Development of a New Correlation of Gas Compressibility Factor (Z-Factor) for High Pressure Gas Reservoirs

Mohamed Mahmoud
Assistant Professor
Department of Petroleum Engineering,
King Fahd University of Petroleum and Minerals,
Dhahran 31261, Saudi Arabia
e-mail addresses: mmahmoud@kfupm.edu.sa
and mohnasreldin80@gmail.com

Gas compressibility factor or Z-factor for natural gas system can be determined from Standing-Katz charts using the pseudocritical gas pressure and temperatures. These charts give accurate values for Z-factors. Reservoir simulation softwares need accurate correlations to estimate the values of Z-factor; one of the well-known correlations is Dranchuk and Abou-Kassem (DAK) Correlation. This correlation gives large errors at high gas reservoir pressures, this error could be more than 100%. The error in estimating Z-factor will lead to big error in estimating all the other gas properties such as gas formation volume factor, gas compressibility, and gas in place. In this paper a new accurate Z-factor correlation has been developed using regression for more than 300 data points of measured Z-factor using MATLAB in addition to other data points at low pressure and temperature from Standing-Katz charts and DAK correlation. Old correlations give good estimation of Z-factor at low gas reservoir pressures below 41.37 MPa (6000 psia), at high pressures the error started to appear. The developed correlation is a function of pseudoreduced pressure and temperature of the gas which makes it simpler than the existing complicated correlations. The new correlation can be used to determine the gas compressibility factor at any pressure range especially for high pressures the error was less than 3% compared to the measured data. The developed correlation is very simple to be used, it just needs the gas specific gravity that can be used to determine the pseudocritical properties of the gas and at last the Z-factor can be determined. A new formula of reduced gas compressibility was developed based on the developed Z-factor correlation which in turn can be used to determine the gas compressibility.

[DOI: 10.1115/1.4025019]

Keywords: Z-factor, natural gas, reduced gas compressibility

1 Introduction

Compressibility factor is a dimensionless quantity and it has different names such as compressibility factor, Z-factor, gas super compressibility, and gas deviation factor. It represents the deviation of a real gas from the ideal behavior and it is a function of temperature (T), pressure (P), and gas composition. It is generally defined as the ratio of the actual volume of the gas (at its pressure and temperature) to the ideal volume of the gas (at standard conditions) that its molecules do not have attraction forces [1]. A Z-factor value of unity represents an ideal gas behavior.

The ideal gas particle is extremely small where its mass is almost zero. Ideal gas particle, therefore, does not have volume while a real gas particle does have real volume since real gases are made up of molecules or atoms that typically take up some space even though they are extremely small. In ideal gas, the collision or impact between the particles are said to be elastic. In other words, there is neither attractive nor repulsive energy included throughout the collision of gas particles. Since there is lack of interparticle energy the kinetic forces will remain unchanged in gas molecules. In contrast, collisions of particles in real gases are nonelastic. Real gases are made up of particles or molecules that may attract one another strongly with the expenditure of repulsive energy or attractive force, just like water vapor, ammonia, sulfur dioxide, etc. At standard conditions gas molecules are quite far apart and the attraction forces are negligible and similarly are the condition at high temperatures because of the increased kinetic motion. Under these conditions, the gas tends to approach ideal behavior and the value of Z-factor approaches one. Contrary, at high pressures the gas molecules come very close to each other resulting in significant attraction forces, therefore, they behave like real gases imposing negative deviation from ideal case at

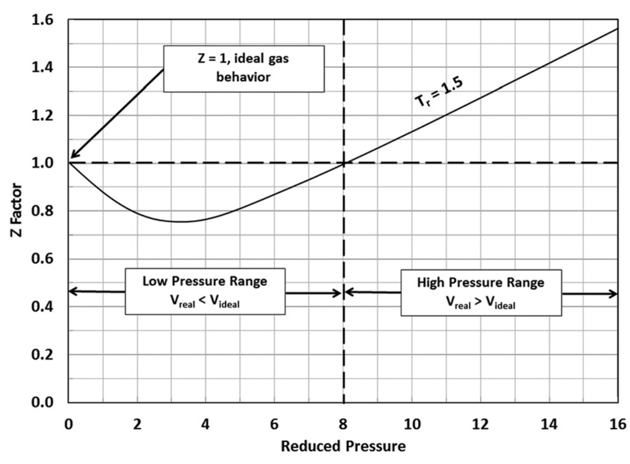

Fig. 1 Z-factor as a function of reduced pressure ($p_r = p/p_c$) at $T_r = 1.5$ (after McCain, 27)

Contributed by the Petroleum Division of ASME for publication in the Journal of Energy Resources Technology. Manuscript received February 8, 2013; final manuscript received May 28, 2013; published online September 12, 2013. Assoc. Editor: Sarma V. Pisupati.

lower pressures and positive deviations at higher pressures. Figure 1 shows several points of interest, at very low pressures; the Z-factor approaches a value of 1.0 which indicates ideal gas behavior. Under these conditions, the gas molecules are physically far enough apart so that there is no interaction among them. However, as pressures increase, the gas molecules are forced closer together allowing attraction forces to influence the volume occupied by the gas. Further increases in pressure force the gas molecules sufficiently close enough that repulsion forces become dominant and cause the actual volume to be higher than that predicted by the ideal equation of state, these conditions are defined by Z-factors greater than one [2,3].

Natural gas pressure volume temperature (PVT) properties are a strong function of gas compressibility factor. Gas properties such as gas formation volume factor, gas density, gas compressibility, and gas viscosity can be estimated using the gas deviation factor. All these properties are necessary in the oil and gas industry for evaluating gas reservoirs, calculating initial gas in place, estimating gas reserves, predicting future gas production, and designing production tubing and pipelines. PVT Laboratory measurements using reservoir samples is best practical technique to determine gas properties [2]. PVT Laboratory measurements are expensive and could be unreached in certain cases, therefore, estimation of gas properties at different pressures and temperatures can be achieved through the development of empirical correlations based on the equations of state (EOS) [2]. Gas deviation factor correlations are easier and faster with accepted accuracy compared to EOS models.

Standing and Katz [4] gas Z-factor chart has become a standard in the industry. Several very accurate methods have been developed to represent the chart digitally. The engineering community typically uses methods published by Yarborough and Hall [5,6], Dranchuk et al. [7], and DAK [8]. These methods all use some forms of an equation of state that has been fitted specifically to the selected digital Z-factor chart data published by Poettmann and Carpenter [9].

Recently, Londono et al. [10] refitted the chart with an expanded data set, resulting in a modified method that can be used to accurately determine the Z-factor. They provided two equations: one fit to an expanded data set from the Standing -Katz Z-factor chart and the other that included single component data.

A general gas Z-factor chart, such as the one developed by Standing and Katz [4], is based on the law of corresponding states [11]. This law states that two substances at the same conditions referenced to critical pressure and critical temperature will have similar Z-factors. These conditions are referred to as reduced pressure (p_r) and reduced temperature (T_r). Therefore, if two substances are compared at the same reduced pressures and temperatures, the substances will have the same Z-factors.

The best way to determine the natural gas deviation factor (especially for gas mixtures containing large quantities of nonhydrocarbon contaminants such as CO_2, N_2, and H_2S) is to measure them in the laboratory; however, the petroleum industry has historically relied upon certain correlations or equation-of-state models that have been developed more than fifty years ago. Brown and Holcomb [12] correlation that was extended and improved by Standing and Katz [4] is still the correlation widely used by the petroleum industry to determine the natural gas compressibility factor. Unfortunately, the range of pressure and temperature conditions represented by the data used to generate the Standing and Katz correlation (Temperature < 300 °F and pressure <89.63 MPa (13,000 psia)) are not typical of those conditions encountered in deep natural gas reservoirs at high pressure and high temperature (HP/HT) conditions.

Improvements to the Standing and Katz correlation as well as extensions to higher pressures and temperatures have been made using mathematical models. Unfortunately, Dranchuk et al. [13] and DAK [8] EOSs were matched to the same data base used to generate the Standing and Katz [4] correlations. The Yarborough and Hall [5] model was matched to the Standing and Katz data, and it was also tested against a limited set of additional data from twelve natural gas reservoirs. Also, these models were not compared to actual measured data to validate the new proposed correlations to estimate gas compressibility factor.

