Sensitivity of natural gas flow measurement to AGA8 or GERG2008 equation of state utilization

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ABSTRACT

The accurate measurement of natural gas flow at metering point is essential for custody transfer. The most used technologies for natural gas measurements are including turbine flow meters, ultrasonic flow meters and orifice flow meters. These flow meters are basically volume flow meter which measure natural gas volume at flow condition. Then the natural gas volume at flow condition should be converted to volume at base (standard) condition by appreciated procedure. Historically, the AGA8 equation of state (EOS) is widely used for such conversion. Recently, a new equation of state (GERG 2008) was presented by European Gas companies for natural gas thermodynamic properties calculation. The main objective of the current study is to present a comparison between AGA8 and GERG2008 EOS in computing conversion factor. Firstly, the Z-factor is calculated based on ISO20765-1 standard which is most recent version of AGA8 EOS. Then, ISO20765-2 standard has been employed to calculate Z-factor based on GERG2008 EOS. Comparing the calculated Z-factor and measured value of previous studies show that the accuracy of GERG2008 EOS is higher than AGA8 for all studied range of pressure and temperature and for various composition ranges. Results also show that GERG2008 equation of state predicts Z-factor higher than AGA8 standard in practical region of measurement. The results also reveal very important findings. Surprisingly, the relative difference is negative for the practical region of measurement. It means that by replacing AGA8 EOS by GERG2008 standard, the less flow is registered by the measurement system. In other words, simply by utilizing the GERG2008 EOS (instead of AGA8 EOS), the buyer benefits.

1. Introduction

Natural Gas (NG), as an important primary energy source in worldwide, consists of up to 21 components such as methane (as the main component), ethane, propane and others (Starling and Savidge, 1992). NG is used for various purposes such as power generation, cooking and space heating (Kayadelen, 2017). Measuring NG mass flow rate is one of the most important tasks in the gas industry and any uncertainty in measurement may resulted into unaccounted for gas (Arpino et al., 2014). Consequently, several methods have developed to measure NG flow rate (Baker, 2005) Mass flow meters as tools for measuring NG mass flow are used in few places in NG industries such as compressed natural gas fueling station (Parvizi et al., 2016). The common instruments for metering NG flow rate are including turbine meters, orifice flow meters and multiple ultrasonic transient-time meters (Frøysa and Lunde, 2005). These instruments (except mass flow meters) are based on metering volume flow rate (Gallagher, 2013). This

volume is usually referred as an actual volume. Due to NG is treated on its volume at standard condition, the actual volume must be converted to standard volume.

Since NG is sold based on standard volume or heat content of standard volume, converting NG volume at flow condition to the volume at standard condition is necessary at custody transfer points. For such conversion, in addition to pressure and temperature, compressibility factor of NG should be also known.

To obtain compressibility factor of a fluid, various approaches have been attempted. Empirical correlations are one of simple and fast approach for calculating compressibility factor. Hall and Yarborough (1973) presented an empirical correlation to calculate compressibility factor of natural gas in 1973 (Dranchuk and Abou-Kassem, 1975). proposed a correlation for computing compressibility factor of dry natural gas. There have been also recent studies with new correlations for obtaining compressibility factor of natural gas including (Heidaryan et al., 2010) and (Azizi and Behbahani, 2017). (Farzaneh-Gord and

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Rahbari, 2011) also proposed a series of correlations for calculating natural gas properties including compressibility factor.

The other approach for calculating the compressibility factor of NG is the intelligent methods. Several intelligent methods have been developed so far including Artificial Neural Network (ANN), Fuzzy Interface System (FIS) and Adaptive Neuro-Fuzzy System (ANFIS) (Mohamadi-Baghmolaei et al., 2015). (Mohamadi-Baghmolaei et al., 2015) have compared these intelligent methods and concluded that ANN method is the most accurate one for calculating compressibility factor. Recently, researches have been carried out on the use of ANN to increase the accuracy of calculating compressibility factor of natural gas, especially compressibility factor which measures the deviations between ideal gas and real gas, and one of the earliest studies in this field was the work (Moghadassi et al., 2009). An ANN system was applied by (Kamyab et al., 2010) to calculate NG compressibility factor. They used Katz diagram to prepare input data of ANN (AlQuraishi and Shokir, 2011). used an ANN with 4445 experimental data for predicting the density of the NG mixture and results of their investigation showed 4.93% average absolute deviation.

The common and most utilized approach for calculating compressibility factor of a fluid is Equation Of State (EOS). The first and most famous EOS for real (non-ideal) gas was proposed and developed by Van der Waals. The accuracy of the Van der Waals EOS was improved by (Redlich and Kwong, 1949), (Soave, 1972) and (Peng and Robinson, 1976) by modifying attractive term of Van der Waals EOS. Other researchers (Guggenheim, 1965), (Carnahan and Starling, 1969) and (Boublik, 1981) has modified repulsive term of Van der Waals EOS to obtain more accuracy. As an example (Christoforakos and Franck, 1986), modified both terms of Van der Waals EOS. To predict the properties of more complex molecules, Perturbed-Hard-Chain-Theory (PHCT) and Statistical-Associating-Fluid-Theory (SAFT) ((Chapman et al., 1990) have been developed. In recent years, Estela-Uribe et al. (2004) (Estela-Uribe and Trusler, 2003), proposed two separate extended EOSs for natural gases and similar mixtures in which one could be employed for a wide range of pressure and temperature and the other was limited to the custody transfer region.

There are few EOSs and methods which commonly used for calculating NG compressibility factor. AGA NG-19 default method is required specific gravity, mole fraction of carbon dioxide and nitrogen for calculating NG compressibility factor. It could be utilized for natural gas with specific gravity less than 0.75, mole fraction of carbon dioxide and nitrogen less than 15%. A modified version of (AGA NX-19, 1987) is still employed to compute the NG compressibility factor for pressure less than 10000 kPa and temperature range from 270 to 450 K. The modified AGA NX-19 is capable of calculating NG compressibility factor for mixtures with a calorific value less than that of methane with an accuracy of about 0.2%. However, this limited range of application, make it useless for many places. The other simple method with limited input is SGERG equation of state which presented by (Jaeschke and Humphreys, 1991). The SGERG EOS is only required mole fraction of the carbon dioxide, the nitrogen, the hydrogen and relative density and calorific value of the mixture.

Two most recent EOSs for natural gas properties calculation are AGA8-DC92 (Starling and Savidge, 1992) the and GREG-2008 (Kunz and Wagner, 2012). Starling and Savidge (1992) have proposed the AGA8 EOS as transmission measurement committee report which contains two methods for calculating NG compressibility factor. The methods are the Gross Characterization Method (GCM) and the Detail Characterization Method (DCM). Although, the GCM requires same inputs as AGA NX-19 but there is difference in procedures and output results. The DCM requires mole percentage of the NG mixture up to 21 components. The original report which later also was adopted as (ISO 12213-2, 1994) is only aimed to present a method for calculating NG compression factor. Along with a few published papers ((Marić, 2007), (Maric and Ivek, 2010), (Marić et al., 2005), (Farzaneh-Gord et al., 2010), (Farzaneh-Gord and Rahbari, 2012)), the (ISO, 20765-1, 2005.) is published which present the standard method for thermodynamic properties calculations.

The most recent equation of state applied in natural gas industry is GERG2008 EOS. This equation of state is developed based on a joint project by European natural-gas companies. The first version of this wide range equation of state is present in a technical monograph (Kunz et al., 2007). The second version of the equation is described in (Kunz and Wagner, 2012) and also adopted as (ISO, 20765-2, 2015) standard. Similar to AGA8 EOS, the GERG2008 could receive up to 21 components as input. The GERG2008 is originally developed to calculate the thermodynamic properties of the natural gas mixtures. It was claimed that the GERG2008 could calculate the density with uncertainty less than 0.1% in the temperature range from 270 K to 450 K at pressures up to 35000 kPa. The accuracy of density calculation is also improved significantly for temperatures ranging from 250 K to 275 K (Kunz and Wagner, 2012).

As mentioned, accurate NG measurement requires the precise knowledge of its compressibility factor. Few previous experimental studies mentioned that the AGA8 EOS is not so accurate in calculating compressibility factor (Patil et al., 2007) even at its normal range. In the current study, the main objective is to investigate sensitivity of NG flow measurement to selection of two most recent EOSs. DCM of AGA8-DC92 and GERG2008 are selected as two most recent EOSs which are currently applied in NG industry. In this investigation, firstly, the NG compressibility factor has been calculated using both EOSs. Then, a comparison has been made between calculated compressibility factors with a large number of measured values to find accuracy of the methods. A comparison has been also made among the two reference EOSs and a few empirical correlations. In addition, the compressibility factor of a few natural gas mixtures flowing into Iranian pipeline have been calculated and compared. Finally, the effects of EOSs selection on converting factor and NG flow measurement have been compared and investigated.

2. Natural gas measurement

The accurate knowledge of natural gas flow rate is essential for custody transfer purposes. Currently, the flow measurement is made with various devices and principles ((Baker, 2005), (Miller and Richard, 1996)). Orifice, turbine and ultrasonic flow meters are commonly used devices for measuring natural gas flow rate in the metering stations. These devices are volume flow meter which means that they measure the volume of flow passing through the meter at flowing condition. A typical metering and pressure drop station is shown in Fig. 1.

Considering Fig. 1, the natural gas volume corrector receives the volume flow at flow condition from a Volume Flow Meter (VFM). The flow temperature and pressure are also detected by appropriated sensors. The natural gas compositions are usually sets at specific time period (from appropriated devices or just a report from natural gas refinery). The main task of the volume corrector is to convert the flow volume at flowing condition into the base or standard condition ($T_b = 15\,°C$ and $P_b = 1\,atm$). The following equation is employed for this conversion (Baker, 2005):

$$Q_b = CF \times Q_f \tag{1}$$

where CF is correction factor and calculated using the below equation (Baker, 2005):

$$CF = \left(\frac{T_b}{T_f}\right)\left(\frac{P_f + P_{atm}}{P_b}\right)\left(\frac{Z(T_b, P_b, X_i)}{Z(T_f, P_f, X_i)}\right) \tag{2}$$

where, P_f is natural gas gauge pressure at flowing condition and P_{atm} is atmospheric pressure at the metering station which depends on the altitude (as an important factor) of the station. As it could be realized from the previous equations, the natural gas volume at base (or standard) condition is highly influenced by Z-factor.
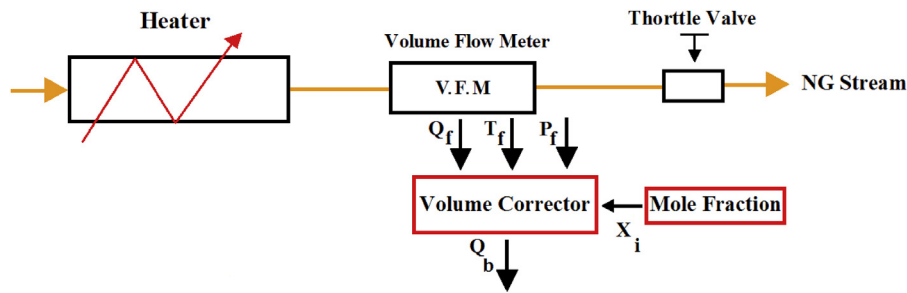
Fig. 1. A typical metering and pressure drop station.

As the value of Q_b is employed for custody transfer, the method of Z-factor calculation is highly important in natural gas industries especially for the case of high flow metering stations. Currently, the AGA8 EOS (K. E. and Savidge, 1992) is employed for Z-factor calculation in Iran and probably most countries. Recently, GERG2008 EOS (Kunz and Wagner, 2012) is also presented by European countries as reference equation of state for natural gases and similar mixtures. In this section, the methods of compressibility factor calculation by these two EOS and seven empirical correlations are discussed, presented.

3. Z-factor calculation

In this section, NG Z-factor calculating procedure are discussed. Two reference equation of state (AGA8-DC92 and GERG 2008) and also seven famous empirical correlations and three well known cubic equation of state are presented.

