) &= A_a + B_a T_r^{\beta_0} + C_a T_r^{2\beta_0} + D_a T_r^{3\beta_0} \\
a_1(T_r) &= A_b + B_b T_r^{\beta_1} + C_b T_r^{2\beta_1} + D_b T_r^{3\beta_1} \\
a_2(T_r) &= A_c + B_c T_r^{\beta_2} + C_c T_r^{2\beta_2} + D_c T_r^{3\beta_2} \\
a_3(T_r) &= A_d + B_d T_r^{\beta_3} + C_d T_r^{2\beta_3} + D_d T_r^{3\beta_3}
\end{aligned} \qquad (23)$$

Where α, β_i ($i = 0, 1, 2, 3$) and A_i, B_i, C_i, D_i ($i = a, b, c, d$) are undetermined coefficients which can be obtained by fitting experimental data. That is, the model coefficients can be obtained as below:

Step 1: Suppose an initial value $\alpha^{(0)}$;
Step 2: Choose a $T_r^{(1)}$ and regress the corresponding experimental data ($P_r^{(m)}$, $Z_{exp}^{(m)}$) using Eq. (23) ($m = 1, 2, ..., n_c$, where n_c is the number of experimental Z-factors. for example, at 313.15 K, $n_c = 7$ and $n_c = 8$ for sample 1 and 3, respectively.), then, one obtains $a_0^{(1)}$, $a_1^{(1)}$, $a_2^{(1)}$, $a_3^{(1)}$;
Step 3: Change $T_r^{(i)}$ ($i = 2, ..., 6$ for Sample 1 and 2; $i = 2, ..., 5$ for Sample 3.), then obtain $a_0^{(i)}$, $a_1^{(i)}$, $a_2^{(i)}$, $a_3^{(i)}$ and AAD;
Step 4: Change the initial value $\alpha^{(1)}$ consecutively, repeat steps 2–3, then one can find the best value $\alpha^{(j)}$ and corresponding $a_0^{(j)}$, $a_1^{(j)}$, $a_2^{(j)}$ and $a_3^{(j)}$ at different temperature, which results in the minimum AAD;
Step 5: Suppose an initial value $\beta_0^{(0)}$;
Step 6: Regress the data ($Tr^{(i)}$, $a_0^{(i)}$), then obtain $A_a^{(0)}$, $B_a^{(0)}$, $C_a^{(0)}$, $D_a^{(0)}$ and an AAD.
Step 7: Change the initial value $\beta_0^{(1)}$ consecutively, repeat step 6, one finally can discover the best value $\beta_0^{(j)}$ and corresponding model parameters A_a, B_a, C_a, and D_a.
Step 8: Similarly, repeat steps 5–7, one can obtain the other parameters which are listed in Table 4.

According to above analysis, the 16 coefficients of temperature correlations are reliable. In essence, we use the trial-and-error method to obtain the model coefficients so as to get the minimum AAD.

4. Comparison of the proposed method and other methods

The tuned coefficients of Eq. (23) can be obtained by fitting experimental data using MATLAB 7.0 (Table 4). But the tuned coefficients of the correlation needed refitting for different samples.

Table 5 showed the absolute relative deviations of calculated compressibility factors of samples 2 and 3 by different methods. Fig. 2(a–c) showed the predicted gas compressibility factors from the new model

Table 4
The tuned coefficients of the proposed model for different samples.

Sample 1	A_a	−8.816390	B_a	24.405726	C_a	−16.945150	D_a	2.132880
	A_b	12.520235	B_b	−31.429384	C_b	21.474317	D_b	−2.280668
	A_c	−5.306294	B_c	13.338221	C_c	−9.046675	D_c	0.813848
	A_d	0.747085	B_d	−1.874226	C_d	1.266354	D_d	0.0965256
	α	0.8	$\beta_0, \beta_1, \beta_2$	2.1	β_3	2.5		
Sample 2	A_a	28.574773	B_a	−45.647110	C_a	20.748488	D_a	−3.328087
	A_b	−41.125073	B_b	65.179604	C_b	−29.974701	D_b	5.006821
	A_c	20.274849	B_c	−30.885941	C_c	14.296895	D_c	−2.482498
	A_d	−3.301408	B_d	4.837914	C_d	−2.249317	D_d	0.4058196
	α	1.1	β_0, β_3	2.2	β_1, β_2	2.3		
Sample 3	A_a	79.235341	B_a	−166.38253	C_a	88.823846	D_a	−13.588054
	A_b	−130.68757	B_b	277.43880	C_b	−149.32077	D_b	22.973990
	A_c	72.278392	B_c	−153.47652	C_c	83.105283	D_c	−12.845033
	A_d	−13.225356	B_d	28.118034	C_d	−15.304644	D_d	2.374806
	α	1.2	$\beta_0, \beta_1, \beta_2, \beta_3$	2.5				

compared to the results of the DAK-SBV and DAK-Kay compressibility factor correlations versus the measured gas compressibility of Sample 3.