The majority of the existing Z-factor correlations have been proven reasonably accurate for a wide range of reservoir conditions and gas compositions typically encountered in natural gas reservoirs. The first Z-factor correlations were formulated by Cope et al. [14] and Brown et al. [15], but were later improved and extended with more data, including binary-component and natural gas mixtures by Brown [16], Brown and Holcomb [12], and Standing and Katz [4]. The principle underlying development of all these early correlations for gas compressibility factor is the law of corresponding states that originally proposed by Van der Waals [17]. The law postulates that two substances should have similar properties at similar conditions that have been referenced to some basic property. Early researchers found that good correlations could be generated if Z-factor comparisons were referenced to dimensionless pressures and temperatures. The reduced pressure and temperature can be determined as follows:

$$p_r = \frac{p}{p_c} \tag{1}$$

$$T_r = \frac{T}{T_c} \tag{2}$$

where p is the absolute pressure; T is the absolute temperature; p_c is the critical pressure; and T_c is the critical temperature. Based on Amagat's law of partial volumes [18] for mixtures, pseudocritical properties are estimated based on molar weighted average of the critical properties of the individual mixture components. The pseudocritical pressure and temperature can be determined as follows:

$$p_{pc} = \sum_{i=1}^{n} y_i p_{ci} \tag{3}$$

$$T_{pc} = \sum_{i=1}^{n} y_i T_{ci} \tag{4}$$

where y_i is the mole fraction of the ith component in the mixture; n is the number of constituents in the mixture; p_{ci} is the critical pressure of the ith component and T_{ci} is the critical pressure of the ith component in the system. For heavier hydrocarbon components the following correlation were proposed by Stewart et al. [19]:

$$T_{pc} = \frac{K^2}{J} \tag{5}$$

$$p_{pc} = \frac{T_{pc}}{J} \tag{6}$$

$$J = \frac{1}{3}\left[\sum_{i=1}^{n} y_i \frac{T_{ci}}{p_{ci}}\right] + \frac{2}{3}\left[\sum_{i=1}^{n} y_i \sqrt{\frac{T_{ci}}{p_{ci}}}\right]^2 \tag{7}$$

$$K = \sum_{i=1}^{n} y_i \sqrt{\frac{T_{ci}}{p_{ci}}} \tag{8}$$

Standing [2] proposed correlations to determine the pseudocritical pressure and temperature for a natural gas based on its specific gravity (γ_g) as follows:

$$p_{pc} = 667 + 15\gamma_g - 37.5\gamma_g^2 \tag{9}$$

$$T_{pc} = 168 + 325\gamma_g - 12.5\gamma_g^2 \tag{10}$$

The values of pseudocritical properties of the condensate gas can be determined using the following correlations [20]:

$$p_{pc} = 756.8 - 13\gamma_g - 3.6\gamma_g^2 \tag{11}$$

$$T_{pc} = 169.2 + 349.5\gamma_g - 74\gamma_g^2 \tag{12}$$

The values of coefficients J and K for gas condensate reservoirs can be estimated as follows [21]:

$$J = 0.11582 - 0.45820 y_{H_2S}\frac{T_{CH_2S}}{p_{cH_2S}} - 0.90348 y_{CO_2}\frac{T_{cCO_2}}{p_{cCO_2}} - 0.66026 y_{N_2}\frac{T_{cN_2}}{p_{cN_2}} + 0.70729\gamma_g - 0.09939\gamma_g^2 \tag{13}$$

$$K = 3.8216 - 0.06534 y_{H_2S}\frac{T_{CH_2S}}{p_{cH_2S}^{0.5}} - 0.42113 y_{CO_2}\frac{T_{cCO_2}}{p_{cCO_2}^{0.5}} - 0.91249 y_{N_2}\frac{T_{cN_2}}{p_{cN_2}^{0.5}} + 17.438\gamma_g - 3.2191\gamma_g^2 \tag{14}$$

After estimating the coefficients K and J, the pseudocritical pressure and pseudocritical temperature can be determined using Eqs. (5) and (6).

The pseudocritical properties of the gas condensate reservoirs also can be computed using the following correlations [22,23]:

$$p_{pc} = 193.941 - 131.347\gamma_g + 217.144 w_{HC} + 1060.349 w_{NHC} + 344.573 w_{HC}^2 - 60.591 w_{NHC}^2 \tag{15}$$

$$T_{pc} = 195.958 + 206.121\gamma_g + 25.855 w_{HC} - 6.421 w_{NHC} + 9.022 w_{HC}^2 + 163.247 w_{NHC}^2 \tag{16}$$

The pseudocritical pressure and temperature can be determined for the defined gas composition especially if nonhydrocarbons are included such CO_2, N_2, and H_2S [24] as follows:

$$p'_{pc} = \frac{p_{pc}(T_{pc} - \varepsilon)}{T_{pc} + y_{H_2S}(1 - y_{H_2S})\varepsilon} \tag{17}$$

$$T'_{pc} = T_{pc} - \varepsilon \tag{18}$$

$$\varepsilon = 120\left[(y_{CO_2} + y_{H_2S})^{0.9} - (y_{CO_2} + y_{H_2S})^{1.6}\right] + 15\left[(y_{H_2S})^{0.5} - (y_{H_2S})^4\right] \tag{19}$$

Another correlation was developed nonlinear regression to modify the coefficients and exponents in Eq. (17) as follows:

$$\varepsilon = 107.6\left[(y_{CO_2} + y_{H_2S}) - (y_{CO_2} + y_{H_2S})^{2.2}\right] + 5.9\left[(y_{H_2S})^{0.06} - (y_{H_2S})^{0.68}\right] \tag{20}$$

If the natural gas composition was unavailable, the pseudocritical properties can be determined through the estimation of the gas specific gravity using Standing correlation [2] or Sutton correlation [25] as follows:

$$\gamma_g = \frac{\gamma_m - (y_{CO_2}M_{CO_2} + y_{H_2S}M_{H_2S})/M_a}{y_g} \tag{21}$$

$$y_g = 1 - y_{CO_2} - y_{H_2S} \tag{22}$$

where γ_m is the mixture specific gravity (hydrocarbon gas plus non hydrocarbons), y_{co2} is the mole fraction of the CO_2 gas, y_{H2S} is the mole fraction of the H_2S gas, M_{CO2} is the molecular weight of the CO_2 gas, M_{H2S} is the molecular weight of the H_2S gas, M_a is the air molecular weight = 28.97. Then the pseudocritical pressure and temperature can be determined as follows [26]:

$$T_{pc} = (1 - y_{CO_2} - y_{H_2S})T_{pcHC} + y_{CO_2}T_{cCO2} + y_{H_2S}T_{cH2S} \tag{23}$$

$$p_{pc} = (1 - y_{CO_2} - y_{H_2S})p_{pcHC} + y_{CO_2}p_{cCO2} + y_{H_2S}p_{cH2S} \tag{24}$$

2 Gas Compressibility Factor Correlations

The gas compressibility factor or Z-factor can be determined at a certain reservoir conditions using DAK [8] correlation by iterations using visual basic program. The error between the Z-factor from Standing and Katz charts and that from the correlation was less than 0.0001. The correlation used for Z-factor calculation can be written as follows [27]:

$$Z = 1 + \left(A_1 + \frac{A_2}{T_{pr}} + \frac{A_3}{T_{pr}^3} + \frac{A_4}{T_{pr}^4} + \frac{A_5}{T_{pr}^5}\right)\rho_{pr} + \left(A_6 + \frac{A_7}{T_{pr}} + \frac{A_8}{T_{pr}^2}\right)\rho_{pr}^2 - A_9\left(\frac{A_7}{T_{pr}} + \frac{A_8}{T_{pr}^2}\right)\rho_{pr}^5 + A_{10}\left(1 + A_{11}\rho_{pr}^2\right)\left(\rho_{pr}^2/T_{pr}^3\right)\mathrm{EXP}\left(-A_{11}\rho_{pr}^2\right) \tag{25}$$

$$\rho_{pr} = 0.27\left(\frac{p_{pr}}{zT_{pr}}\right) \tag{26}$$

The values of A_1 to A_{11} are listed in Table 1. In this case, we did iteration to get the Z-factor value as we should assume value first to calculate ρ_{pr}, which was used to calculate Z. In the iteration process we can put tolerance or clearance between the assumed values and the estimated ones. The iteration will continue till fulfill the condition of the difference between the assumed and estimated value should be less than the clearance or the error which we can set as low as 0.0001.