3.1. AGA8-DC92 formulation

Here, in this section, a brief description for calculating Z-factor of natural gas mixture based on DCM of AGA8 EOS (K. E. and Savidge, 1992) is presented. The AGA8 EOS was originally presented as an equation explicit in compression factor. The equation later is used for calculating thermodynamic properties of natural gases. The AGA8 EOS is only capable to calculate the properties in the gas phase. It is limited to temperatures range from 143 to 673 K and pressure up to 280000 kPa. However, the uncertainty in Z-factor calculation depends on the temperature and pressure range. Considering the real gas equation of state as below equation:

$$P = \frac{ZRT}{v} \tag{3}$$

The Z-factor could be calculated using various ways including AGA8 EOS (K. E. and Savidge, 1992) as:

$$Z = 1 + \frac{DB}{K^3} - D \sum_{n=13}^{18} C_n^* T^{-u_n}$$
$$+ \sum_{n=13}^{58} C_n^* T^{-u_n} \left(b_n - c_n k_n D^{k_n}\right) D^{b_n} \exp\left(-c_n D^{k_n}\right) \tag{4}$$

in which, K is mixture size coefficient, B is second virial coefficient, D is reduced density, C_n^* are the temperature dependent coefficients and b_n, c_n and k_n are the parameters.

The gas molar density, d, and reduced density, D, are presented as:

$$D = K^3 d \tag{5}$$

$$d = \frac{P}{ZRT} \tag{6}$$

The mixture size coefficient and the second virial coefficients could be computed using the following equations:

$$K^5 = \left[\sum_{i=1}^{N} X_i K_i^{5/2} \right]^2 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} X_i X_j (K_{ij}^5 - 1)(K_i K_j)^{5/2} \tag{7}$$

$$B = \sum_{n=1}^{18} a_n T^{-u_n} \sum_{i=1}^{N} \sum_{j=1}^{N} X_i X_j E_{ij}^{u_n} (K_{ij}^5 - 1)(K_i K_j)^{5/2} B_{nij}^* \tag{8}$$

where the coefficients B_{nij}^*, E_{ij} and G_{ij} are computed as follow:

$$B_{nij}^* = (G_{ij} + 1 - g_n)^{g_n} (Q_i Q_j + 1 - q_n)^{q_n} \left(F_i^{1/2} F_j^{1/2} + 1 - f_n \right)^{f_n}$$
$$(S_i S_j + 1 - s_n)^{s_n} \times (W_i W_j + 1 - w_n)^{w_n} \tag{9}$$

$$E_{ij} = E_{ij}^* \times (E_i E_j)^{1/2} \tag{10}$$

$$G_{ij} = \frac{G_{ij}^* \times (G_i + G_j)}{2} \tag{11}$$

where T is temperature, N is the number of the components, X_i is the molar fraction of the component i, a_n, f_n, g_n, q_n, s_n, u_n and w_n are the EOS parameters, E_i, F_i, G_i, K_i, Q_i, S_i and W_i are the corresponding characterization parameters. Also, E_{ij}^* and G_{ij}^* are the corresponding binary interaction parameters. C_n^*, $n = 1, ..., 58$, temperature dependent coefficients, are defined by the following relations:

$$C_n^* = a_n (G + 1 - g_n)^{g_n} (Q^2 + 1 - q_n)^{q_n} (F + 1 - f_n)^{f_n} U^{u_n} \tag{12}$$

and the mixture parameters U, G, Q and F are calculated using the following equations:

$$U^5 = \left[\sum_{i=1}^{N} X_i E_i^{5/2} \right]^2 + 2 \times \sum_{i=1}^{N-1} \sum_{j=i+1}^{N-1} X_i X_j (U_{ij}^5 - 1)(E_i E_j)^{5/2} \tag{13}$$

$$G = \sum_{i=1}^{N} X_i G_i + \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} X_i X_j (G_{ij}^* - 1)(G_i + G_j) \tag{14}$$

$$Q = \sum_{i=1}^{N} X_i Q_i \tag{15}$$

$$F = \sum_{i=1}^{N} X_i^2 F_i \tag{16}$$

where U_{ij} is the binary interaction parameter for mixture energy.

The detailed equations and method for calculating Z-factor using AGA8 EOS are presented in AGA8/1992, ISO12213-2 and recently in ISO20765-1.

It should be also noted that the AGA8 EOS has limited composition range for each component. These ranges are classified in normal and expanded range. The composition range of each component are presented in Table 1.

3.2. GERG2008 formulation

The GERG2008 equation of state, which is an expansion of GERG2004 EOS, is developed by European gas companies (**G**roup

Table 1
The accepted composition range in AGA8 EOS (K. E. and Savidge, 1992).

Expanded Range	Normal Range	Quantity
0 to 100	45 to 100	Mole Percent Methane
0 to 100	0 to 50	Mole Percent Nitrogen
0 to 100	0 to 30	Mole Percent Carbon Dioxide
0 to 100	0 to 10	Mole Percent Ethane
0 to 12	0 to 4	Mole Percent Propane
0 to 6	0 to 1	Mole Percent Total Butanes
0 to 4	0 to 0.3	Mole Percent Total Pentanes
0 to Dew Point	0 to 0.2	Mole Percent Hexanes Plus
0 to 3	0 to 0.2	Mole Percent Helium
0 to 100	0 to 10	Mole Percent Hydrogen
0 to 3	0 to 3	Mole Percent Carbon Monoxide
0 to 1	0	Mole Percent Argon
0 to 21	0	Mole Percent Oxygen
0 to Dew Point	0 to 0.05	Mole Percent Water
0 to 100	0 to 0.02	Mole Percent Hydrogen Sulfide

Europeén de **R**echerches **G**azières) in order to obtain more accurate equation for natural gases (Kunz and Wagner, 2012). The GERG EOS basically combines developed pure gas EOSs into a single equation of state for natural gas mixture. In this work, GERG2008 EOS (Kunz and Wagner, 2012) is also employed to calculate the compressibility factor of natural gases. The GERG2008 EOS is also adopted as a standard (ISO20765-2) for calculating thermodynamic properties of natural gases.

As it is more convenience to derive the properties from Helmholtz free energy, the GERG2008 is explicit in Helmholtz free energy (Kunz and Wagner, 2012). The Helmholtz free energy of fluid mixture is expressed as function of density, temperature and compositions as below [ISO 20765-2]:

$$\alpha(\rho, T, \overline{X}) = \alpha^0(\rho, T, \overline{X}) + \alpha^r(\rho, T, \overline{X}) \tag{17}$$

Similar to AGA8 EOS, GERG2008 gets density and not pressure as independent variable. The pressure is then calculated by an iterative manner. It is more practical to present the above equation in dimensionless form $\alpha = \frac{a}{RT}$ as:

$$\alpha(\delta, \tau, \overline{X}) = \alpha^0(\rho, T, \overline{X}) + \alpha^r(\delta, T, \overline{X}) \tag{18}$$

in which, $\delta = \frac{\rho}{\rho_r(x_i)}$ is reduced fluid mixture density and $\tau = \frac{T_r(x_i)}{T}$ is inverse reduced temperature. It should be noted that these parameters are only function of the mixture compositions and are computed as follow:

$$\frac{1}{\rho_r(\overline{X})} = \sum_{i=1}^{N} \sum_{j=1}^{N} X_i X_j \beta_{v,ij} \gamma_{v,ij} \frac{X_i + X_j}{\beta_{v,ij}^2 x_i + x_j} \left[\frac{1}{8}\right] \left(\frac{1}{\rho_{c,i}^{1/3}} + \frac{1}{\rho_{c,j}^{1/3}}\right)^3 \tag{19}$$

$$T_r(\overline{X}) = \sum_{i=1}^{N} \sum_{j=1}^{N} X_i X_j \beta_{T,ij} \gamma_{T,ij} \frac{X_i + X_j}{\beta_{T,ij}^2 X_i + X_i} (T_{c,i}. T_{c,j})^{0.5} \tag{20}$$

The δ and τ are developed based on quadratic mixing rules. $\beta_{v,ij}$, $\gamma_{T,ij}$, $\beta_{T,ij}$ and $\gamma_{T,ij}$ are binary mixtures parameters and their values could be found in ISO 20765-2. The critical parameters $\rho_{c,i}$ and $T_{c,i}$ of the pure components are also given in ISO 20765-2.

The Helmholtz free energy ideal part of gas mixture, α^o, is represented as:

$$\alpha^0(\rho, T, \overline{X}) = \sum_{i=1}^{N} X_i [\alpha_{0i}^0(\rho, T) + Ln(X_i)] \tag{21}$$

Where $\sum X_i Ln(X_i)$ is the contribution of entropy due to mixing, and $\alpha_{0i}^0(\rho, T)$ is the ideal dimensionless Helmholtz free energy of the component i.

The reduced Helmholtz free energy residual part, α^r, is divided into two types of binary departure functions, namely a generalized departure function and specific departure function as (Kunz and Wagner, 2012):

$$\alpha^r(\delta, \tau, \overline{X}) = \alpha_0^r(\delta, \tau, \overline{X}) + \Delta\alpha^r(\delta, \tau, \overline{X}) \tag{22}$$

The generalized departure function, α_{or}^r, shows contribution of pure substances residual parts of the reduced Helmholtz free energy and may be calculated as below:

$$\alpha_0^r(\delta, \tau, \overline{X}) = \sum_{i=1}^{N} X_i \alpha_{0i}^r(\delta, \tau) \tag{23}$$

The $\Delta\alpha^r$ is the specific departure function and developed for the respective binary mixtures. The specific departure function is calculated as:

$$\Delta\alpha^r(\delta, \tau, \overline{X}) = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \Delta\alpha_{ij}^r(\delta, \tau, \overline{X}) \tag{24}$$

with

$$\Delta\alpha_{ij}^r(\delta, \tau, \overline{X}) = X_i X_j F_{ij} \alpha_{ij}^r(\delta, \tau) \tag{25}$$

In above equation, F_{ij} are model parameters and $\alpha_{ij}(\delta, \tau)$ is part of the specific departure function which only depended on reduced temperature and density. It is expressed as below:

$$\alpha_{ij}^r(\delta, \tau) = \sum_{k=1}^{K_{Pol,ij}} n_{ij,k} \delta^{d_{ij,k}} \tau^{t_{ij,k}}$$
$$+ \sum_{K=K_{Pol,ij}+1}^{K_{Pol,ij}+K_{Exp,ij}} n_{ij,k} \delta^{d_{ij,k}} \tau^{t_{ij,k}} e^{-\eta_{ij,k}(\delta-\varepsilon_{ij,k})^2 - \beta_{ij,k}\left(\delta-\gamma_{ij,k}\right)} \tag{26}$$

The values of the coefficients $n_{ij,k}$, the exponents $d_{ij,k}$ and $t_{ij,k}$ and the parameters $\eta_{ij,k}$, $\varepsilon_{ij,k}$, $\beta_{ij,k}$, and $\gamma_{ij,k}$ could be found in ISO 20765-2.

The equation for calculating Z-factor in GERG2008 EOS is expressed as:

$$Z = 1 + \delta\alpha_\delta^r \tag{27}$$

As the actual input values in natural gas industries are pressure, temperature and natural gas components, an iterative method is required to found pressure firstly and then Z-factor.

The entire range of validity of GERG2008 EOS covers the following temperatures and pressures:

- Normal range: 90 K ≤ T ≤ 450 K P ≤ 35000 kPa
- Extended range: 60 K ≤ T ≤ 700 K P ≤ 70000 kPa

Moreover, the equation can be reasonably extrapolated beyond the extended range, and each component can basically cover the entire composition range, i.e., (0–100) %.

In addition, the GERG2008 EOS could be also reasonably extrapolated beyond the extended range. This EOS could be also employed to compute the properties of each component individually.

3.3. AGA8 and GERG2008 standard volume flow calculation procedure

Fig. 2 shows the procedure for calculating standard flow volume using AGA8 and GERG2008 EOSs. As it could be realized, the procedure required T, P, X and Q_f as inputs and it generate Q_b as output. As it was discussed before T, P, X and Q_f are measured from appreciated sensors and volume flow meter respectively. The procedure finally generate Q_b as custody volume.

