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Prediction of compressibility factor for gas condensate under a wide range of pressure conditions based on a three-parameter cubic equation of state

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ABSTRACT

The gas compressibility factor as an essential thermodynamic parameter is often used to analyze PVT behavior in natural gas engineering. To accurately predicate it for various gas condensates, a data base containing 916 data sets covering a wide range of experimental conditions is employed to establish and test the prediction model based on a three-parameter cubic equation of state (EoS). The presented model which based on EPT EoS combines with Elliott–Daubert binary interaction coefficients correlation, Ahmed et al. splitting and Hosseinifar–Jamshidi characterization methods is superior to conventional empirical correlations with three mixing rules and two-parameter EoSs as SRK, PR, PRSV and MPR2. Statistical error analysis shows that it outperforms empirical correlations with average absolute relative errors of 1.45% and coefficient of determination of 0.989. At pressure and temperature up to 95.04 MPa and 429.3 K, respectively, the model also outperforms two-parameter EoSs with average absolute relative errors of 1.65% and coefficient of determination of 0.992. The presented model is efficient and practical for predicting the compressibility factor of gas condensate.

1. Introduction

Gas condensate as an important part of natural gas resources is usually located in the deep strata under high temperature high pressure conditions (Ungerer et al., 1995; Sun et al., 2012). It is mainly composed of methane and derived its high molecular weight from the quantity of heavy hydrocarbon fractions (Sutton, 1985). When gas condensate is exploited from the formation and transported by the pipeline, a serious of pressure and temperature changes will occur. In some cases, this phenomenon should be avoided, since it leads to forming hydrocarbon condensates which may cause damage to petroleum production facilities and transmission pipelines (Galatro and Marín-Cordero, 2014). As an essential parameter, the gas compressibility factor is often used to analyze PVT behavior in most upstream and downstream petroleum and natural gas engineering calculations (Elsharkawy, 2004; Chamkalani et al., 2013a).

The sources of compressibility factor values are determined by means of experimental measurements, equations of state, empirical correlations and other intelligent approaches (Kamyab et al., 2010; Chamkalani et al., 2013b). Experimental measurements can provide direct and repeatable results, but they are costly and time consuming. Empirical correlations have limited application range due to the experimental conditions for building the correlations (Fayazi et al., 2014). Several models built by advanced algorithms have the shortcomings that complicated steps are required. Therefore, the thermodynamic model based on cubic EoS which is applicable at high pressures for both liquid and vapor phases of natural gas systems is considered as a better solution (Erdogmus and Adewumi, 2000; Li et al., 2012; Yan et al., 2013).

Coupled with van der Waals one fluid mixing rules, EoSs are used as powerful tools to predicate different properties of gas mixtures (Haghtalab et al., 2010). A two-parameter cubic EoS will generate large deviation in the density prediction due to its independent way to predict a critical compressibility factor (Esmaeilzadeh and Roshanfekr, 2006). But a substance dependent empirical critical compressibility factor which is introduced to the three-parameter cubic EoSs can develop the predictive ability (Valderrama, 2003). Although the original Patel and Teja (1982) (PT) EoS is a frequently used three-parameter EoS to predict thermodynamic properties for gas mixtures, it has disadvantages on temperature dependence of the attractive term and the EoS

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parameters (Forero and Velásquez, 2013). Several modified forms of PT EoS have been proposed to improve the predictive ability for gas mixtures containing heavy compositions (Valderrama, 1990; Erdogmus and Adewumi, 2000; Forero and Velásquez, 2013). However, these presented EoSs can achieve satisfactory results when they were used to calculate thermodynamic properties of pure substances and some binary mixtures at low temperature and low pressure conditions, while their adaptabilities for predicting complex mixtures like gas condensate containing heavy fractions at higher conditions were not examined.

For gas condensate, the plus fractions need to be split into a series of pseudo components with splitting methods before tunning the EoS. Based on different principles of splitting methods, the single carbon numbers (SCN) and its corresponding properties, such as molecular weight and mole fraction, are different (Duan et al., 2013). These splitting methods are including those of Katz (1983), Whitson (1983), Pedersen et al. (1984) and Ahmed et al. (1985). The physical properties of each pseudo component can be determined by several proposed characterization correlations (Edmister, 1958; Cavett, 1964; Kesler and Lee, 1976; Sim and Daubert, 1980; Watanasiri et al., 1985; Riazi and Daubert, 1987; Hosseinifar and Jamshidi, 2014). However, affected by the application scopes, both the splitting methods and pseudo components characterization correlations need to be optimized before tunning the EoS.