DAK [8] used Benedict-Webb-Rubin [28] equation of state to develop a model to determine the Z-factor of a gas mixture. The Benedict-Webb-Rubin Equation of State can be written as follows:

$$p = RT\rho_m + \left(B_oRT - A_o - \frac{C_o}{T^2}\right)\rho_m^2 + (bRT - a)\rho_m^3 + a\alpha_m^6 + \left(\frac{c\rho_m^3}{T^2}\right)(1 + \gamma\rho_m^2)\exp(-\gamma\rho_m^2) \tag{27}$$

where ρ_m is the molar density, the Benedict-Webb-Rubin EOS is a modification of the Beattie-Bridgeman [29] EOS, however, the Benedict-Webb-Rubin EOS is completely empirical since the eight constants (A_0, B_0, C_0, a, b, c, α, and γ) cannot be determined theoretically, they must be estimated for each pure constituent from experimental properties of both gas and liquid.

AL-Anazi and Al-Quraishi [30] have used data base of 977 experimental Z-factor measurement that were collected from different sour and natural gas composition at different pressures and temperatures. The data points they have used covers measurements at wide ranges of pressure, temperature and molecular

Table 1 Constants values in DAK correlation [8]

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

weight. They developed a new model and tested for Z-factor prediction using linear genetic programming technique. The genetic programming software they have used was run for 1000 generations with a maximum population size of 500. The compressibility factor correlation they have developed can be written as follows:

$$Z = \frac{2E}{1.0482} + F \tag{28}$$

$$F = \frac{D}{E^2} - E \tag{29}$$

$$E = \frac{C + D}{1.0474 T_{pr}} + 0.9178 \tag{30}$$

$$D = (-2A)(B)(C) \tag{31}$$

$$C = B - (-2A)(B) \tag{32}$$

$$B = \frac{(3A)^2 - 1.427}{T_{\mathrm{pr}}} + 0.9178 \tag{33}$$

$$A = -0.06708 p_{\mathrm{pr}} + 0.2360 \tag{34}$$

Based on this extensive literature survey, the objectives of this study are to (1) develop a new correlation for Z-factor, (2) compare the new correlation with the old correlations in predicting the Z-factor for low and high pressure gas reservoirs and compare all correlations with the measured data, and (3) use the proposed correlation to estimate the gas density, reduced density, gas compressibility, and gas viscosity.

3 The New Proposed Correlation

The new correlation was developed using measured data and calculated data for different gas mixtures from previous publications [4,7,8,31]. We used data from Standing-Katz Charts [4], Dranchuk et al. [7], DAK correlation [8], and from Rushing et al. [31]. The correlation was developed by relating the Z-factor to the pseudoreduced pressure as a second degree polynomial, and then the coefficient of this polynomial was determined by regression as a function of pseudoreduced temperature. The new proposed correlation was developed using two step regression. The data used in developing the new correlation include actual measured data points from a pressure range of 3.447 MPa (500 psia) to 137.9 MPa (20,000 psia) at temperature values of 422 K (300 °F) and 477.59 K (400 °F). Low pressure and low temperature data also were used in developing the correlation. The correlation was obtained by fitting the data through linear regression function and the following correlation was obtained:

$$Z = a p_{\mathrm{pr}}^2 + b p_{\mathrm{pr}} + c \tag{35}$$

Then, the parameters a, b, and c in the previous equation are function of the reduced or pseudoreduced temperature, and also they can be determined by regression as follows:

$$a = 0.702 e^{-2.5 T_{\mathrm{pr}}} \tag{36}$$

$$b = -5.524 e^{-2.5 T_{\mathrm{pr}}} \tag{37}$$

$$c = 0.044 T_{\mathrm{pr}}^2 - 0.164 T_{\mathrm{pr}} + 1.15 \tag{38}$$

The final proposed new correlation to determine Z-factor can be found by combining Eqs. (35)–(38) as follows:

$$Z = \left(0.702 e^{-2.5 T_{\mathrm{pr}}}\right)\left(p_{\mathrm{pr}}^2\right) - \left(5.524 e^{-2.5 T_{\mathrm{pr}}}\right)\left(p_{\mathrm{pr}}\right) + \left(0.044 T_{\mathrm{pr}}^2 - 0.164 T_{\mathrm{pr}} + 1.15\right) \tag{39}$$

The first derivative of Z-factor with respect to p_{pr} can be found from the first derivative of Eq. (39)

$$\frac{\partial Z}{\partial p_{\mathrm{pr}}} = \left(e^{-2.5 T_{\mathrm{pr}}}\right)\left(1.404 p_{\mathrm{pr}} - 5.524\right) \tag{40}$$

Equation (40) can be used to determine the reduced gas compressibility and gas compressibility at different pressure values.

Once the gas deviation factor determined using Eq. (39), the gas density can be estimated easily using the following equation:

$$\rho_{\mathrm{g}} = \frac{pM}{ZRT} \tag{41}$$

where p is the pressure in kPa; M is the gas molecular weight $= M_{\mathrm{air}}\, \gamma_{\mathrm{g}}$ (where M_{air} is the air molecular weight and it equals 29), R is the general gas constant $= 8.3145$ kPa m^3/(kmoles K), T is the absolute temperature, K. The gas compressibility can be determined as follows:

$$C = \frac{C_{\mathrm{r}}}{p_{\mathrm{c}}} \tag{42}$$

where p_{c} is the gas critical or pseudocritical pressure; and C_{r} or C_{pr} is the reduced gas compressibility that can be determined as follows:

$$C_{\mathrm{pr}} = \frac{1}{p_{\mathrm{pr}}} - \frac{1}{Z}\left(\frac{\partial Z}{\partial p_{\mathrm{pr}}}\right)_{T_{\mathrm{pr}}} \tag{43}$$

$$C_{\mathrm{pr}} = \frac{1}{p_{\mathrm{pr}}} - \frac{1}{Z}\left[\left(1.404 e^{-2.5 T_{\mathrm{pr}}}\right)\left(p_{\mathrm{pr}}\right) - \left(5.524 e^{-2.5 T_{\mathrm{pr}}}\right)\right] \tag{44}$$

The gas viscosity can be determined through correlations; some of these correlations depend on the gas density in which the Z-factor will be important to be determined first. The gas viscosity correlations can be summarized as follows:

$$\mu_{\mathrm{g}} = \mu_{\mathrm{gSC}} e^{\left[X \rho_{\mathrm{g}}^{Y}\right]} \tag{45}$$

$$X = 3.47 + \frac{1588}{T} + 0.0009 M \tag{46}$$

$$Y = 1.66378 - 0.04679 X \tag{47}$$

$$\mu_{\mathrm{gSC}} = 10.5^{-4}\left[\frac{M^3 P_{\mathrm{pc}}^4}{T_{\mathrm{pc}}}\right]^{1/6}\left[0.807 T_{\mathrm{pr}}^{0.618} - 0.357 e^{\left(-0.449 T_{\mathrm{pr}}\right)} + 0.34 e^{\left(-4.058 T_{\mathrm{pr}}\right)} + 0.018\right] \tag{48}$$

The gas viscosity can be determined using Jossi et al. correlation [32], he developed the gas viscosity correlation for two different ranges of reduced temperature. The gas viscosity at standard conditions for $T_{\mathrm{pr}} < 1.5$ can be determined as follows:

$$\mu_{\mathrm{gSC}} = \frac{6.25 \times 10^{-5} T_{\mathrm{pr}}^{0.94} M^3 P_{\mathrm{pc}}^4}{T_{\mathrm{pc}}} \tag{49}$$

The gas viscosity at standard conditions for $T_{\mathrm{pr}} > 1.5$ can be determined as follows:

$$\mu_{gSC} = \frac{3.27\times10^{-5}\left(4.58T_{pr}-1.67\right)^{5/8}M^3P_{pc}^4}{T_{pc}} \quad (50)$$

Finally the gas viscosity at any temperature and pressure can be estimated using the following correlation:

$$\mu_g = \mu_{gSC} + \frac{M^3P_{pc}^4}{5.398T_{pc}}\left\{\left[0.1023+0.02336\rho_{pr}+0.058533\rho_{pr}^2 - 0.040758\rho_{pr}^3+0.009332\rho_{pr}^4\right]^4 - 10^{-4}\right\} \quad (51)$$

Dean and Stiel [33] developed a correlation for gas viscosity that based on the reduced pseudogas density, the correlation can be written as follows for $T_{pr} < 1.5$:

$$\mu_{gSC} = 6.25\times10^{-5}T_{pr}^{0.89}\left(\frac{M^3P_{pc}^4}{T_{pc}}\right)^{1/6} \quad (52)$$

The gas viscosity at standard conditions for $T_{pr} > 1.5$ can be determined as follows:

$$\mu_{gSC} = 30.663\times10^{-5}\left(0.1338T_{pr}-0.0932\right)^{5/9}\left(\frac{M^3P_{pc}^4}{T_{pc}}\right)^{1/6} \quad (53)$$

$$\mu_g = \mu_{gSC} + \left(10.8\times10^{-5}\right)\left(\frac{M^3P_{pc}^4}{T_{pc}}\right)^{1/6}\left[e^{\left(1.439\rho_{pr}\right)} - e^{\left(-1.111\rho_{pr}^{1.858}\right)}\right] \quad (54)$$

The gas compressibility factor as mentioned earlier can be used to determine the gas density which in turn can be used to determine the minimum gas flow velocity to carry the liquid oil during production to enhance the production from gas wells. This velocity was found to equal the terminal liquid rise velocity than can be determined as follows [34]:

$$V_{\min} = \left[\frac{40g\sigma(\rho_L-\rho_G)}{\rho_G^2C_D}\right]^{1/4} \quad (55)$$

where $V_{\min}$ is the minimum gas flow velocity to carry liquid; g is the acceleration gravity; σ is the gas/liquid interfacial tension; ρ_L is the liquid density; ρ_G is the gas density; and C_D is the drag coefficient.