3.4. Empirical correlations

Apart from AGA8-DC92 or GERG2008 EOSs, a few empirical correlations have been presented for calculating Z-factor. These correlations could be easily employed to find natural gas Z-factor. These
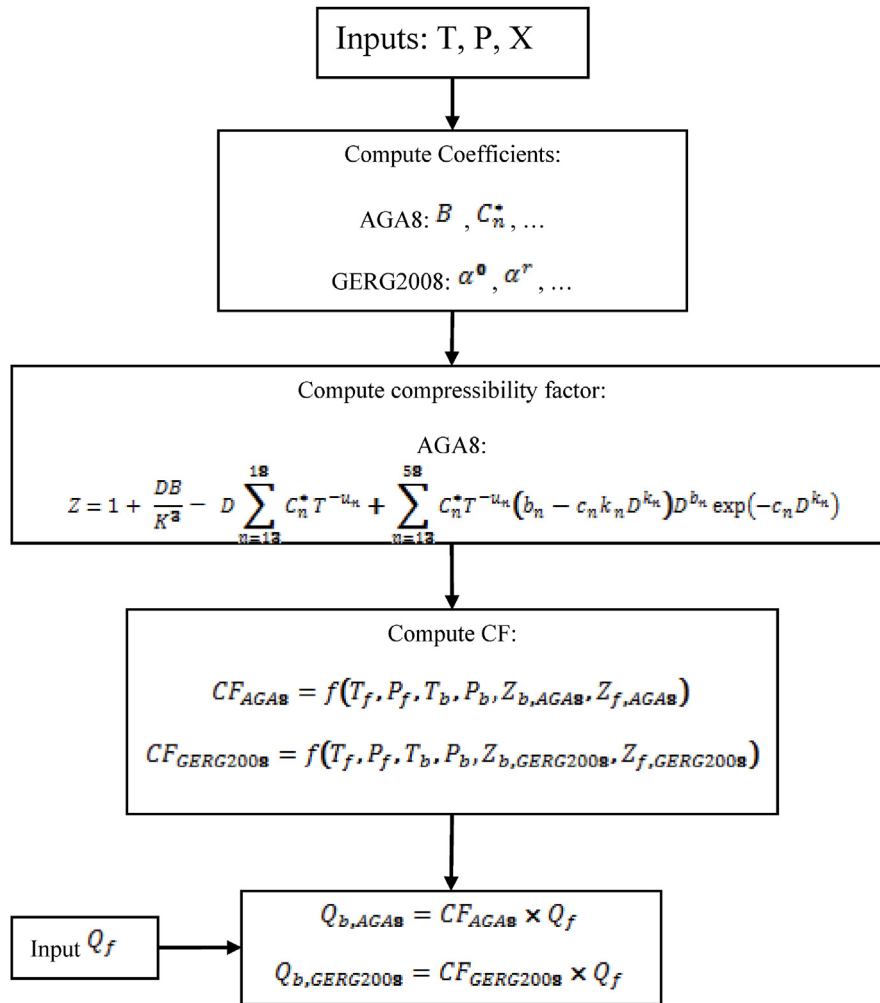
Inputs: T, P, X

Compute Coefficients:

AGA8: B , C_n^* , ...

GERG2008: α^0 , α^r , ...

Compute compressibility factor:

AGA8:

$$Z = 1 + \frac{DB}{K^3} - D \sum_{n=13}^{18} C_n^* T^{-u_n} + \sum_{n=13}^{58} C_n^* T^{-u_n} (b_n - c_n k_n D^{k_n}) D^{b_n} \exp(-c_n D^{k_n})$$

Compute CF:

$$CF_{AGA8} = f(T_f, P_f, T_b, P_b, Z_{b,AGA8}, Z_{f,AGA8})$$

$$CF_{GERG2008} = f(T_f, P_f, T_b, P_b, Z_{b,GERG2008}, Z_{f,GERG2008})$$

Input Q_f

$$Q_{b,AGA8} = CF_{AGA8} \times Q_f$$

$$Q_{b,GERG2008} = CF_{GERG2008} \times Q_f$$

Fig. 2. The standard volume flow calculating procedure flowchart.

correlations are usually required pseudo-reduced temperature, T_{pr}, and pseudo-reduced pressure, P_{pr}, as input for calculating Z-factor. The seven most famous empirical correlations including (Dranchuk et al., 1973), (Hall and Yarborough, 1973) are presented in Table 2.

3.5. Cubic EOS

Since Van der Waals presented the first cubic equation of state in 1873, many changes have been made to this equation to improve the results (Valderrama, 2003). In this section, three well known cubic equation of state, Van der waals (Kwak and Mansoori, 1986), Soave-Redlich-Kwong and Peng-Robinson, have been employed to find Z factor. To compute Z factor using these cubic equation of states, Aspen Hysis software package has been utilized (ASPEN HYSIS, 2010). These three cubic equation of states with their mixing rules are as follows:

3.5.1. Van der Waals
The Van der Waals equation of state could be presented as follows:

$$P = \frac{RT}{V - b} - \frac{a}{V^2} \tag{35}$$

It could be also written in Z form as below:

$$Z^3 - (1 + B)Z^2 + AZ - AB = 0 \tag{36}$$

Where A and B are as follow

$$A = \frac{aP}{R^2 T^2} , \ B = \frac{bP}{RT} \tag{37}$$

The following mixing rules are employed for obtaining a and b:

$$a = \sum_i^n \sum_j^n x_i x_j a_{ij}, \ b = \sum_i^n \sum_j^n x_i x_j b_{ij} \tag{38}$$

$$a_{ij} = (1 - k_{ij})(a_{ii} a_{jj})^{0.5}, \ b_{ij} = \frac{b_{ii} + b_{jj}}{2} \tag{39}$$

3.5.2. Soave Redlich-Kwong
The Soave Redlich-Kwong equation of state has the following form:

$$P = \frac{RT}{V - b} - \frac{a}{V(V + b)} \tag{40}$$

It could be presented in Z form as equation (41) where the constants as mixing rules are presented in equation (42)–(47):

$$Z^3 - Z^2 + (A - B - B^2)Z - AB = 0 \tag{41}$$

$$A = \frac{aP}{(RT)^2}, \ B = \frac{bP}{RT} \tag{42}$$

$$b = \sum_{i=1}^n x_i b_i, \ a = \sum_{i=1}^n \sum_{j=1}^n x_i x_j (a_i a_j)^{0.5} (1 - k_{ij}) \tag{43}$$

$$b_i = 0.08664 \frac{RT_{ci}}{P_{ci}}, \ a_i = a_{ci} \alpha_i \tag{44}$$

Table 2
The most famous empirical correlations for natural gas Z-factor calculation.

Empirical correlations	Formula	
(Dranchuk et al., 1973)	$$Z = 1 + \left(A_1 + \frac{A_2}{T_r} + \frac{A_3}{T_r^3}\right)\rho_r + \left(A_4 + \frac{A_5}{T_r}\right)\rho_r^2 + \frac{A_5 A_6 \rho_r^5}{T_r} + \frac{A_7 \rho_r^2}{T_r^3}(1 + A_8\rho_r^2)\exp(-A_8\rho_r^2)$$ $A_1 = 0.31506237$ $A_2 = -1.0467099$ $A_3 = -0.5783272$ $A_4 = 0.53530771$ $1.05 \leq T_{pr} \leq 3$ $A_5 = -0.61232032$ $A_6 = -0.10488881$ $3A_8 = 0.68446549$ $0.2 \leq P_{pr} \leq 30$ $A_7 = 0.68157001$	(28)
(Dranchuk and Abou-Kassem, 1975)	$$Z = 1 + \left(A_1 + \frac{A_2}{T_r} + \frac{A_3}{T_r^3} + \frac{A_4}{T_r^4} + \frac{A_5}{T_r^5}\right)\rho_r + \left(A_6 + \frac{A_7}{T_r} + \frac{A_8}{T_r^2}\right)\rho_r^2 - A_9\left(\frac{A_7}{T_r} + \frac{A_8}{T_r^2}\right)\rho_r^5$$ $$+ A_{10}(1 + A_{11}\rho_r^2)\frac{\rho_r^3}{T_r^3}\exp(-A_{11}\rho_r^2)$$ $A_1 = 0.3265$ $A_2 = -1.07$ $A_3 = -0.5339$ $A_4 = 0.01569$ $A_5 = -0.05165$ $1 \leq T_{pr} \leq 3$ $A_6 = 0.5475$ $A_7 = -0.7361$ $A_9 = 0.1056$ $A_8 = 0.1844$ $A_9 = 0.1056$ $0.2 \leq P_{pr} \leq 30$ $A_{10} = 0.6134$ $A_{11} = 0.721$	(29)
(Hall and Yarborough, 1973)	$$Z = \frac{1 + \rho_r + \rho_r^2 - \rho_r^3}{(1-\rho_r)^3} - (A_1 T_r^{-1} - A_2 T_r^2 + A_3 T_r^3)\rho_r + (A_4 T_r^{-1} - A_5 T_r^{-2} + A_6 T_r^{-3})\rho_r^{(A_7 + A_8 T_r^{-1})}$$ $A_1 = 14.76$ $A_2 = 9.76$ $A_3 = 4.58$ $A_4 = 90.7$ $1.2 \leq T_{pr} \leq 3$ $A_5 = -242.2$ $A_6 = 42.4$ $A_7 = 1.18$ $A_8 = 2.82$ $0 \leq P_{pr} \leq 15$	(30)
(Beggs and Brill, 1973)	$$Z = A_1(T_{pr} - A_2)^{1/2} - A_3 T_r - A_4 + \frac{1 - A_1(T_{pr} - A_2)^2 - A_3 T_{pr} - A_4}{\exp\left((A_5 - A_6 T_{pr})P_{pr} + \frac{A_7}{T_{pr} - A_8} - A_9\right)P_{pr}^2 - A_9} + \frac{A_{10}P_{pr}^6}{10^{A_{11}(T_{pr}-1)}}$$ $$+ (A_{12} - A_{13}\log(T_{pr}))P_{pr}^{10(A_{14} - A_{15}T_{pr} + A_{16}T_{pr}^2)}$$ $A_1 = 1.39$ $A_2 = 0.92$ $A_3 = 0.36$ $A_4 = 0.101$ $A_5 = 0.62$ $A_6 = 0.23$ $1.15 \leq T\_pr \leq 2.4$ $A_7 = 0.06$ $A_8 = 0.86$ $A_9 = 0.037$ $A_{10} = 0.32$ $A_{11} = 9$ $A_{12} = 0.132$ $0.2 \leq P_{pr} \leq 15$ $A_{13} = 0.32$ $A_{14} = 0.3106$ $A_{15} = 0.49$ $A_{16} = 0.1824$	(31)
(Shell Oil Company, 2003)	$$Z = -A_1 - A_2 T_{pr} + A_3(T_{pr} - A_4)^{\frac{1}{2}} + \left(A_5 + \frac{A_6}{T_{pr} - A_7}\right)P_{pr}$$ $$+ \left(1 + A_1 + A_2 T_{pr} - A_3(T_{pr} - A_4)^{\frac{1}{2}}\right)\exp\left(-P_{pr}\left(A_8 - A_9 T_{pr} + \left(\frac{A_{10}}{T_{pr} - A_{11}} - A_{12}\right)P_{pr}\right)\right)$$ $$+ A_{13}\exp(-A_{14}(T_{pr} - 1)) - (A_{15}\exp(-A_{14}(T_{pr} - 1)))\left(\frac{P_{pr}}{10}\right)^4$$ $A_1 = 0.101$ $A_2 = 0.36$ $A_3 = 1.3868$ $A_4 = 0.919$ $A_5 = 0.021$ $1.01 \leq T_{pr} \leq 3$ $A_6 = 0.04275$ $A_7 = 0.65$ $A_8 = 0.6222$ $A_9 = 0.224$ $A_{10} = 0.0657$ $0.01 \leq P_{pr} \leq 10$ $A_{11} = 0.85$ $A_{12} = 0.037$ $A_{13} = 0.32$ $A_{14} = 19.53$	(32)
(Papp, 1979)	$$Z = 1 + (A_1 \times T_{pr}^{A_2}) \times \left(\frac{P_{pr}}{T_{pr}^2} - T_{pr} - A_3 + \frac{A_4}{T_{pr}}\right) \times \left(1 - \exp\left(A_5 \times \frac{P_{pr}}{T_{pr}^2} + A_6 \times \left(\frac{P_{pr}}{T_{pr}^2}\right)^2\right)\right)$$ $A_1 = 0.1219$ $A_2 = 0.638$ $A_3 = 7.76$ $A_4 = 14.75$ $A_5 = 0.3$ $1.2 \leq T_{pr} \leq 3$ $A_6 = 0.441$ $0 \leq P_{pr} \leq 15$	(33)
(Mahmoud, 2013)	$$Z = (A_1 \exp(-A_2 T_{pr}))P_{pr}^2 - (A_3 \exp(-A_2 T_{pr}))P_{pr} + (-A_4 T_{pr}^2 - A_5 T_{pr} + A_6)$$ $A_1 = 0.702$ $A_2 = 2.5$ $A_3 = 5.524$ $A_4 = 0.044$ $A_5 = 0.164$ $1 \leq T_{pr} \leq 2.5$ $A_6 = 1.15$ $0 \leq P_{pr} \leq 30$	(34)