In this study, for the purpose of accurately predicating the compressibility factor for various gas condensates at a wide range of pressure conditions, PT (Patel and Teja, 1982), VPT (Valderrama, 1990), EPT (Erdogmus and Adewumi, 2000) and FPT (Forero and Velásquez, 2013) three-parameter cubic EoSs are optimized. The following impact factors are considered: four PT family EoSs, binary interaction coefficients (BIC), heavy hydrocarbon fraction splitting method, critical properties and acentric factor for SCN groups. Further, comparisons of ten published empirical correlations with three mixing rules, and SRK (Soave, 1972), PR (Peng and Robinson, 1976), PRSV (Stryjek and Vera, 1986) and MPR2 (Haghtalab et al., 2011) two-parameter EoSs are presented.

2. Prediction methods for gas compressibility factor

Compressibility factor of the real gas can be expressed as a function of pressure, volume and temperature as following:

$$Z = PV/nRT \tag{1}$$

where P is pressure, V is volume, n is the number of gas, R is gas constant, T is temperature, and Z is the compressibility factor.

Based on the theory of corresponding states, Z is also can be defined as a function of pseudo reduced pressure (P_{pr}) and pseudo reduced temperature (T_{pr}) as follows (Chamkalani et al., 2013b):

$$P_{\mathrm{pr}} = P/P_{\mathrm{pc}} \tag{2}$$

$$T_{\mathrm{pr}} = T/T_{\mathrm{pc}} \tag{3}$$

where P_{pc} and T_{pc} stand for the pseudo critical pressure and temperature, respectively.

The pseudo critical temperature and pressure can be determined by some mixing rules (Stewart et al., 1959; Sutton, 1985; Corredor et al., 1992; Piper et al., 1993; Elsharkawy et al., 2001; Elsharkawy, 2004). Along with these works, several correlations were developed to calculate the pseudo critical parameters through using gas specific gravity (Standing, 1981; Elsharkawy, 2001; Elsharkawy and Elkamel, 2001; Londono Galindo et al., 2005; Sutton, 2007).

2.1. Equations of state (EoSs)

Among virial type, cubic and complex or molecular based principles EoSs, cubic EoSs are more widely recommended and used (Forero and Velásquez, 2013). They are simple expressions and have ability to describe the phase behavior of vapor and liquid over a wide range of pressures, temperatures and thermodynamic properties of fluids quickly and reliably (Farrokh-Niae et al., 2008; Guria and Pathak, 2012). According to the number of parameters that appear in the repulsive and attractive terms, cubic EoSs can be divided into two-parameter, three-parameter, four and five parameters cubic equations of state (Forero and Velásquez, 2012). The SRK (Soave, 1972) and PR (Peng and Robinson, 1976) equations belong to two-parameter cubic EoSs, and PT (Patel and Teja, 1982) equation is a three-parameter cubic EoS. They are the commonly used volumetric properties predicating methods for sour gases and gas condensates, and the application of modified and other EoSs is also popular in recent years.

2.2. Empirical correlations

For the sake of calculating compressibility factors, more than twenty empirical correlations have been proposed (Heidaryan et al., 2010a). This kind of compressibility factor calculating method is classified into two categories: indirect models and direct methods (Chamkalani et al., 2013b). The empirical correlations adopted in this study are presented in the following sections.

2.2.1. Papay (1968)

Papay (1968) proposed a simple relationship to calculate the compressibility factor as following:

$$Z = 1 - \frac{P_{\mathrm{pr}}}{T_{\mathrm{pr}}}\left[0.3648758 - 0.04188423\left(\frac{P_{\mathrm{pr}}}{T_{\mathrm{pr}}}\right)\right] \tag{4}$$

2.2.2. Beggs and Brill (1973)

Beggs and Brill (1973) proposed a correlation which generated from Standing–Katz chart to predict compressibility factor:

$$Z = A + \frac{(1-A)}{e^{B}} + CP_{\mathrm{pr}}^{D} \tag{5}$$

where

$$\begin{aligned}
A &= 1.39(T_{\mathrm{pr}} - 0.92)^{0.5} - 0.36T_{\mathrm{pr}} - 0.101\\
B &= (0.62 - 0.23T_{\mathrm{pr}})P_{\mathrm{pr}} + \left[\frac{0.066}{(T_{\mathrm{pr}} - 0.86)} - 0.037\right]P_{\mathrm{pr}}^{2}\\
&\quad + \left(\frac{0.32}{10^{9(T_{\mathrm{pr}}-1)}}\right)P_{\mathrm{pr}}^{6}\\
C &= 0.132 - 0.32\log(T_{\mathrm{pr}})\\
D &= 10^{\left(0.3016 - 0.49T_{\mathrm{pr}} + 0.1824T_{\mathrm{pr}}^{2}\right)}
\end{aligned} \tag{6}$$

2.2.3. Shell oil company

Kumar (2004) referenced the shell oil company model for calculation of compressibility factor as:

$$Z = A + BP_{\mathrm{pr}} + (1-A)\exp(-C) - D\left(\frac{P_{\mathrm{pr}}}{10}\right)^{4} \tag{7}$$

where