The developed gas compressibility factor correlation is a simple function of gas reduced pressure and temperature, this will facilitate the process of estimation Z-factor especially in gas lift or gas well deliverability calculations. These calculations require a lot of iteration to get the correct value of Z-factor, using the developed correlation will help in predicting the gas lift performance better and also in the prediction of gas well deliverability. In a gas lift well, the fluid flows from reservoir to surface facilities through tubing. The fluid flow model in a gas lift well consists of two flow components in a well system; they are reservoir fluid flow and tubing fluid flow. In the tubing model, two phase correlation is needed to estimate the mixture properties (liquid and gas). The gas properties such as density, viscosity, and Z-factors are required to determine the mixture properties that will be used to determine the tubing flow model [35]. Quick estimation of the Z-factor will facilitate the calculations of gas density, viscosity, and the mixture properties. The tubing flow model includes the calculation of pressure drop inside the tubing and the mixture velocity (liquid + gas superficial velocities) is required in this model, Z-factor is an essential parameter in these calculations. The gas superficial velocity can be determined as follows:

$$u_{sg} = \frac{q_L(\mathrm{GLR_t} - R_s(1/(1+\mathrm{WOR})))}{A_t}\cdot\frac{\mathrm{ZTP_{sc}}}{T_{sc}P} \quad (56)$$

where u_{sg} is the gas superficial velocity; q_L is the liquid velocity; $\mathrm{GLR_t}$ is the total gas liquid ratio; WOR is the water/oil ratio; A_t is the total flow area; P_{sc} is the pressure at standard conditions; T_{sc} is the temperature at standard conditions; Z is the gas deviation factor; T is the flow temperature; and P is the flow pressure.

Parameters such as gas density, viscosity, and gas superficial velocity in addition to the mass flow rate of the gas are important to model the multiphase flow in natural gas pipelines [36]. The developed equation of Z-factor also can be used to determine the nonisothermal storage gas material balance equation that can be written as follows [37]:

$$\Psi(t) = \frac{\dfrac{P_iT(t)}{Z_iT_i(t)}\left[1-\dfrac{G_p(t)}{G_i}\right]}{1-\dfrac{W_e(t)E_i}{G_i}} \quad (57)$$

where $\psi(t)$ is variable and equals $P_g/Z(t)$; P_g is the reservoir gas pressure; $Z(t)$ is the gas deviation factor at P_g; G_p is the cumulative gas produced; G_i is the initial gas in place; P_i is the reservoir initial pressure; $T(t)$ is the reservoir temperature; T_i is the initial reservoir temperature, Z_i is the gas deviation factor at initial reservoir pressure, $W_e(t)$ is the water influx; and E_i is the initial gas expansion factor.

Equation (39) can be also expressed in terms of temperature as follows:

$$Z = \left(0.702e^{-2.5T/T_c}\right)\left(p_{pr}^2\right) - \left(5.524e^{-2.5T/T_c}\right)(p_{pr}) + \left(0.044(T/T_c)^2 - 0.164T/T_c + 1.15\right) \quad (58)$$

The change of Z-factor with temperature at constant pressure (nonisothermal conditions) can be determined as follows:

$$\frac{\partial Z}{\partial T} = \left(\frac{-1.755}{T_c}e^{-2.5T/T_c}\right)(p_{pr})^2 + \left(\frac{13.81}{T_c}e^{-2.5T/T_c}\right)(p_{pr}) + \left(\frac{0.088T}{T_c} - \frac{0.164}{T}\right) \quad (59)$$

Equation (59) can be written as function of gas pressure and temperature as follows:

$$\frac{\partial Z}{\partial T} = \left(\frac{-1.755}{T_c}e^{-2.5T/T_c}\right)\left(\frac{p}{p_c}\right)^2 + \left(\frac{13.81}{T_c}e^{-2.5T/T_c}\right)\left(\frac{p}{p_c}\right) + \left(\frac{0.088T}{T_c} - \frac{0.164}{T}\right) \quad (60)$$

This function $\partial Z/\partial T$ can be used in the nonisothermal compressor station optimization process that was developed by Abbas pour et al. [38]. The function $\partial Z/\partial T$ is just function of gas pressure, temperature, and gas gravity (critical pressure and temperature); and the same can be done to find the change of the Z-factor with pressure at constant temperature that can be written as follows:

$$\frac{\partial Z}{\partial p} = \left(\frac{1.404p}{p_c}e^{-2.5T/T_c}\right) - \left(\frac{5.524}{p_c}e^{-2.5T/T_c}\right) \quad (61)$$

4 Results and Discussions

The new proposed correlation can be used to determine the gas deviation factor at different reduced pressures and temperatures. The correlation results are shown in Fig. 2. Figure 3 shows a comparison between the proposed, Al-Anazi, and DAK correlations

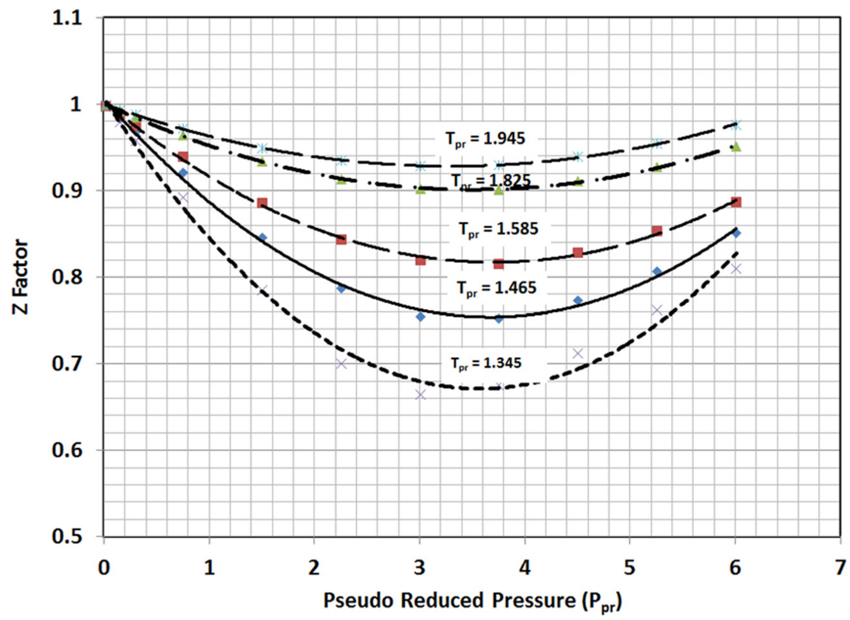

Fig. 2 Z-factor as a function of reduced pressure ($p_r = p/p_c$) at different reduced temperatures generated by the new proposed correlation, Eq. (39)

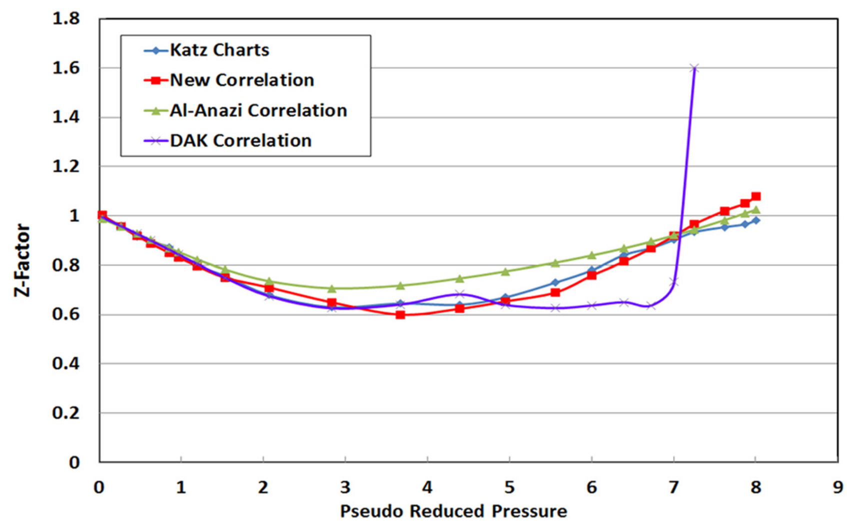

Fig. 3 Z-factor as a function of reduced pressure ($p_r = p/p_c$) at reduced temperature of 1.3. Comparison between the proposed, DAK, Al-Anazi correlations, and Standing-Katz charts