$$a_{ci} = 0.42748 \frac{(RT_{ci})^2}{P_{ci}} \tag{45}$$

$$\alpha_i^{0.5} = 1 + m_i(1 - T_{ri}^{0.5}) \tag{46}$$

$$m_i = 0.48 + 1.574\omega_i - 0.176\omega_i^2 \tag{47}$$

3.5.3. Peng Robinson

The Peng Robinson equation of state has the following form:

$$P = \frac{RT}{V - b} - \frac{a}{V(V + b)} \tag{48}$$

It could be presented in Z form as equation (49) where the constants as mixing rules are presented in equation (50)–(55):

$$Z^3 + (1 - B)Z^2 + (A - 2B - 3B^2)Z - (AB - B^2 - B^3) = 0 \tag{49}$$

$$A = \frac{aP}{(RT)^2}, \quad B = \frac{bP}{RT} \tag{50}$$

$$b = \sum_{i=1}^{n} x_i b_i, \quad a = \sum_{i=1}^{n} \sum_{j=1}^{n} x_i x_j (a_i a_j)^{0.5}(1 - k_{ij}) \tag{51}$$

$$b_i = 0.077796 \frac{RT_{ci}}{P_{ci}}, \quad a_i = a_{ci}\alpha_i \tag{52}$$

$$a_{ci} = 0.457235 \frac{(RT_{ci})^2}{P_{ci}} \tag{53}$$

$$\alpha_i^{0.5} = 1 + m_i(1 - T_{ri}^{0.5}) \tag{54}$$

$$m_i = \begin{cases} 0.37464 + 1.54226\omega_i - 0.26992\omega_i^2 & , \\ \omega_i \leq 0.49 \\ 0.379642 + (1.48506 - (0.164423 - 1.016666\omega_i)\omega_i)\omega_i, & \omega_i > 0.49 \end{cases} \tag{55}$$

4. Results and discussion

In this section, firstly, based on the statistical parameters presented in Table 3, the computed Z-factors are compared with measured values of various researches and also empirical correlations. Then, the sensitivity of Z-factors on NG measurement for 5 different Iranian NG mixtures are compared.

Table 3 presents 4 different statistical parameters which employed for comparing the numerical values of Z-factor with the measured values. These parameters are selected to show the accuracy of studied EOS in calculating the Z-factor ((Heidaryan et al., 2010), (ligne, 1973)).

4.1. Accuracy of Z-factor calculation

The accuracy of the two reference EOSs on Z-factor calculation has

Table 3
The statistical parameters for validating the two reference EOS.

Average Percent Relative Error (APRE %)	$APRE\% = \dfrac{\sum_{i=1}^{N_d}\left(\dfrac{Z_i^{Calculated} - Z_i^{Experimental}}{Z_i^{Experimental}}\right)}{N_d} \times 100$
Percent Relative Error (PRE %)	$PRE\% = 100 \times \left(\dfrac{Z_i^{Calculated} - Z_i^{Experimental}}{Z_i^{Experimental}}\right)$
Average Absolute Percent Relative Error (AAPRE %)	$AAPRE\% = \dfrac{\sum_{i=1}^{N_d}\left(\left\|\dfrac{Z_i^{Calculated} - Z_i^{Experimental}}{Z_i^{Experimental}}\right\|\right)}{N_d} \times 100$
Root Mean Square Error (RMSE)	$RMSE = \sqrt{\dfrac{\sum_{i=1}^{N_d}\left(Z_i^{Calculated} - Z_i^{Experimental}\right)^2}{N_d}}$

Table 4
Review of the previous experimental measurement of Z-factor for various natural gases.

Authors	T/K	P/kPa	Number of Mixtures
(Ahmadi et al., 2017)	323.31–414.45	1301–58374	1
(Staby and Mollerup, 1991)	275–345	222.301–60499.7	1
(Čapla et al., 2002)	253.15–323.15	996–15023	2
(Fenghour et al., 1999)	316.07–479.31	8769–48139	6
(Fenghour et al., 1996)	429.9–698.75	7491–30382	7
(Assael et al., 2001)	241.094–454.968	242–14040	1
(Hwang et al., 1997)	249.996–324.99	183.1–10406.9	1
Pure Methane	220–400	200–10100	1
(Patil et al., 2007)	269.98–340.03	3450–34543	1
(Li et al., 2014)	322.0389–435.9278	4826.33–81564.98	29

been investigated and compared in this section. For this purpose, firstly, the measured values of 10 accurate experimental studies are selected for comparison. Secondly, a comparison has been made among the two reference EOSs, empirical correlations and selected measured values.

Table 4 shows a review of accomplished studies. These studies measured Z-factor of various NG mixture in specified pressure and temperature range. In addition of these experimental data, the pure methane density is also employed for comparison. Table 4 to Table 10 presents 50 natural gas compositions used for comparison. These various compositions are classified into 6 groups. Table 5 contains dry natural gasses with no water in their compositions. These gases do not actually contain any acidic gasses (Hydrogen sulfide and Carbon dioxide). Table 6 contains the second classified group. The table contains the gasses with water and again without any acidic gasses. The third classified group is presented in Table 7 as sour natural gasses. These gasses contain Hydrogen sulfide and Carbon dioxide. Composition range of these 3 classified groups are in expanded range of AGA8 standard. Table 8, Table 9 and Table 10 contain the dry, wet and sour gases with the compositions range are in the normal range of AGA8 standard.

4.1.1. Comparing with the measured values

In Table 11, the accuracy of the GERG2008 and AGA8 Equation of states in calculation of Z-factor have been presented and compared for 50 natural gas mixtures. As it was stated previously, these compositions are classified into 6 different groups.

The Z-factor comparison is presented in Table 11 for dry natural gases in expanded AGA8 composition range (group 1, NG.1 to NG.4). It could be realized that the Average Percent Relative Error for AGA8 reach up to 5.7% while it is 1% for GERG 2008. The highest value of average absolute percent relative error is 5.7% and 1.03% for AGA8 and GERG2008 respectively. The AGA8 and GERG2008 root mean square error are 9.3% and 1.07 respectively. Considering the mentioned values, one could conclude that the accuracy of GERG2008 is much higher than AGA8 in this composition range. Considering the

Table 5
The compositions of dry natural gases in expanded composition range of AGA8 EOS.

Component	Dry natural gas in expanded AGA8 composition range			
	NG.1 (Fenghour et al., 1999)	NG.2 (Fenghour et al., 1999)	NG.3 (Fenghour et al., 1999)	NG.4 (Fenghour et al., 1999)
Methane	0.3724	0.3458	0.4396	0.3522
n-Butane	0.6276	0.6542	0.5604	0.6478

Table 6
The compositions of wet natural gases in expanded composition range of AGA8 EOS.

Component	Wet natural gas in expanded AGA8 composition range	
	NG.5 (Fenghour et al., 1996)	NG.6 (Fenghour et al., 1996)
Methane	0.3993	0.3239
Water	0.6007	0.6761

Table 7
The compositions of sour natural gases in expanded composition range of AGA8 EOS.

Component	Sour natural gas in AGA8 expanded composition range					
	NG.7 (Li et al., 2014)	NG.8 (Li et al., 2014)	NG.9 (Li et al., 2014)	NG.10 (Li et al., 2014)	NG.11 (Li et al., 2014)	NG.12 (Li et al., 2014)
Methane	0.4033	0.4382	0.4331	0.4033	0.1937	0.4241
Nitrogen	0.0383	0.0455	0.0394	0.0383	0.0386	0.0258
Carbon dioxide	0.0608	0.0644	0.0679	0.0608	0.6352	0.0319
Ethane	0.0448	0.0471	0.0494	0.0448	0.0303	0.0024
Propane	0.0248	0.0243	0.0277	0.0248	0.0174	0.0007
Isobutane	0.006	0.0055	0.0067	0.006	0.0033	0.0002
n-Butane	0.0132	0.012	0.014	0.0132	0.0093	0.0003
Isopentane	0.0079	0.0068	0.0074	0.0079	0.0039	0.0002
n-Pentane	0.0081	0.0069	0.0071	0.0081	0.0047	0.0001
n-Hexane	0.0121	0.0096	0.0077	0.0121	0.0051	0.0002
n-Heptane	0.0991	0.063	0.0214	0.0991	0.0551	0.0004
Hydrogen sulfide	0.282	0.277	0.318	0.2816	0.0034	0.5137

composition range of the studied gases, which is in expanded range of AGA8, the low accuracy of AGA8 was expected.

The Z-factor comparisons for second group (wet natural gas in expanded AGA8 composition range) are presented in Table 11 for NG.5 and NG.6 mixtures. Although, the error in calculation of Z-factor is relatively high for both EOSs but AGA8 EOS accuracy is much lower than GERG2008 especially for NG.6. Again, AGA8 has low accuracy in these composition range is expected but low accuracy of GERG2008 is surprising.

The Z-factor comparison for third group (sour natural gas in expanded AGA8 composition range) is presented in Table 11 for NG.7 to NG.12 mixtures. The accuracy of Z-factor calculation is high for both EOSs. The AGA8 accuracy is about 6%–8% while GERG2008 ranging from 4 to 6% for all studied statistical parameters. Again, as expected for expanded range of AGA8, the accuracy of GERE2008 is higher than AGA8.

The Z-factor comparison for forth group (The dry natural gases in normal composition range of AGA8 EOS) are shown in Table 11 for NG.13 to NG.30 mixtures. In this composition range, the accuracy of GERG2008 is slightly higher than AGA8 EOS except for NG.32 in which the AGA8 predict the better results. The high accuracy of AGA8 in normal range for dry gasses are expected.

The Z-factor comparisons for fifth group (The wet natural gases in normal composition range of AGA8 EOS) are shown in Table 11 for NG.31 and NG.37 mixtures. In this composition range, the accuracy of GERG2008 is much higher than AGA8 EOS. This show that the accuracy of AGA8 in predicting Z-factor is depended on the water contain of the gases.

The Z-factor comparisons for sixth group (The sour natural gases in normal composition range of AGA8 EOS) are shown in Table 11 for NG.38 and NG.50 mixtures. In this composition range, the accuracy of GERG2008 is again higher than AGA8 EOS. The accuracy of both EOSs are reduced as the percentage of hydrogen sulfide increases. This show

Table 8
The compositions of dry natural gases in normal composition range of AGA8 EOS.

Component	NG.13 (Ahmadi et al., 2017)	NG.14 (Staby and Mollerup, 1991)	NG.15 (Čapla et al., 2002)	NG.16 (Čapla et al., 2002)	NG.17 (Assael et al., 2001)	NG.18 (Hwang et al., 1997)	NG.19 Pure methane	NG.20 (Patil et al., 2007)	NG.21 (Li et al., 2014)	NG.22 (Li et al., 2014)	NG.23 (Li et al., 2014)	NG.24 (Li et al., 2014)	NG.25 (Li et al., 2014)	NG.26 (Li et al., 2014)	NG.27 (Li et al., 2014)	NG.28 (Li et al., 2014)	NG.29 (Li et al., 2014)	NG.30 (Li et al., 2014)
Methane	0.879427	0.6265	0.90362	0.92436	0.8484	0.81299	1	0.90991	0.6583	0.7074	0.738	0.7559	0.7583	0.7485	0.7292	0.7284	0.8616	0.85
Nitrogen	0.01502	0.1209	0.01474	0.05751	0.056	0.13575	0	0.02031	0.0137	0.0155	0.0161	0.0166	0.0163	0.0155	0.0143	0.015	0.0041	0
Carbon dioxide	0.02013	0	0.00647	0.00052	0.0066	0.00994	0	0.00403	0.0231	0.0242	0.0248	0.0253	0.0258	0.0262	0.0266	0.0017	0.0097	0.0061
Ethane	0.06	0.2526	0.05708	0.01285	0.084	0.03294	0	0.02949	0.0803	0.0817	0.0821	0.0839	0.0863	0.0905	0.0944	0.0847	0.0355	0.06
Propane	0.02043	0	0.01124	0.00348	0.005	0.00637	0	0.01513	0.0417	0.0411	0.0404	0.0402	0.0415	0.0447	0.0495	0.0418	0.0154	0.0332
Isobutane	0.001995	0	0.00301	0.00041	0	0.00101	0	0.00755	0.0078	0.0073	0.007	0.0069	0.0073	0.0082	0.0091	0.011	0.0046	0.0085
n-Butane	0.002998	0	0.00169	0.00046	0	0.001	0	0.00755	0.0184	0.017	0.0162	0.0159	0.0167	0.0186	0.0208	0.0171	0.0046	0.0129
Isopentane	0	0	0.00059	0.00015	0	0	0	0.00299	0.0075	0.0067	0.0062	0.006	0.0062	0.007	0.008	0.0088	0.0026	0.0057
n-Pentane	0	0	0.00029	0.00014	0	0	0	0.00304	0.0108	0.0097	0.0089	0.0084	0.0086	0.0096	0.0107	0.0084	0.002	0.0066
n-Hexane	0	0	0.00058	0.00012	0	0	0	0	0.0116	0.011	0.0103	0.0086	0.0078	0.0082	0.0092	0.0124	0.0035	0.0109
n-Heptane	0	0	0.00035	0	0	0	0	0	0.1268	0.0784	0.05	0.0323	0.0252	0.023	0.0282	0.0707	0.0564	0.0062
n-Octane	0	0	0.00008	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oxygen	0	0	0.00011	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Helium	0	0	0.00015	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 9
The compositions of wet natural gases in normal composition range of AGA8 EOS.