As can be seen from Table 5 and Fig. 2, the proposed method was the most accurate of the three methods tested, giving an overall average absolute deviation of 0.42%. In the order of accuracy DAK-Kay (AAD = 1.63%) and DAK-SBV (AAD = 1.64%) came in the second and third order. In addition, the new method had an additional advantage of non-iterative computation.

5. Conclusions

In this work, compressibility factors of natural gasses with different CO_2 contents (9.84, 28.86 and 50.99 mol%, respectively) in the temperatures from 263.15 K to 313.15 K and pressures from 4 MPa to 15 MPa were measured. On the basis of limited experimental evidence, it can be concluded that gas compressibility factors reduce with increasing CO_2 content in natural gasses and increase with increasing temperatures.

The proposed model was an explicit correlation and yielded the most accurate prediction with the lowest average absolute deviation (0.42%) among three tested gas compressibility factor correlations.

Table 5
The results of average relative deviation by different method (ARD,%).

Pressure/ MPa	This model	DAK-SBV	DAK-Kay's	This model	DAK-SBV	DAK-Kay's	This model	DAK-SBV	DAK-Kay's
Sample 1									
313.15 K			303.15 K			293.15 K			
3.00	0.02	0.96	0.88	0.02	1.59	1.51	0.16	2.09	1.99
5.00	0.02	0.91	0.78	0.08	1.33	1.18	0.10	2.20	2.02
7.00	0.08	0.40	0.20	0.29	0.87	0.63	0.04	1.35	1.08
9.00	0.37	0.14	0.41	0.13	0.48	0.79	0.09	0.41	0.04
11.00	0.22	1.15	1.48	0.64	0.82	1.20	0.68	0.27	0.72
13.00	0.59	1.49	1.88	0.65	1.98	2.43	0.54	1.67	2.19
15.00	0.71	1.84	2.27	1.09	2.75	3.23	0.72	2.70	3.25
283.15 K			273.15 K			263.15 K			
3.00	0.31	3.12	3.01	0.20	2.90	2.77	0.10	3.15	3.01
5.00	0.13	2.95	2.74	0.34	2.58	2.34	0.01	2.09	1.81
7.00	0.22	2.28	1.96	0.05	2.14	1.77	0.10	1.28	0.83
9.00	0.26	1.08	0.65	0.12	0.68	0.16	0.17	0.02	0.63
11.00	0.09	0.50	1.03	0.31	0.89	1.54	0.10	0.51	1.32
13.00	0.01	1.86	2.47	0.17	1.56	2.28	0.55	1.60	2.47
15.00	0.10	2.82	3.46	0.15	2.49	3.24	0.42	1.96	2.82
Sample 2									
313.15 K			303.15 K			293.15 K			
4.50	–	–	–	–	–	–	0.39	0.10	0.47
5.00	0.57	0.03	0.36	0.95	0.45	0.82	0.63	0.47	0.04
6.00	0.30	1.06	0.64	0.41	0.99	0.50	0.41	0.76	0.20
7.00	0.05	0.98	0.46	0.43	1.53	0.92	0.77	1.45	0.75
9.00	0.46	0.68	0.05	1.03	1.22	0.37	0.49	0.40	0.61
11.00	0.05	1.27	0.33	0.26	1.70	0.58	0.03	0.94	0.40
13.00	1.50	2.72	1.56	0.13	1.74	0.40	0.12	1.13	0.46
15.00	1.72	2.78	1.48	1.01	1.79	0.29	0.48	2.84	1.07
283.15 K			273.15 K			265.65 K			
4.21	0.46	0.85	1.24	–	–	–	–	–	–
4.50	–	–	–	0.28	0.61	0.10	–	–	–
5.00	0.39	0.04	0.54	0.79	1.14	0.54	0.04	1.83	1.13
6.00	0.04	0.41	1.07	0.43	0.78	0.03	0.42	3.11	2.15
7.00	0.19	0.67	1.50	0.02	0.30	0.73	0.52	3.60	2.32
9.00	0.41	0.08	1.31	0.17	0.19	1.38	0.10	2.63	0.63
11.00	0.59	0.32	1.32	1.08	1.15	3.21	0.32	1.61	0.97
13.00	0.82	1.11	0.82	0.81	0.63	2.96	0.20	1.89	0.88
15.00	0.71	1.45	0.59	2.48	2.64	4.92	0.48	0.73	1.86