Table 2 Gas composition for the mixtures used in calculating Z-factor (Rushing et al. [31])

Composition	Critical pressure, MPa (Psia)	Critical temperature, K (°R)	Mixture 1, mole fraction	Mixture 2, mole fraction
CH_4	4.60 (667.8)	190.74 (343.33)	0.96	0.768
C_2H_6	4.88 (707.8)	305.11 (549.20)	0.03	0.024
C_3H_8	4.25 (616.3)	370.03 (666.06)	0.01	0.008
CO_2	7.38 (1071)	304.22 (547.6)	0.00	0.200

with respect to Standing-Katz Charts at low reduced temperature (1.3). The proposed correlation gave better estimation of Z-factor compared to DAK and Al-Anazi Correlations. The correlation results were compared to the actual measured data for gas deviation factor at high pressure and temperature, the measured values were taken from Rushing et al. [31]. The gas compressibility factor was determined for two different mixtures listed in Table 2. The critical pressure and temperature for mixture 1 are 4.6 MPa (668.5 psia) and 195.96 K (352.73 °R), respectively, and for mixture 2 are 5.16 MPa (749 psia) and 217.78 K (392 °R), respectively.

Figures 4 and 5 show Z-factor as a function of pseudoreduced pressure for gas mixture 1 (natural gas without CO_2). Figure 4 shows the results from three different correlations compared to the actual measured data at pseudoreduced temperatures (T_{pr}) of 2.438. The three correlations give almost the same values as the

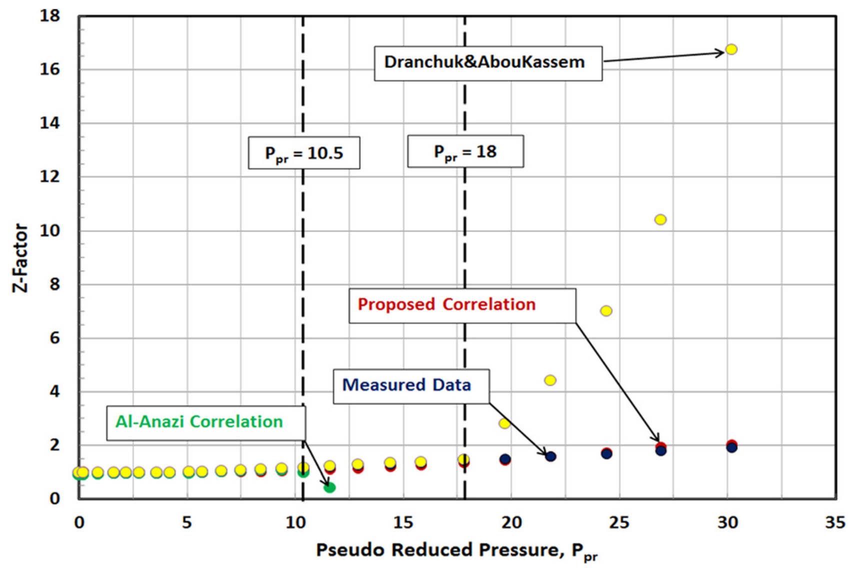

Fig. 4 Comparison between the different Z-factor correlation with actual measured data for gas mixture 1 at $T_{pr} = 2.438$. After p_{pr} value of 10.5 Al-Anazi correlation start to give values less than zero. The proposed correlation is the best one to predict the gas compressibility factor at high pressures. The reservoir pressure for this mixture at $p_{pr} = 30$ is 137.895 MPa (20,000 psi).

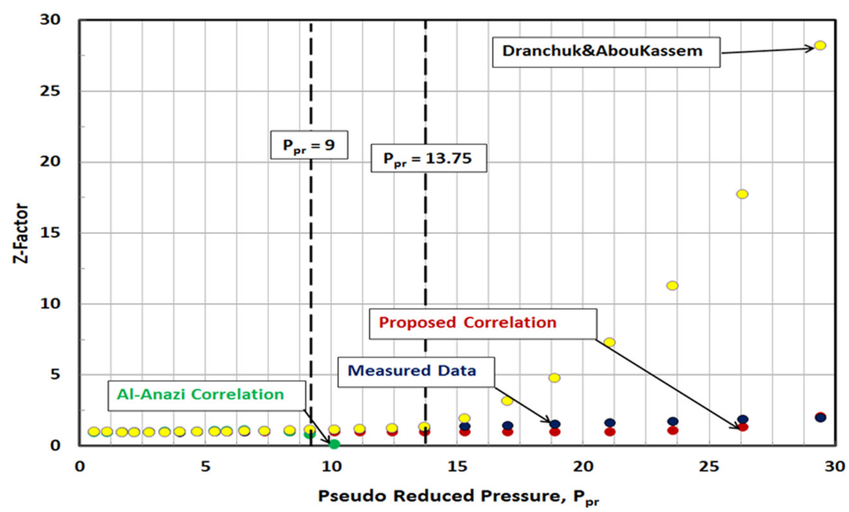

Fig. 5 Comparison between the different Z-factor correlation with actual measured data for gas mixture 1 at $T_{pr} = 2.155$. After p_{pr} value of 9 Al-Anazi correlation start to give values less than zero. The proposed correlation is the best one to predict the gas compressibility factor at high pressures. The reservoir pressure for this mixture at $p_{pr} = 30$ is 137.895 MPa (20,000 psi).

measured for p_{pr} less than 10.5 which means that the three correlations can be used to predict the gas compressibility factor at low pressure ranges. The pressure range that the three correlations gave the same as the measured data is 48.26 MPa (7000 psi), which could not be the situation in high pressure gas reservoirs. From these results we can conclude that Al-Anazi correlation cannot be used for high pressure gas reservoirs because after P_{pr} of 10.5 its prediction deviates from the measured data trend and for P_{pr} values greater than12, it gave negative results. The proposed correlation and DAK correlation after P_{pr} of 10.5 still matches the measured data trend, but after P_{pr} of 18 the DAK correlation started to deviate from the measured data trend. The DAK correlation could not predict the gas compressibility factor for P_{pr} greater than 18 or 82.74 MPa (12,000 psi) for this mixture. The proposed correlation is the only one that can predict the Z-factor for very high pressure gas reservoirs as shown in Fig. 4. The predicted data match the measured data up to P_{pr} of 30 or 137.89 MPa (20,000 psi) for mixture 1. Figure 6 shows the Z-factor predicted using the three correlations compared to the measured data at $T_{pr} = 2.155$ (300 °F) for mixture 1. Reducing the temperature from 477.59 to 422.04 K (400 to 300 °F) reduces the accurate prediction of Al-Anazi and DAK correlations. Al-Anazi correlation predicted Z-factor accurately for reduced pressure range less than 10.5 at $T_{pr} = 2.438$, reducing T_{pr} to 2.155 reduced the range of accurate prediction of this correlation to less than P_{pr} of 9. The same results for DAK correlation, the accurate prediction range reduced from less than $P_{pr} = 18$ at T_{pr} 2.438 to $P_{pr} = 13.75$ at $T_{pr} = 2.155$. The same for mixture 2 shown in Table 2, the three correlations (Al-Anazi, DAK, and the New Proposed) were used to predict the value of Z-factor and compare the prediction from the three correlations to the measured data as shown in Fig. 6. The new proposed correlation was the only correlation that predicted