Component	Wet natural gas in normal range						
	NG.31 (Fenghour et al., 1996)	NG.32 (Fenghour et al., 1996)	NG.33 (Fenghour et al., 1996)	NG.34 (Fenghour et al., 1996)	NG.35 (Fenghour et al., 1996)	NG.36 (Fenghour et al., 1996)	NG.37 (Fenghour et al., 1996)
Methane	0.924	0.8261	0.7366	0.6623	0.5991	0.5427	0.4609
Water	0.076	0.1739	0.2634	0.3377	0.4009	0.4573	0.5391

Table 10
The compositions of sour natural gases in normal composition range of AGA8 EOS.

Component	Sour natural gas in normal range												
	NG.38 (Li et al., 2014)	NG.39 (Li et al., 2014)	NG.40 (Li et al., 2014)	NG.41 (Li et al., 2014)	NG.42 (Li et al., 2014)	NG.43 (Li et al., 2014)	NG.44 (Li et al., 2014)	NG.45 (Li et al., 2014)	NG.46 (Li et al., 2014)	NG.47 (Li et al., 2014)	NG.48 (Li et al., 2014)	NG.49 (Li et al., 2014)	NG.50 (Li et al., 2014)
Methane	0.4641	0.4807	0.4844	0.4688	0.6771	0.7564	0.6619	0.7352	0.6857	0.7414	0.5213	0.5601	0.6459
Nitrogen	0.0476	0.0473	0.0461	0.0434	0.0064	0.002	0.0011	0.0244	0.1019	0.004	0.0037	0.0304	0.0061
Carbon dioxide	0.0669	0.0685	0.0694	0.0699	0.0096	0.0058	0.0576	0.0163	0.0209	0.0616	0.0866	0.0287	0.0451
Ethane	0.0481	0.0487	0.0493	0.0496	0.0871	0.0706	0.0412	0.0498	0.059	0.0327	0.1165	0.082	0.0084
Propane	0.0239	0.0237	0.0239	0.0252	0.0384	0.0336	0.0188	0.0181	0.0282	0.0121	0.0142	0.0345	0.0093
Isobutane	0.0051	0.0049	0.0049	0.0055	0.005	0.0104	0.0044	0.0059	0.0047	0.0022	0.0039	0.0085	0.0027
n-Butane	0.0111	0.0106	0.0106	0.0114	0.0156	0.0135	0.0076	0.0073	0.0116	0.0061	0.0083	0.011	0.002
Isopentane	0.006	0.0055	0.0053	0.0058	0.0056	0.0072	0.0032	0.004	0.0085	0.0057	0.0095	0	0.002
n-Pentane	0.006	0.0054	0.0052	0.0057	0.0082	0.0055	0.0036	0.0037	0	0	0	0.0071	0.001
n-Hexane	0.0078	0.0066	0.006	0.0063	0.0083	0.0077	0.0052	0.0053	0.0035	0.0046	0.0103	0.0028	0.0012
n-Heptane	0.0412	0.0286	0.0217	0.0192	0.0656	0.049	0.0261	0.0253	0.008	0.0218	0.0431	0.0022	0.0032
Hydrogen sulfide	0.272	0.27	0.273	0.289	0.0708	0.0383	0.1693	0.1047	0.068	0.1078	0.1826	0.2327	0.273

Table 11
The AGA8 and GERG EOS accuracy comparison in Z-factor calculation.

NG	AAPRE$_{GERG}$	AAPRE$_{DETAIL}$	RMSE$_{GERG}$	RMSE$_{,DETAIL}$	NG	AAPRE$_{GERG}$	AAPRE$_{DETAIL}$	RMSE$_{GERG}$	RMSE$_{DETAIL}$
NG.1	1.0383	3.4469	1.0739	4.9433	NG.26	1.8467	1.5996	1.8467	1.5996
NG.2	0.3292	2.4614	0.3965	3.5466	NG.27	1.8580	1.7010	1.8580	1.7010
NG.3	0.2029	5.7409	0.2559	9.3062	NG.28	0.9837	1.5964	0.9837	1.5964
NG.4	0.2859	4.8834	0.3150	5.5149	NG.29	8.7424	9.6860	8.7424	9.6860
NG.5	8.0597	11.3465	8.1112	11.4052	NG.30	3.0281	2.8670	3.0281	2.8670
NG.6	0.5833	6.4143	0.5932	6.4290	NG.31	0.1161	0.3634	0.1300	0.3888
NG.7	3.5945	8.3401	3.5945	8.3401	NG.32	0.3213	0.9538	0.3542	0.9893
NG.8	4.0777	6.2766	4.0777	6.2766	NG.33	0.3480	1.4065	0.3630	1.4272
NG.9	2.4908	3.1033	2.4908	3.1033	NG.34	0.4338	1.9666	0.4655	1.9922
NG.10	3.5412	8.3391	3.5412	8.3391	NG.35	0.3071	2.3332	0.3380	2.3543
NG.11	4.1294	5.0448	4.1294	5.0448	NG.36	0.2425	2.8504	0.3047	2.8770
NG.12	2.8633	4.4161	2.8633	4.4161	NG.37	3.8855	6.8295	3.9269	6.8760
NG.13	0.1942	0.1926	0.5275	0.5256	NG.38	3.3409	4.2710	3.3409	4.2710
NG.14	0.1506	0.1572	0.3248	0.3273	NG.39	2.1181	2.6171	2.1181	2.6171
NG.15	0.0913	0.0153	0.1438	0.0168	NG.40	1.6525	2.3534	1.6525	2.3534
NG.16	0.0184	0.0135	0.0268	0.0226	NG.41	2.0046	2.7263	2.0046	2.7263
NG.17	0.0446	0.0321	0.0792	0.0709	NG.42	0.5274	0.7105	0.5274	0.7105
NG.18	0.0105	0.0175	0.0177	0.0336	NG.43	1.6040	2.0174	1.6040	2.0174
NG.19	0.0765	0.0794	0.0859	0.0890	NG.44	2.7000	2.4476	2.7000	2.4476
NG.20	0.1294	0.1801	0.1729	0.2285	NG.45	0.6561	0.3257	0.6561	0.3257
NG.21	6.8866	8.3705	6.8866	8.3705	NG.46	0.1882	0.2740	0.1882	0.2740
NG.22	2.6165	2.4557	2.6165	2.4557	NG.47	0.0683	0.1343	0.0683	0.1343
NG.23	0.8270	0.1135	0.8270	0.1135	NG.48	0.1985	1.9610	0.1985	1.9610
NG.24	0.4174	0.4581	0.4174	0.4581	NG.49	1.2285	2.1676	1.2285	2.1676
NG.25	1.2354	0.7114	1.2354	0.7114	NG.50	0.2050	0.0060	0.2050	0.0060

that both standards fails to predict Z-factor precisely for the sour gases.

4.1.2. Comparing with empirical correlations and cubic equation of states

In this section, the Z-factor are calculated based on the empirical correlations, cubic equation of states and two reference EOSs. Then, the Z-factor are compared with measured values to compare the accuracy of the empirical correlations, cubic EOSs and the reference EOSs. The statistical parameters for each method (the empirical correlations, cubic EOSs, AGA8 and GERG2008 EOSs) are calculated based on 10 different measured values and are presented in Table 12.

Looking at the statistical parameters in Table 12, one could realize that the accuracy of Z-factor calculation based on AGA8 and GERG2008 are much higher than the empirical correlations and cubic EOSs. This is the main reason for not employing these correlations in natural gas industries for Z-factor calculation and consequently natural gas measurement.

It could be understood from Table 12 that for the cubic EOSs, Van de waals EOS, as expected, has less accuracy comparing with Peng

Table 12
The compressibility factor statistical error calculation for studied methods.