(a)

(b)

(c)
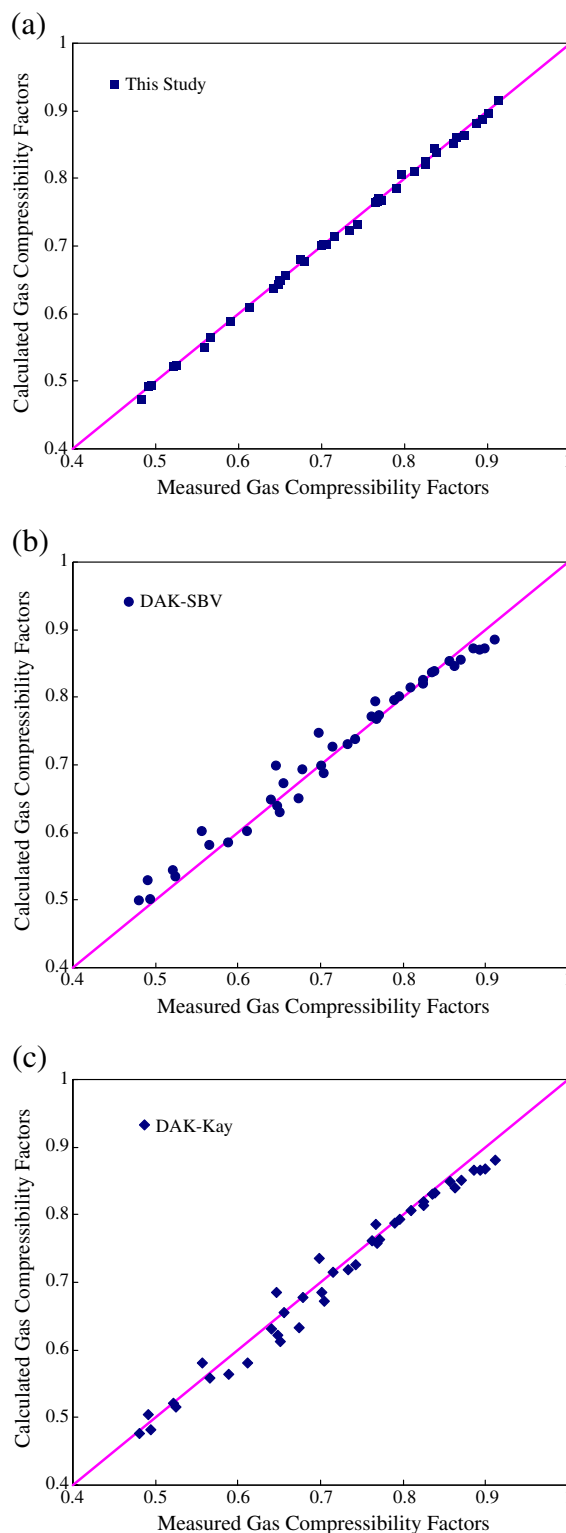
Fig. 2. Predicted Z-factors from the new model, DAK-SBV, and DAK-Kay vs. the measured Z-factors.

Nomenclature

A	mole fraction of $CO_2 + H_2S$
B	mole fraction of H_2S
A_i, B_i, C_i, D_i $(i = a, b, c, d)$	tuning coefficient
AAD	average absolute deviation,%
ARD	absolute relative deviation,%

J	SBV parameter, $K \cdot MPa^{-1}$
K	SBV parameter, $K \cdot MPa^{-0.5}$
n_c	the number of data
P	system pressure, MPa
P_{ci}	critical pressure of the component i, MPa
P_{pc}	pseudo-critical pressure, MPa
P'_{pc}	corrected pseudo-critical temperature with Wichert-Aziz correlation, MPa
P_r	reduced pressure
P_s	ambient pressure, MPa
T	system temperature, K
T_{ci}	critical temperature of the component i, K
T_{pc}	pseudo-critical temperature, K
T'_{pc}	corrected pseudo-critical temperature with Wichert-Aziz correlation, K
T_r	reduced temperature
T_s	ambient temperature, K
V_s	volume of gas released at ambient pressure and temperature, ml
ΔV	volume of gas bled from the PVT vessel, ml
y_i	mole fraction of component i
Z	gas compressibility factor
$\alpha, \beta_i \ (i=0, 1, 2, 3)$	tuning exponent
ρ_r	reduced density
ξ	Wichert-Aziz pseudo-critical correction
$Cal.$	calculated value
$Exp.$	experimental data or exact value

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