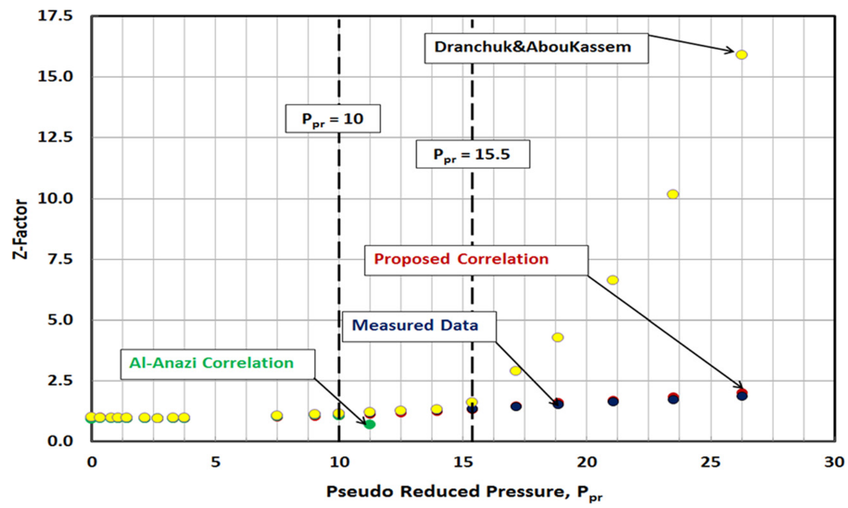

Fig. 6 Comparison between the different Z-factor correlation with actual measured data for gas mixture 2 at $T_{pr} = 2.155$. After p_{pr} value of 10 Al-Anazi correlation start to give values less than zero. The proposed correlation is the best one to predict the gas compressibility factor at high pressures. The reservoir pressure for this mixture at $p_{pr} = 30$ is 137.895 MPa (20,000 psi).

Table 3 Accuracy of the proposed correlation compared to other correlations

Mixture 1, $p = 137.895$ MPa (20,000 psi), $T = 422.04$ K (300 °F)	$Z_{measured}$ 1.99	$Z_{Al\text{-}Anazi}$ −500	Z_{DAK} 28.21	$Z_{proposed}$ 2.05
Error, %	—	25,200	1300	2.5
Mixture 1, $p = 137.895$ MPa (20,000 psi), $T = 477.59$ K (400 °F)	$Z_{measured}$ 1.94	$Z_{Al\text{-}Anazi}$ −497	Z_{DAK} 16.75	$Z_{proposed}$ 2.01
Error, %	—	255,000	760	3.6

accurate values for Z-factor at high pressure range. The amount of CO_2 in mixture 2 was 20% where it was 0% in mixture 1, the proposed correlation gave accurate prediction in the two cases for both mixtures. From the results shown in Figs. 4–6, we can conclude that Al-Anazi and DAK correlations are not useful for the prediction of Z-factor at high pressure range, whereas the new proposed correlation can be used to predict the Z-factor at high pressure high temperature gas reservoirs with high accuracy. Table 3 shows the accuracy of the proposed correlation in predicting Z-factor at high pressure high temperature gas system, the proposed correlation was the most accurate compared to DAK and Al-Anazi correlations.

The new proposed correlation can be used to predict the Z-factor accurately and the predicted Z-factor can then be used to determine the gas density using Eq. (42). Figure 7 shows a comparison between the predicted gas density and the measured one for mixture 1. The predicted gas density showed a good match with the measured data especially at high pressures, which confirms the validity of the proposed correlation to be used in the determination of gas properties.

Figure 8 shows comparison between the proposed, DAK, and Al-Anazi correlations in estimating Z-factor at temperature of 377.59 K (220 °F) and pressures lower than 34.474 MPa (5000 psia) ($p_{pr} < 7.6$). The estimated Z-factor from the three correlations was compared with measured Z-factor values by

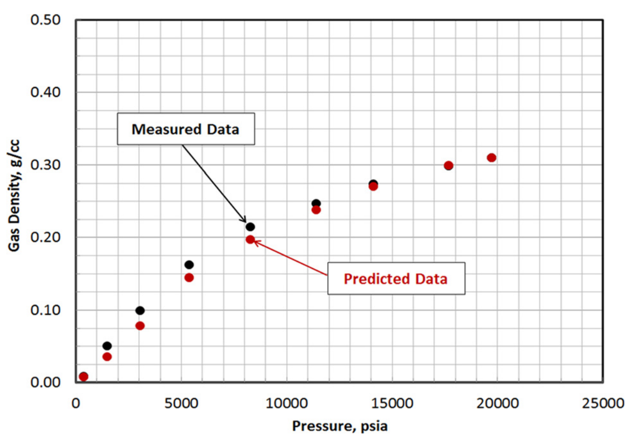

Fig. 7 Gas density for mixture 1 at 422.04 K (300 °F), the proposed correlation gives accurate prediction at high pressures

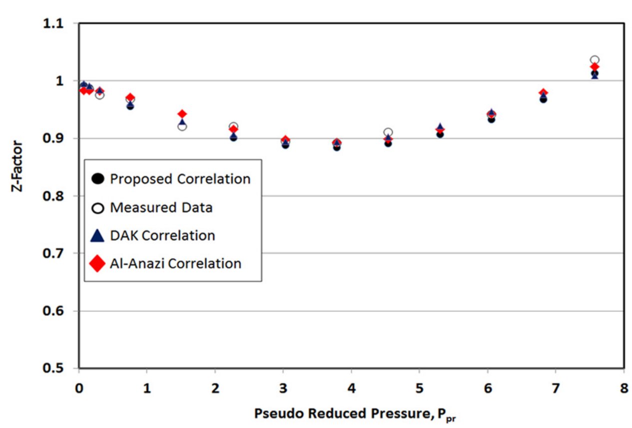

Fig. 8 Gas compressibility factor at 377.59 K (220 °F), $T_r = 1.93$, using the proposed correlation

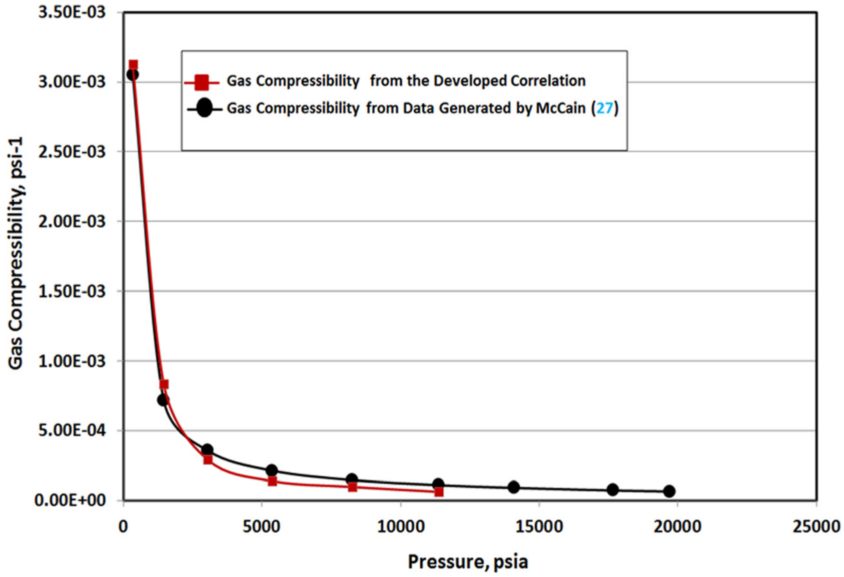

Fig. 9 Gas compressibility for mixture 1 at 422.04 K (300 °F) using the proposed correlation and comparing it with charts developed by McCain (27)

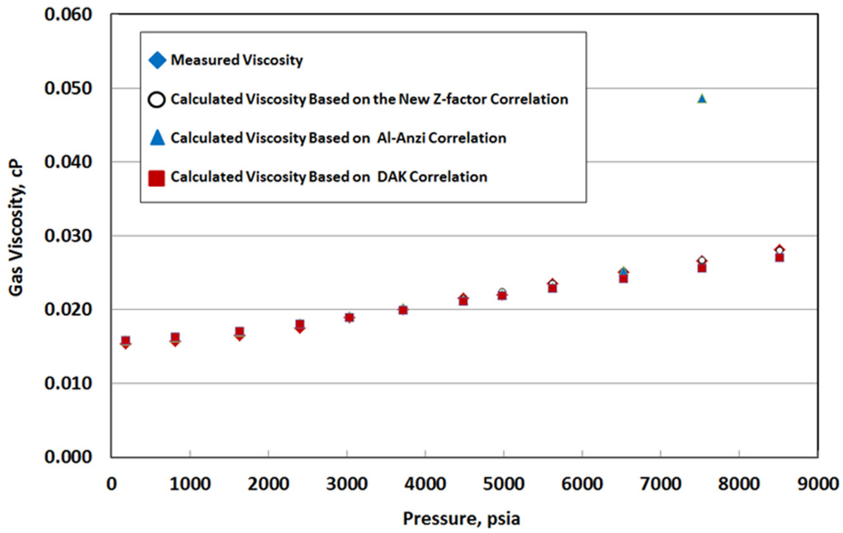

Fig. 10 Comparison between measured gas viscosity and gas viscosity estimated based on the Z-factor from proposed, DAK, and Al-Anzi correlations for methane gas at 422.04 K (300 °F)

Adisoemarta et al. [39] at the same conditions of pressure and temperature as shown in Fig. 8. The three correlations gave good estimate to Z-factor compared to the measured one. The proposed correlation gave accurate estimation of Z-factor at low pressure as well as at high pressure and also it can be used for a wide temperature range. The proposed correlation gave accurate estimation of the Z-factor for a temperature range from 377.59 to 477.59 K (220 to 400 °F). The new proposed correlation can be used for high HPHT gas wells as well as low pressure or medium pressure gas reservoirs.