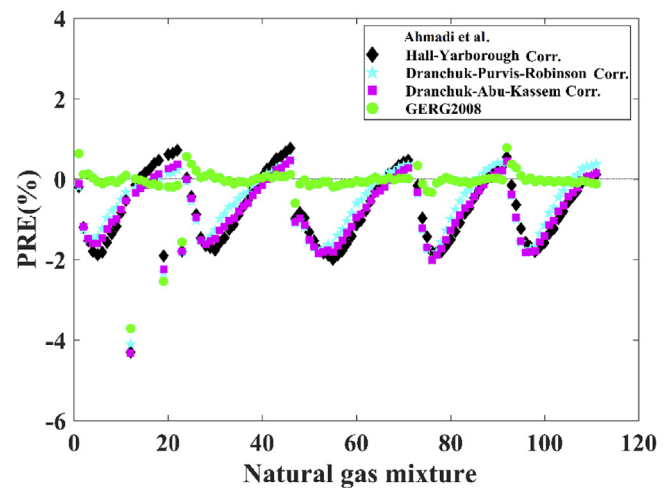| Correlation	Statistical parameters	(Li et al., 2014) N- G:7,8,9,10,11,12,21-,22,23,24,25,26,27,-28,29,30,38,39,40,4-1,42,43,44,45,46,47-,48,49,50	(Patil et al., 2007) NG:20	Pure Methane NG:19	(Hwang et al., 1997) NG:18	(Assael et al., 2001) NG:17	(Fenghour et al., 1996) N- G:5,6,31,32,33,-34,35,36,37	(Fenghour et al., 1999) NG:1,2,3,4	(Čapla et al., 2002) NG:15,16	(Staby and Mollerup, 1991) NG:14	(Patil et al., 2007) NG:20
(Mahmoud, 2013)	R^2	0.9585	0.9614	0.9301	0.9918	0.9904	0.9420	0.8594	0.9920	0.7488	0.8560
	RMSE	0.1436	0.0325	0.0161	0.0133	0.0175	0.0608	0.1419	0.0202	0.1975	0.0991
	AAPRE	10.8812	3.4182	1.6605	1.1634	1.6836	6.2423	21.2748	2.2991	3.7303	5.1435
(Papp, 1979)	R^2	0.9514	0.9922	0.9658	0.9979	0.9967	0.9764	0.9946	0.9917	0.9951	0.9957
	RMSE	0.0711	0.0158	0.0054	0.0117	0.0173	0.0576	0.0219	0.0203	0.0161	0.0168
	AAPRE	6.9289	1.6700	0.5094	0.7374	1.4601	5.8660	2.9261	2.1393	1.2959	1.4686
(Shell Oil Company, 2003)	R^2	0.9546	0.9965	0.9446	0.9977	0.9967	0.9113	0.9978	0.9957	0.9960	0.9935
	RMSE	0.0693	0.0099	0.0087	0.0082	0.0111	0.0550	0.0161	0.0124	0.0125	0.0131
	AAPRE	6.6417	1.0551	0.7343	0.5829	0.9404	5.3516	2.4998	1.3015	1.0007	1.0786
(Hall and Yarborough, 1973)	R^2	0.9558	0.9987	0.9766	0.9992	0.9983	0.9757	0.9994	0.9987	0.9976	0.9974
	RMSE	0.0676	0.0057	0.0079	0.0074	0.0095	0.0536	0.0112	0.0096	0.0109	0.0113
	AAPRE	6.3269	0.6129	0.7921	0.6069	0.8783	5.5722	1.6559	1.0733	0.9024	0.9604
(Dranchuk et al., 1973)	R^2	0.9539	0.9989	0.9326	0.9990	0.9982	0.9773	0.9995	0.9988	0.9981	0.9975
	RMSE	0.0670	0.0047	0.0092	0.0074	0.0096	0.0551	0.0111	0.0093	0.0097	0.0100
	AAPRE	6.1727	0.4640	0.8678	0.5864	0.8849	5.8194	1.7151	1.0388	0.8234	0.7863
(Dranchuk and Abou-Kassem, 1975)	R^2	0.9563	0.9990	0.9323	0.9990	0.9980	0.9770	0.9994	0.9987	0.9978	0.9976
	RMSE	0.0669	0.0047	0.0087	0.0069	0.0093	0.0544	0.0120	0.0089	0.0098	0.0108
	AAPRE	6.2131	0.4759	0.8132	0.5397	0.8415	5.7330	1.8268	0.9740	0.7952	0.8903
(Beggs and Brill, 1973)	R^2	0.9514	0.9922	0.9658	0.9979	0.9967	0.9764	0.9946	0.9917	0.9951	0.9957
	RMSE	0.0711	0.0158	0.0054	0.0117	0.0173	0.0576	0.0219	0.0203	0.0161	0.0168
	AAPRE	6.9289	1.6700	0.5094	0.7374	1.4601	5.8660	2.9261	2.1393	1.2959	1.4686
Van der waals	R^2	0.9595	0.7535	0.6797	0.9941	0.9876	0.9719	0.9818	0.9657	0.9126	0.9602
	RMSE	0.0485	0.0647	0.0207	0.0166	0.0263	0.0697	0.1454	0.0279	0.0667	0.0794
	AAPRE	4.6092	5.2035	1.9138	1.2140	2.3534	7.5098	19.0360	3.0228	2.8696	5.1849
Soave Redlich-Kwong	R^2	0.9779	0.9844	0.9521	0.9989	0.9953	0.9982	0.9992	0.9965	0.9962	0.9938
	RMSE	0.0394	0.0249	0.0062	0.0050	0.0105	0.0195	0.0456	0.0173	0.0127	0.0215
	AAPRE	2.6877	2.6198	0.5071	0.2894	0.8206	1.8644	7.1380	1.6698	0.8963	1.9412
Peng-Robinson	R^2	0.9792	0.9840	0.9727	0.9974	0.9971	0.9982	0.9983	0.9973	0.9675	0.9850
	RMSE	0.0687	0.0263	0.0147	0.0107	0.0140	0.0074	0.0186	0.0161	0.0293	0.0475
	AAPRE	4.8082	2.8146	1.5324	0.9371	1.3498	0.5994	1.5937	1.8551	1.8184	3.8797
GERG2008	R^2	0.9862	0.9999	0.9995	1.0000	0.9999	0.8616	0.9998	1.0000	0.9993	0.9981
	RMSE	0.0377	0.0016	0.0008	0.0002	0.0007	0.0200	0.0032	0.0007	0.0034	0.0055
	AAPRE	2.3499	0.1292	0.0766	0.0105	0.0447	0.9556	0.3950	0.0549	0.1515	0.1958
AGA8-DC92	R^2	0.9694	0.9999	0.9995	1.0000	0.9999	0.7816	0.9534	1.0000	0.9993	0.9981
	RMSE	0.0463	0.0017	0.0008	0.0003	0.0007	0.0359	0.0674	0.0002	0.0034	0.0054
	AAPRE	3.1639	0.1806	0.0795	0.0175	0.0321	2.5851	10.5102	0.0144	0.1581	0.1942
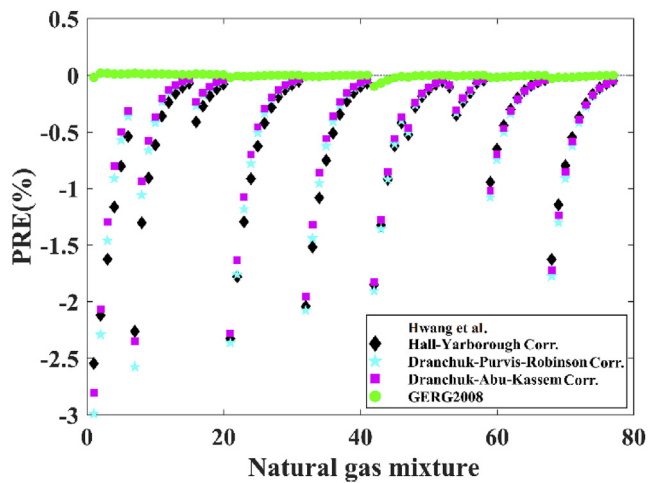
Fig. 3. PRE variation of studied methods with the measured value of (Hwang et al., 1997).
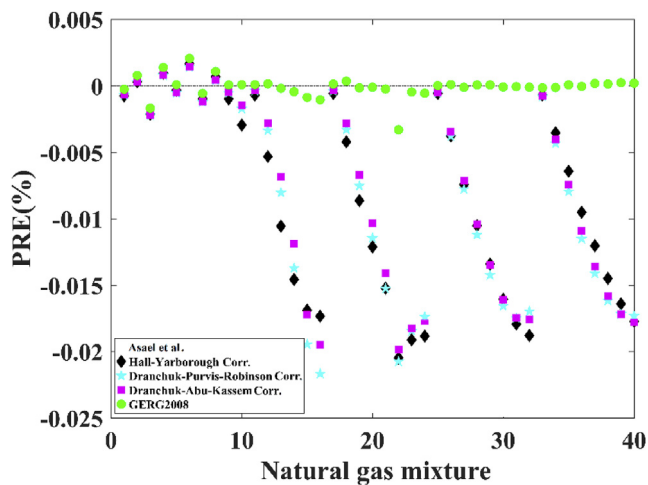

Fig. 4. PRE variation of studied methods with the measured value of (Assael et al., 2001).
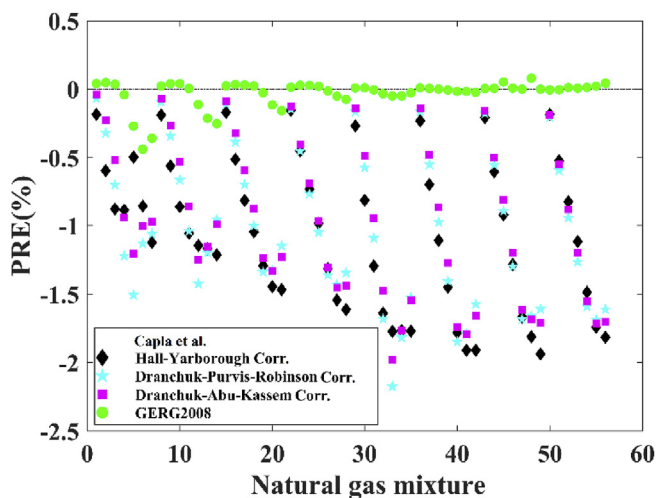

Fig. 5. PRE variation of studied methods with the measured value of (Čapla et al., 2002).

Robinson and Soave Redlich Kwong EOSs. Soave Redlich Kwong EOS can predict Z-factor more precise than Peng Robinson EOS. It could be also easily seen that these cubic EOSs are less precise than GERG2008

Fig. 6. PRE variation of studied methods with the measured value of (Ahmadi et al., 2017).

Table 13
Five typical Iranian natural gas compositions.

Mole Fraction	GASHO	KANGAN	KHANGIRAN	PARS	TURKMAN
Methane	0.7908	0.9004	0.98548	0.87	0.9421
Nitrogen	0.0514	0.0448	0.005	0.031	0.019
Carbon dioxide	0.0708	0	0	0.0171	0.0014
Ethane	0.0091	0.0369	0.00647	0.054	0.0225
Propane	0.0036	0.0093	0.00069	0.017	0.0053
Isobutane	0.0009	0.002	0.00018	0.003	0.0036
n-Butane	0.0018	0.0029	0.00039	0.0045	0
Isopentane	0.0008	0.0014	0.00018	0.0013	0.0026
n-Pentane	0.0007	0.0008	0.00021	0.0011	0
n-Hexane	0.0069	0.0014	0.0014	0.0007	0.0017
n-Heptane	0	0.0001	0	0.0003	0.0018
n-Octane	0	0	0	0	0
n-Nonane	0	0	0	0	0
n-Decane	0	0	0	0	0
Hydrogen	0	0	0	0	0
Oxygen	0	0	0	0	0
Carbon monoxide	0	0	0	0	0
Water	0	0	0	0	0
Hydrogen sulfide	0.0632	0	0	0	0
Helium	0	0	0	0	0
Argon	0	0	0	0	0
$T_c[K] = \sum x_i T_{ci}$	211.78	195.81	191.83	202.48	195.72
$P_c[kPa] = \sum x_i P_{ci}$	4996.1	4542.6	4591.4	4606.9	4571.7

and AGA8.

In Figs. 3 to 6, Percent Relative Error (PRE) variation of GERG2008 EOS, (Hall and Yarborough, 1973), (Dranchuk et al., 1973) and (Dranchuk and Abou-Kassem, 1975) correlations for various measured studies are calculated and presented. Again, it could be concluded that the accuracy of GERG2008 is much higher than the studied correlations.

It should be noted that although the accuracy of the reference EOSs are much higher that the empirical correlations but the empirical correlations could compute Z-factor much easier than the reference EOSs. These correlations may be used for natural gas property calculation but their accuracy are not acceptable for natural gas measurement.

4.2. The sensitivity of EOS selection on natural gas measurements

In this section, the sensitivity of AGA8 or GERG2008 selection on natural gas measurement has been studied. For this purpose, 5 typical natural gases which flowing into Iranian pipeline network are selected as case studies. The compositions of these NG mixtures are presented in Table 13. Note, the NG measurements are currently made in the
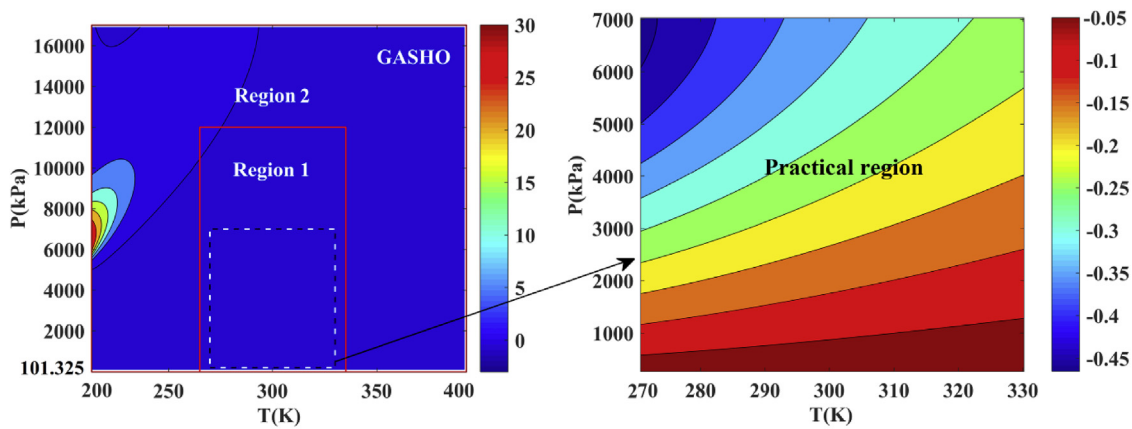
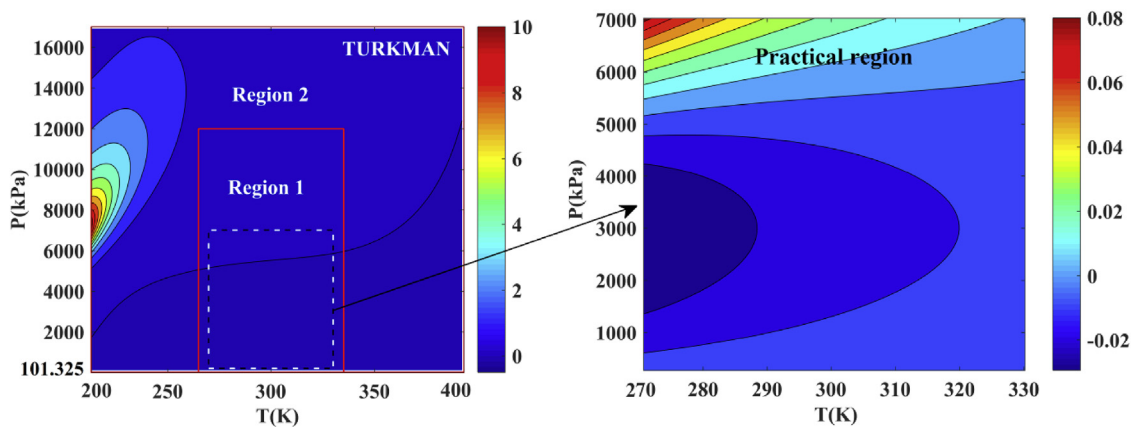**Fig. 7.** Relative difference in Z-factor calculation [Gasho Composition].

Fig. 8. Relative difference in Z-factor calculation [Turkman Composition].
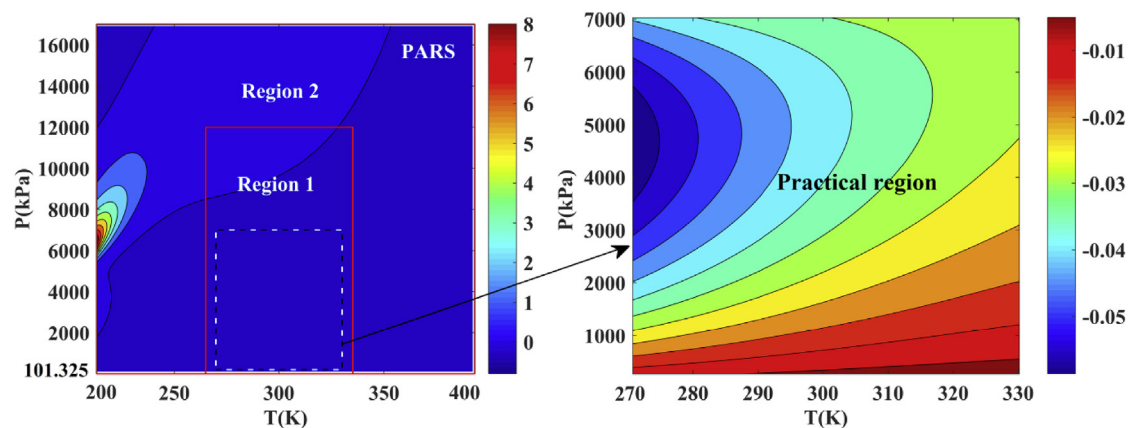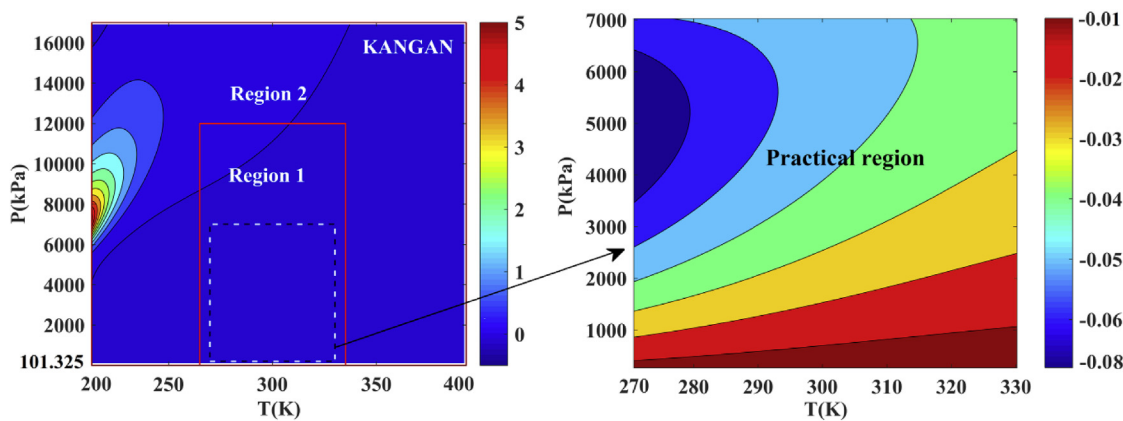

Fig. 9. Relative difference in Z-factor calculation [Pars Composition].

metering station while the NG compositions are very similar to these mixtures. Also, the ranges of compositions are in the normal range of both AGA8 and GERG2008 EOSs.

4.2.1. Difference in Z factor calculation

For better comparison between two reference EOSs, the relative difference in Z-factor is defined and presented as the following equation:

$$Rel_Z = \left(\frac{Z_{GREG2008} - Z_{AGA8}}{Z_{GERG2008}} \right) \times 100 \tag{56}$$

The relative difference have been calculated for studied natural gas

compositions presented in Table 13 in region of $213.15 \le T\,[K] \le 393.15$ and $P\,[kPa] \le 17000$. These range are in typical range of NG measurement in Iranian metering stations. Fig. 7 shows the relative difference of Z-factor for the Gasho composition (see Table 13). The Gasho natural gas has lowest methane percentage among the studied Iranian natural gases. It is also the only natural gases with a trace of hydrogen sulfide in its composition. It could be realized from the figure, the relative difference in Z-factor is high for range of $213.15 \le T\,[K] \le 240$ and $6000 \le P\,[kPa] \le 7000$. The difference could reach as high as 30% which is a considerable amount. Note this high difference occurs at a point which the measurements are not usually made. It should be also pointed out that the relative difference is relative small for Region 1. It

Fig. 10. Relative difference in Z-factor calculation [Kangan Composition].
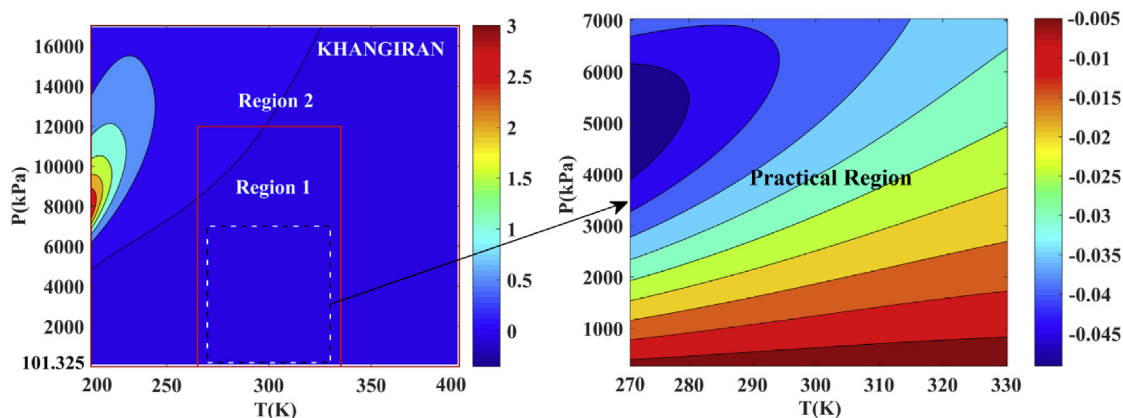
Fig. 11. Relative difference in Z-factor calculation [Khangiran Composition].
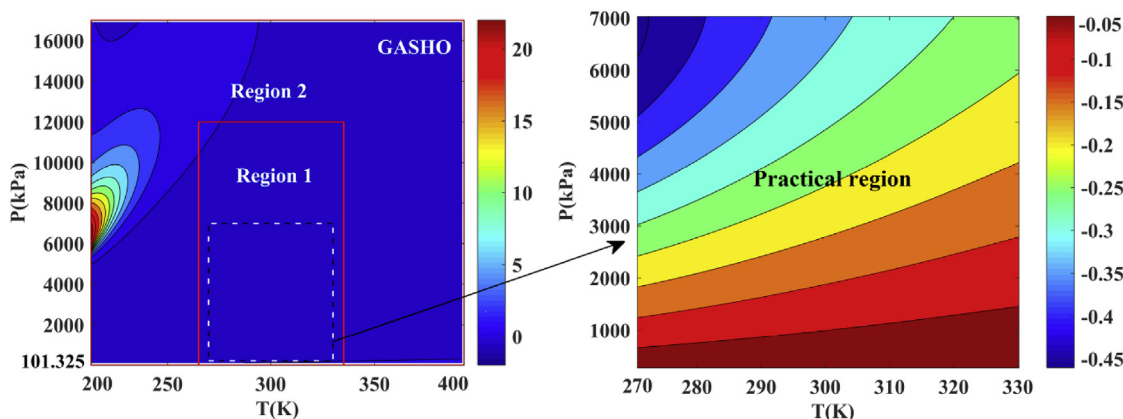
Fig. 12. Relative difference in standard volume flow calculation [Gasho Composition].

should be also noted that in practical region of measurement (270 K < T < 330 K and 200 kPa < P < 7000 kPa) GERG2008 always predict Z-factor higher than AGA8. The absolute maximum relative error is about 0.45% and occurs near 270 K and P < 1000 kPa.

Fig. 8 shows the Z-factor relative difference for the Turkman composition (see Table 13). There is a maximum of 10% relative difference in Z-factor at about $T = 213\,K$ and $P = 6500\,kPa$. Again, there is a small Z-factor relative difference in region 1 (the measurement region). Note from the figure, in small part of the practical region, AGA8 predicts Z-factor higher than GERG2008 which the biggest error is around 0.08 that occurs at 270 K and 7000 kPa. The amount of n-heptane and n-hexane are highest in this natural gas.

Fig. 9 show the Z-factor relative difference for the Pars composition

(see Table 13). There is a maximum of 8% relative difference in Z-factor at about $T = 213\,K$ and $P = 6800\,kPa$. Again, there is a small Z-factor relative difference in region 1. Please note, GERG2008 predicts Z-factor higher than AGA8 in practical region of measurement (270 K < T < 330 K and 200 kPa < P < 7000 kPa) which maximum absolute relative difference is about 0.05% and occurs at 270 K and 3500 < P < 5500.

Fig. 10 shows the Z-factor relative difference for the Kangan composition (see Table 13). There is a maximum of 5% relative difference in Z-factor at about $T = 213\,K$ and $P = 7200\,kPa$. Again, there is a small Z-factor relative difference in region 1. Again, GERG2008 predicts Z-factor higher than AGA8 in practical region of measurement (270 K < T < 330 K and 200 kPa < P < 7000 kPa) with lowest
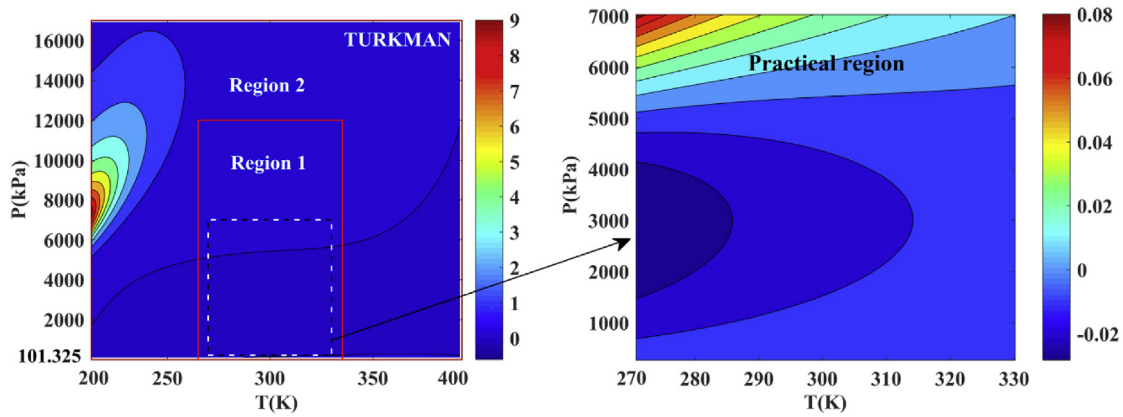
Fig. 13. Relative difference in standard volume flow calculation [Turkman Composition].
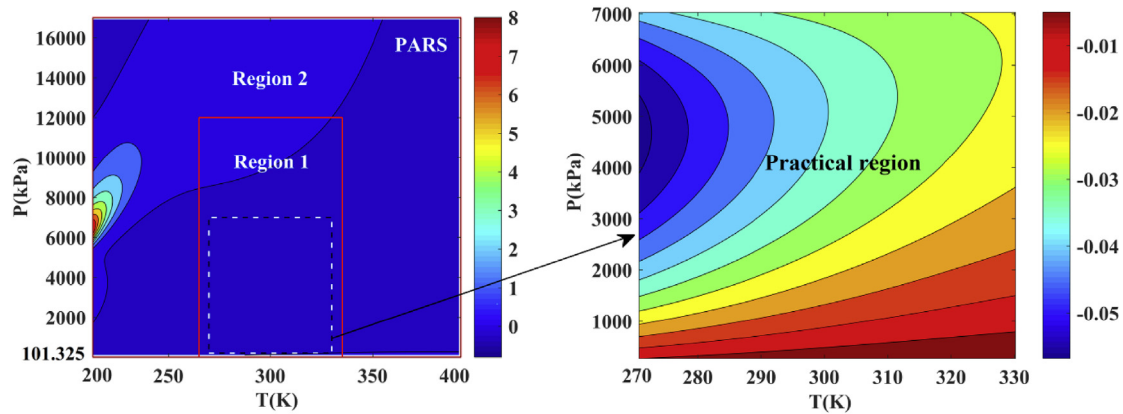