The proposed correlation can be used to determine the term $\partial Z/\partial p_{pr}$ in equation (44) to determine the reduced compressibility of the gas then Eq. (43) can be used to determine the gas compressibility. The results of gas compressibility are shown in Fig. 9. The estimated gas compressibility using the developed correlation was compared to that obtained from the compressibility charts generated by McCain [27]. The properties of gas mixture 1 were used to determine the gas compressibility at different pressures, there was good match between the gas compressibility estimated from the new proposed correlation and that estimated from McCain charts. The gas compressibility charts developed by McCain can be used only for maximum gas pressure of 79.29 MPa (11,500 psia). Gas compressibility is widely used in oil and gas reservoir modeling to estimate the total compressibility. The gas compressibility is a very important factor that is being used in the determination of the wellbore storage period in well testing of oil and gas reservoirs [40].

Lee et al. [41] measured the viscosity of four natural gases over temperature range 311.11 to 444.44 K (560–800 °R), up to 55.16 MPa (8000 psia), and developed the following correlation:

$$\mu_g = 10^{-4} a \exp\left[b\left(\rho_g/62.4\right)^c\right] \qquad (62)$$

where $a = (9.379 + 0.0160\,M)\,T^{1.5}/(209.2 + 19.26\,M + T)$, $b = 3.448 + 0.01009\,M + (986.4/T)$, and $c = 2.4 - 0.2\,b$.

The gas viscosity is a strong function of gas density which is also a strong function of Z-factor, bad estimation of Z-factor will lead to big error in the estimation of gas viscosity. Measured viscosity data were obtained from Ling et al. [42] at temperature of 300 °F (760 °R) up to pressure of 172.369 MPa (25,000 psia). The proposed correlation, DAK, and Al-Anazi correlations were used to estimate the Z-factor at the same conditions of pressure and temperature from the same natural gas which is methane and the results were compared with the actual measured data. Figure 10 shows the accuracy of the proposed correlation in estimating the Z-factor that in turn will give accurate estimation of the gas density and viscosity. The viscosity estimated based on Z-factor obtained from Al-Anazi correlation started to deviate from the measured data after pressure value of 44.816 MPa (6500 psia). The same problem will be faced with DAK correlation for high pressure range as discussed before. Accurate estimation of Z-factor will guarantee accurate estimation of all natural gas PVT properties that are widely used in production rate estimation, well testing [40], reserve estimation, and reservoir simulation. Gas viscosity is an important factor in modeling of the three phase flow through pipes or through the reservoir and the accuracy of modeling this flow depends on the accuracy of many parameters such as Z-factor, gas density, and gas viscosity [43,44]. The gas flow rate estimation or prediction is a strong function of the gas viscosity, the gas viscosity affects the non-Darcy flow coefficient or turbulent coefficient, accurate determination of gas viscosity will enhance the accuracy of non-Darcy flow deliverability prediction for vertical and horizontal wells [45].

5 Conclusions

The gas compressibility or gas deviation factor is an extremely important parameter in natural gas engineering. The determination of the gas deviation factor is a must to determine the gas density, gas viscosity, gas compressibility, gas reservoir simulation, material balance calculation, and PVT prediction for oil and gas wells. The old correlations of Z-factor cannot be used to predict Z-factor at high pressures. In this study we developed a new correlation that can be used to predict the gas deviation factor at high pressure and high temperature gas reservoirs. The new proposed correlation showed good match with the measured data of Z-factor at high and low pressure compared to DAK and Al-Anazi correlations. The proposed correlation can be used to predict the gas deviation factor for different natural gas mixtures at high and low pressure with high accuracy. The gas density was predicted accurately using the predicted Z-factor from the proposed correlation. The gas compressibility was determined using the new formula of gas reduced compressibility that was developed based on the new proposed correlation. The proposed correlation also can be used to determine Z-factor at low pressures and also low temperatures. The gas viscosity determined based on the Z-factor showed good match with the measured viscosity data at the same conditions.

Nomenclature

A = area
C = gas compressibility
C_D = drag coefficient
g = acceleration gravity
G_i = initial gas in place
GLR = gas liquid ratio
G_p = produced gas
M = gas molecular weight
p = pressure
q = flow rate
R = general gas constant
R_s = solution gas oil ratio
T = temperature
t = production time
u_{sg} = gas superficial velocity
V = velocity
W_e = water influx
WOR = water oil ratio
y = mole fraction
Z = gas compressibility factor

Greek Symbols

γ = specific gravity
μ = viscosity
ρ = density
σ = interfacial tension
$\psi(t)$ = variable $= P_g/Z(t)$

Subscripts

c = critical
g = gas
i = ith component
L = liquid
m = mixture
min = minimum
pc = pseudocritical
pr = pseudoreduced
r = reduced
SC = standard conditions
t = total

References

[1] Kumar, M. N., 2004, "Compressibility Factors for Natural and Sour Reservoir Gases by Correlations & Cubic Equations of State," Texas Tech University, Lubbock, TX.
[2] Standing, M. B., 1981, *Volumetric and Phase Behavior of Oil Hydrocarbon System*, SPE of AIME, Dallas, TX.
[3] Ahmed, T. H., 1989, *Hydrocarbon Phase Behavior*, Gulf Publishing, Houston.
[4] Standing, M. B., and Katz, D. L., 1942, "Density of Natural Gases," Trans. AIME, **146**, pp. 140–149.
[5] Yarborough, L., and Hall, K. R., 1973, "A New Equation of State for Z-Factor Calculations," Oil & Gas J., **71**, pp. 82–92.
[6] Yarborough, L., and Hall, K. R., 1974, "How to Solve Equation of State for Z-Factors?," Oil & Gas J., **72**, pp. 86–88.
[7] Dranchuk, P. M., Purvis, R. A., and Robinson, R. A., 1973, "Computer Calculation of Natural Gas Compressibility Factors Using the Standing and Katz Correlations," Paper CIM 73-112 presented at the 24th Annual Technical Meeting of the Petroleum Society of CIM, Edmonton, Alberta, Canada, May 8–12.
[8] Dranchuk. P. M., and Abou-Kassem, J. H., 1975, "Calculation of Z Factor for Natural Gases Using Equation of State," J. Can. Pet. Technol., **14**(3), pp. 34–36.
[9] Poettman, F. H., and Carpenter, P. G., 1952, "The Multiphase Flow of Gas, Oil, and Water Through Vertical Flow Strings With Application to the Design of Gas Lift Installations," Drilling and Production Practices, API, pp. 257–317.
[10] Londono, F. E., Archer, R. A., and Blasingame, T. A., 2002," Simplified Correlations for Hydrocarbon Gas Viscoisty and Gas Density-Validation and Correlation of Behavior Using a Large Scale Database," Presented at the SPE Gas Technology Symposium, Calgary, Apr. 30–May2, Paper No. SPE 75721.
[11] Katz, D. L., Cornell, D., Kobayashi, R., Poettmann, F. H., Vary, J. A., and Elenbass, J. R., 1959, *Handbook of Natural Gas Engineering*, McGraw-Hill Book Company, New York.
[12] Brown, G. G., and Holocomb, D. E., 1940, "The Compressibility of Gases: I. Gaseous Mixtures," Pet. Eng., **11**, pp. 23–28.
[13] Dranchuk, P. M., Purvis, R. A., and Robinson, R. A., 1974, "Computer Calculation of Natural Gas Compressibility Factors Using the Standing and Katz Correlations," Institute of Petroleum Technical Series, Paper No. IP-74008, pp. 1–13.
[14] Cope, J. Q., Lewis, W. K., and Weber, H. C., 1931, "Generalized Properties of Higher Hydrocarbon Vapors," Ind. Eng. Chem., **28**, pp. 887–892.
[15] Brown, G. G., Souders, M., and Smith, R. L., 1932, "Pressure Volume Temperature Relations of Paraffin Hydrocarbons," Ind. Eng. Chem., **24**, pp. 513–515.
[16] Brown. G. G., 1940, "The Compressibility of Gases: I. Pure Gases," Pet. Eng., **11**, pp. 21–24.
[17] Mac Dougall, F. H., 1916, "The Equation of State for Gases and Liquids," J. Amer. Chem. Soc., **38**, pp. 528–555.
[18] Kay, W. B., 1936, "Density of Hydrocarbon Gases and Vapors at High Temperature and Pressure," Ind. And Eng. Chem., **28**(9), pp. 1014–1019.
[19] Stewart, W. F., Bukhard, S. F., and Voo, D., 1959, "Prediction of Pseudo-Critical Parameters for Mixtures," Paper Presented at the AIChE Meeting, Kansas City, MO, May 18.
[20] Sutton, R. P., 1985, "Compressibility Factor for High-Molecular-Weight Reservoir Gases," Presented at the SPE Annual Technical Conference and Exhibition, Las Vegas, Nevada, Sept. 22–26, Paper No. SPE 14265.