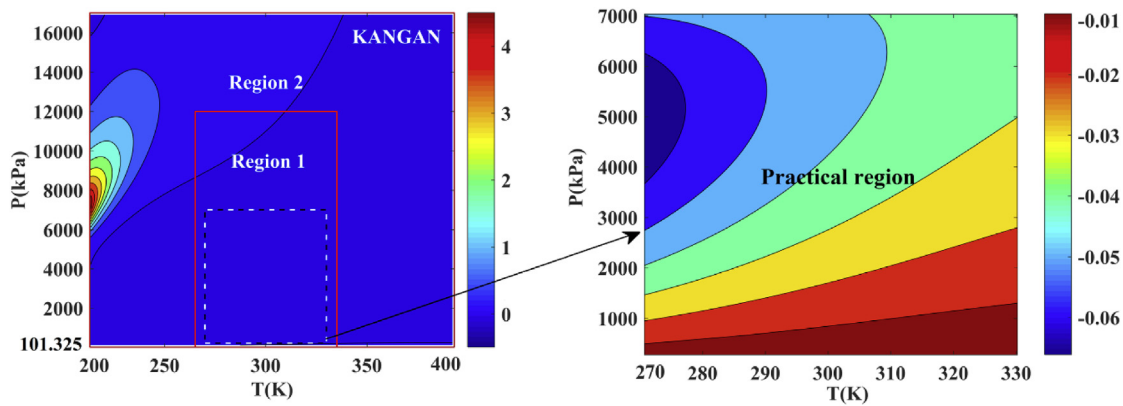**Fig. 14.** Relative difference in standard volume flow calculation [Pars Composition].

Fig. 15. Relative difference in standard volume flow calculation [Kangan Composition].

value of -0.08% at 270 K and $3500 < P\,[kPa] < 6500$.

Fig. 11 shows the Z-factor relative difference for the Khangiran composition (see Table 13). There is a maximum of 3% relative difference in Z-factor at about $T = 213\,K$ and $P\,[kPa] = 8000\,kPa$. Again, there is a small Z-factor relative difference in region 1. Among studied natural gas compositions presented in Table 4, the Khangiran gas has highest methane percentage and lowest Z-factor relative difference. Please note, GERG2008 always predicts Z-factor higher than AGA8 in practical region of measurement (270 K < T < 330 K and 200 kPa < P < 7000 kPa) with lowest value of -0.045% at 270 K and $4000 < P\,[kPa] < 6000$.

4.2.2. Difference in volume flow measurement

In this section the relative difference in volume flow measurement is calculated and presented. The relative volume flow difference is calculated using following equation:

$$Rel_Q = \left(\frac{Q_{b,GREG2008} - Q_{b,AGA8}}{Q_{b,GREG2008}} \right) \tag{57}$$

As, Q_b value is the base for custody transfer and considering that all other input parameters (T, P, X and Q_f) are the same, actually, Rel_Q indicates the relative difference in payment for the same amount of the gas.

Figs. 12 to 16 show the relative difference in volume flow measurement for Gasho, Turkman, Pars, Kangan and Khangiran natural
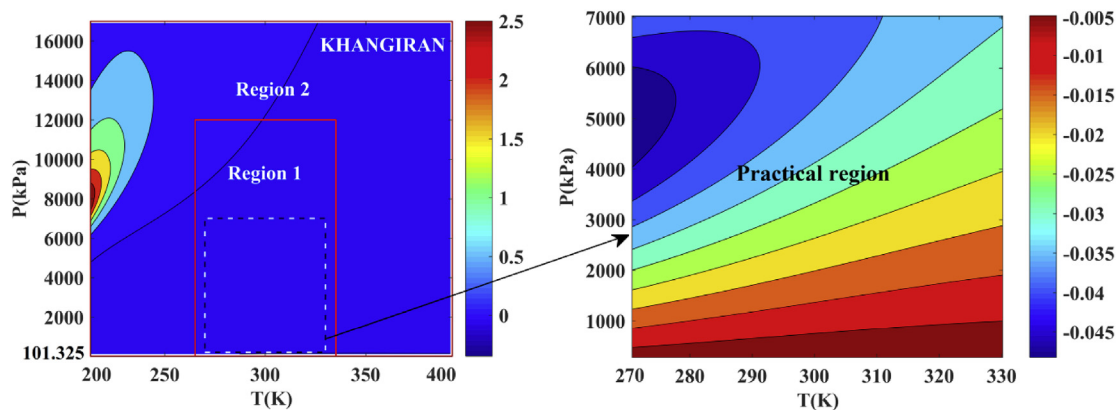
Fig. 16. Relative difference in standard volume flow calculation [Khangiran Composition].

Table 14
A sample standard volume flow calculation based on AGA8 and GERE2008 EOSs for GASHO natural gas mixture.

Flow condition	Q_f (m3)	CF (GERG 2008)	CF (AGA8)	Q_b (m3) GERG2008	Q_b (m3) AGA8	$Q_{b,GERG2008} - Q_{b,AGA8}$	Buyer benefits (US Dollars)
P = 7029 kPa and T = 323 K	1000000	68.78426435	68.94927227	68784264	68949272	−165008	82504$

gases respectively. For all studied natural gases (see Table 13), the highest relative difference in volume flow measurement is occurred near critical points. The volume flow relative difference could reach up to 22% for Ghasho natural gas with a trace of hydrogen sulfide. The lowest volume flow relative difference is observed for Khangiran gas which has highest methane percentage.

The relative difference in practical flow measurement region (270 K < T < 330 K and 200 kPa < P < 7000 kPa) are also presented in these figures. As it could be realized, there is a difference between AGA8 and GERG2008 standard in calculating volume flow relative difference. The highest difference is occurred for Gasho natural gas mixture. One important and surprising finding is that the relative difference is negative for these range of pressure and temperature except in Turkman gas (only for P > 5000 kPa in this mixture). This means that GERG2008 calculates flow less than AGA8 at the measuring points. This is very important finding at custody transfer point as one could realize that by employing GERG2008 standard instead of AGA8, the buyer will be benefited. This is due to the fact that in the such standard replacement, the natural gas volume correctors calculate higher natural gas standard volume. To show the importance of this finding, one example is given in Table 14. Suppose, 1 million cubic meter of natural gas is measured by a volume flow meter at P = 7029 kPa T = 323 K. The GERG2008 and AGA8 calculate the standard volume of 68784264 and 68949272 cubic meter respectively. For such small amount of natural gas, the buyer is actually pay 80000$ less if the GERG2008 is employed as the standard.

5. Conclusions

The natural gas is mainly measured at flow (actual) condition using volume flow meters. As the natural gas is treated (sold) based on its volume at standard condition (P = 1 atm and T = 15 °C), a converting factor is required to convert NG volume from flow condition to the standard condition. For calculating this factor, the NG compressibility factor is required.

The converting NG volume from actual (or flow) condition to the

standard condition is a vital problem. Although, it was claimed that AGA8 EOS has accepted accuracy for calculating Z-factor, but the previous measured studies show that the accuracy is not as good as declared. The accuracy seems to be highly depended on the natural gas compositions. To improve the accuracy of the natural gas measurement, GERG2008 EOS is developed and presented by natural gas industries.

In this study, firstly, both AGA8 and GERG2008 EOSs are employed to calculate the natural gas Z-factor. Comparing the calculated Z-factor and measured values of 10 different previous experimental studies, shows that the accuracy of GERG2008 EOS is generally higher than AGA8. Also, the Z-factor are calculated using the most famous empirical correlations and cubic EOSs and compared with the measured and AGA8 and GERG2008 EOSs. The results show that the accuracy of AGA8 and GERG2008 EOSs are much higher that the empirical correlations.

Secondly, the Z-factor and converting factor for 5 different natural gas mixtures have been calculated based on GERG2008 and AGA8 EOSs. Comparing numerical results show that AGA8 EOS predicts Z-factor higher than GERG2008 EOS for the practical region of the measurement. The relative difference in Z-factor calculation could reach up to 30% for one studied natural gas mixture. The highest difference occurs near the critical point which is outside of practical region of measurement.

Comparing the standard flow volume reveals very important findings. The surprising thing is that the GERG2008 predicts standard flow volume lower than the AGA8 in the practical region of measurement. It means that by replacing AGA8 EOS by GERG2008 standard, the less flow is registered by the measurement system for same amount of flow which measured by flow meters. In other words, simply by utilizing the GERG2008 EOS (instead of AGA8 EOS), the buyer benefits.

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Glossary

NG: Natural Gas

Q: Flow volume($\frac{m^3}{s}$)

CF: Correction Factor

T: Temperature(K)

P: Pressure (kPa)

Z: Z-factor

X: Mole fraction

v: Gas volume

B: Second virial coefficient

K: Mixture size coefficient

D: Gas Reduced density

d: Gas molar density

C_n^*: Temperature dependent coefficient

a_n, b_n, c_n, f_n, g_n, q_n, s_n, u_n : Parameters of AGA8 EOS

E_i, F_i, G_i, K_i, Q_i, S_i, W_i: Corresponding characterization parameters of AGA8 EOS

U, G, Q, F: Mixture parameters of AGA8 EOS

E_{ij}^*, G_{ij}^*: AGA8's corresponding binary interaction parameters

U_{ij}: Binary interaction parameter for mixture energy of AGA8 EOS

R*:* Gas constant $\left(\frac{J}{Kmol}\right)$

N*:* Number of natural gas components, N = 21

α*:* Helmholtz free energy

δ*:* Reduced fluid mixture

$\beta_{v,ij}$, $\gamma_{T,ij}$, $\beta_{T,ij}$, $\gamma_{T,ij}$*:* Binary mixtures parameters of GERG2008 EOS

α^0*:* Helmholtz free energy ideal part of gas mixture

α^0_{0i}*:* Ideal dimensionless Helmholtz free energy of the component i of GERG2008 EOS

$n_{ij,k}$, $d_{ij,k}$, $t_{ij,k}$, $\eta_{ij,k}$, $\varepsilon_{ij,k}$, $\beta_{ij,k}$, $\gamma_{ij,k}$*:* Parameters of GERG2008 EOS

α^r*:* Reduced Helmholtz free energy residual part

ρ*:* Density

τ*:* Inverse reduced temperature $\left(\frac{1}{K}\right)$

α^r_{or}*:* Generalized departure function

ω_i*:* Acentric factor of component i

a, b, a_i, b_i, a_{ii}, b_{ii}, a_{ij}, b_{ij}, k_{ij}, m_i, α_i*:* Mixing rules parameters of cubic EOSs

N_d*:* Number of data points

APRE: Average Percent Relative Error

PRE: Percent Relative Error

AAPRE: Average Absolute Percent Relative Error

RMSE: Root Mean Square Error

Rel$_Z$: Relative difference in Z-factor

Rel$_Q$: Relative difference in volume flow measurement

N: Number of natural gas components, $N = 21$

$P_{c,i}$*:* Critical pressure for component i

$T_{c,i}$*:* Critical temperature for component i

P_{pc}*:* Pseudo critical pressure, $P_{pc} = \sum_{i=1}^{N} P_{c,i} \times X_i$

T_{pc}*:* Pseudo critical temperature $T_{pc} = \sum_{i=1}^{N} T_{c,i} \times X_i$

P_{pr}*:* Pseudo-reduced pressure $P_{pr} = \frac{P}{P_{pc}}$

T_{pr}*:* Pseudo-reduced temperature $T_{pr} = \frac{T}{T_{pc}}$

Subscripts

b: Standard condition T = 15 °C,P = 1 atm

f: Flow condition

c: Critical point

r: Reduced