[21] Piper. L. D., McCain, W. D., and Corredor, J. H., 1993, "Compressibility Factors for Naturally Occurring Petroleum Gases," Presented at the 68th Annual Technical Conference and Exhibition of SPE, Houston, TX, Oct. 3–6, Paper No. SPE 26668.
[22] Elsharakawy, A. M., and Alikan, A. A., 1997, "Correlations for Predicting Solution Gas/Oil Ratio, Oil Formation Volume Factor, and Under-Saturated Oil Compressibility," J. Pet. Sci. Eng., **17**, pp. 291–302.
[23] Elsharkawy, A. M., and Elkamel, A., 2000, "Compressibility Factor for Sour Gas Reservoirs," Presented at the 2000 SPE Asia Pacific Oil & Gas Conference and Exhibition, Brisbane, Australia, Oct. 16–18, Paper No. SPE 64284.
[24] Lee, W. J., and Wattenbarger, R. A., 1996, "Properties of Natural Gases: Gas Reservoir Engineering," Vol. 5 (SPE Textbook Series), Society of Petroleum Engineering, Richardson, TX, pp. 1–32.
[25] Sutton, R. P., 2007, "Fundamentals PVT Calculations for Associated and Gas/Condensate Natural-Gas Systems," SPE Reservoir Eng. Eval. J., **10**(3), pp. 270–284.
[26] Whitson, C. H., and Brule, M. R., 2000, "Gas and Oil Properties and Correlations," Phase Behavior, Vol. 20, SPE Monograph, SPE, Richardson, TX, pp. 18–46, Chap. 3.
[27] McCain. W. D., 1996, *Equations of State: The Properties of Petroleum Fluids*, 2nd ed., Penn-Well Books, Houston, TX, pp. 90–128.
[28] Benedict, M., Webb, G. B., and Rubin, L. C., 1940, "An Empirical Equation of Thermodynamic Properties of Light Hydrocarbon and Their Mixtures, I. Methane, Ethane, Propane, and n-Butane," J. Chem. Phys., **8**, pp. 334–345.
[29] Beattie, J. A., and Bridgeman, O. C., 1929, "A New Equation of State for Fluids," Proc. Am. Acad. Arts Sci., **63**, pp. 229–308.
[30] Al-Anazi, B. D., and Al-Quraishi, A. A., 2010, "New Correlation for Z—Factor Using Genetic Programming Technique," Presented at the SPE Oil and Gas India Conference and Exhibition, Mumbai, India, Jan. 20–22, Paper No. SPE 128878.
[31] Rushing. J. A., Newsham, K. E., Van Fraassen, K. C., Mehta, S. A., and Moore, G. R., 2008, "Natural Gas Z-Factor at HP/HT Reservoir Conditions: Comparing Laboratory Measurements With Industry-Standard Correlations for a Dry Gas," Presented at the CIPC/SPE Gas Technology Symposium 2008 Joint Conference. Calgary, Alberta. Canada, June 16–19, Paper No. SPE 114518.
[32] Jossi, J. A., Stiel, L. I., and Thodos, G., 1962, "The Viscosity of Pure Substances in the Dense Gaseous and Liquid Phases," AIChE J., **8**(1), pp. 59–62.
[33] Dean, D. E., and Stiel, L. I., 1965, "The Viscosity of Nonpolar Gas Mixtures at Moderate and High Pressures," AIChE J., **11**, pp. 526–532.
[34] Rudolf, J. J., Heidrick, T. R., Fleck, B. A., Ridley, R. K., and Rajan, R. V., 2004," A Pumping System to Enhance Production From Gas Wells," ASME J. Energy Resour. Technol., **126**(4), pp. 311–319.
[35] Sukarno, P., Saepudin, D., Dewi, S., and Soewono, E., 2009, "Optimization of Gas Injection Allocation in Dual Gas Lift System," ASME J. Energy Resour. Technol., **131**(3), p. 033101.
[36] Ayala, L. F., and Alp, D., 2008, "Evaluation of "Marching Algorithms" in the Analysis of Multiphase Flow in Natural Gas Pipelines," ASME J. Energy Resour. Technol., **130**(4), p. 043003.
[37] Liu, N., and Civan, F., 2005, "Underground Gas Storage Inventory Analysis by Nonitertaive Method," ASME J. Energy Resour. Technol., **127**(2), pp. 163–165.
[38] Abbaspour, M., Chapman, K. S., and Krishnaswami, P., 2005, "Nonisothermal Compressor Station Optimization," ASME J. Energy Resour. Technol., **127**(2), pp. 131–141.
[39] Adisoemarta, P. S., Frailey, S. M., and Lawal, A. S., 2004, "Measured Z-Factor of CO_2-Dry Gas/Wet Gas/Gas Condensates for CO_2 Storage in Depleted Gas Reservoirs," Presented at the SPE/DOE Fourteenth Symposium on Improved Oil Recovery, Tulsa, Oklahoma, Apr. 17–21, Paper No. SPE 89466.
[40] Haghighi, A. M., and Pourafshary, P., 2012," A Noniterative Blind Deconvolution Approach to Unveil Early Time Behavior of Well Testings Contaminated by Wellbore Storage Effects," ASME J. Energy Resour. Technol., **134**(2), p. 022901.
[41] Lee, A., Gonzalez, M. H., and Eakin, B. E., 1966, "The Viscosity of Natural Gases," J. Pet. Technol., **18**(8), pp. 997–1000.
[42] Ling, K., Teodoriu, C., Davani, E., and Falcone, G., 2009, "Measurement of Gas Viscosity at High Pressures and High Temperatures," Presented at the SPE International Petroleum Technology Conference, Dec. 7–9, Doha, Qatar, Paper No. SPE IPTC 13528.
[43] Al-lababidi, S., Yan, W., and Yeung, H., 2012," Sand Transportation and Deposition Characteristics in Multiphase Flow in Pipelines," ASME J. Energy Resour. Technol., **134**(3), p. 034501.
[44] Zaghloul, J., Adewumi, M., and Ityokumbul, M. T., 2008," Hydrodynamic Modeling of Three-Phase Flow in Production and Gathering Pipelines," ASME J. Energy Resour. Technol., **130**(4), p. 043004.
[45] Lu, J., Ghedan, S., Zhu, T., and Tiab, D., 2011, "Non-Darcy Binomial Deliverability Equations for Partially Penetrating Vertical Gas Wells and Horizontal Gas Wells," ASME J. Energy Resour. Technol., **133**(4), p. 043101.

Dr. Mohamed Ahmed Nasr El-Din Mahmoud *is currently working as an assistant professor, department of petroleum engineering, KFUPM, Dhahran, KSA. Dr. Mahmoud is adjunct assistant professor in the department of petroleum engineering, Suez University, Egypt. He got his B.S. and M.S. degrees from Suez Canal University, Egypt, and got his PH.D degree from Texas A&M University, College Station, Texas, USA. All degrees in petroleum Engineering. He published more than 30 technical papers and 10 reviewed journal papers. Dr. Mahmoud areas of research are carbonate and sandstone acidizing, formation damage, hydraulic and acid fracturing of conventional and unconventional reservoirs, enhanced oil recovery of sandstone and carbonate reservoirs, drilling fluids, advanced well logging, multiphase flow in pipes, filter cake removal and characterization, sequestration and storage of carbon dioxide, and rock petrophysics. Mahmoud holds several patents in the areas of production enhancement and enhanced oil recovery.*