



A novel method for calculating natural gas density based on Joule Thomson coefficient



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ABSTRACT

In natural gas measuring techniques, the natural gas mass flow rate is usually measured employing experimental facilities for density calculation, volume flow meters and other peripheral equipment such as temperature and pressure sensors. In order to simplify natural gas mass flow metering at natural gas pressure drop stations (CGS), this work presents an easy and precise method for measuring natural gas density. The method is based on a correlation that calculates the molecular weight and density of natural gas stream as a functional of the temperatures and pressures of natural gas before and after a throttle valve. These easily measurable properties at the natural gas pressure drop station are employed to calculate, firstly, the Joule Thomson (JT) coefficient and then density based on a developed correlation. For developing the corresponding correlation and also validating the results, a huge database including the practical data of 6 selected main natural gas fields of Iran is used. In fact, 50% of the available experimental data (three fields) have been used to develop the correlation and the remaining 50% (the other three fields) are used in accuracy assessment step. The results show that the error in calculating density doesn't exceed 1.2%, while for more than 70% of the states the error is even less than 0.6% and the average error is less than 0.4%. MAE (mean absolute error) and STD (standard deviation of absolute error) are also employed in order to validate the correlation results. The validation shows satisfactory calculation accuracy.

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1. Introduction

In addition to many places in the natural gas industry in which mass flow metering is required, in many countries such as some European countries, the natural gas is sold on a basis of mass flow rate. Thus, density metering along with volume flow metering is required in such places. The natural gas flow rate should be measured in many places including pressure drop stations (usually called City Gate Stations, CGSs). Over the last years, many devices such as multiple ultrasonic transient-time meters, conventional orifice plates and turbine meters are employed in order for fiscal metering of natural gas (Froysa and Lunde, 2005). Basically, all of these devices measure the volume flow rate of natural gas stream. On the other hand, natural gas density can also be directly measured by various instruments such as Coriolis density meters, gas

chromatographs and etc. These instruments have their own problems. For example, the main problems of Coriolis density meters are potential erosion because of abrasive particles, sensitivity to pulsation and vibration close to operating frequency (Ridder et al., 2014). Gas chromatograph, on the other hand, is only appropriate for volatile samples and specific operational conditions (Meng et al., 2015). The other common problem of such instruments is the frequent calibrations required. In fact, as gas meters tend to drift due to environmental effects and vibrations, frequent recalibration of the density meters are inevitable. That's why; reducing the number of such devices in metering stations is highly addressed in the previous studies (Ridder et al., 2014; Meng et al., 2015).

For natural gas mass flow metering, also, many studies have already been done and a few instruments have also been invented for this objective [4–6]. For example, in Smalling et al. (1986), an apparatus has been introduced for measuring gas mass flow rate in tubes. The main disadvantage of this apparatus is that it is only suitable for low concentration gases in low velocity range of

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0–15 m/s. Clearly, this device could not be used for metering in CGS where both the natural gas concentration and velocity are very high. Hiismaeki (1993) points out to another instrument that is applicable for pressure ranges in which natural gas behaves like an ideal gas. As natural gas state in transmission pipelines (specifically CGSs), due to its very high pressure, is far away from an ideal gas, this device could also not be considered appropriate for this objective. In another work, Valdes and Cadet (1991) employs the heavy virial equation (Hirschfelder et al., 1964) to calculate the molecular weight of gas based on the calculated sound speed as a functional of pressure, temperature and gas compositions. Although the accuracy is really good, the big disadvantage of this method is that the compositions of natural gas mixture are required. In addition to the referred systems, there are many more instruments that can be mentioned, however, the common problem of all these mass flow meters is that they are not applicable for high mass flow rate and pressure ranges (as in CGSs) and also recalibration is required when the natural gas compositions change (Hammond, 2001; Watson and White, 1982; Dell'isola et al., 1997; Buonanno et al., 1998; Farzaneh-Gord et al., 2015a).

Moreover, equations of state (EOSs) are widely used for computing natural gas density. Most broadly employed standard EOSs are AGA8 and GERG2008 (AGA8, 1992; Farzaneh-Gord and Rahbari, 2011; Kunz and Wagner, 2012). EOSs also need the natural gas mixture temperature, pressure and compositions to calculate its density. While the natural gas mixture compositions could only be measured by employing experimental facilities, both pressure and temperature are easily measurable. By applying different sets of advanced experimental equipment for a specific reservoir and specific pipeline conditions, EOSs can be utilized to calculate the natural gas density accordingly (AGA8, 1992). In addition, several correlations have also been developed for calculating natural gas density. Dranchuk and Abou-Kassem (1975) developed a gas density calculator correlation utilizing 1500 data points, including pure gases and gas mixtures from different sources. Londono et al. (2002) reported simplified correlations for calculating the density of hydrocarbon gases like natural gas. AlQuraishi and Shokir (2009) employed Alternating Conditional Expectations (ACE) algorithm and presented a new equation for computing the density of hydrocarbon gases and pure and impure gas mixtures. There are also other authentic references in this field (Gysling, 2007; Kenneth et al., 1995; Anderson et al., 1996; Standing and Katz, 1942; Weberg, 1990). In one of the last studies, Farzaneh-Gord and Rahbari (2011) developed novel correlations for calculating most thermodynamic and thermal properties of natural gas such as density based on AGA8 EOS. In the study, each thermodynamic property is a functional of natural gas pressure, temperature and specific gravity. These methods were developed by Farzaneh-Gord and Rahbari (2011) and were previously presented in Farzaneh-Gord et al. (2010), Farzaneh-Gord and Rahbari (2012) and Marić (2005, 2006), Marić et al. (2004).

The standard method for calculating density is presented in AGA8 report (AGA8, 1992). Based on the standard, the natural gas compositions should be measured in order to calculate density. The real time measurement of the compositions is a difficult task and usually not carried out in the metering points. In Iran, the composition measurements usually carried out on yearly bases in CGSs. In this work, the main objective is to present a novel method of real time density measurement in the CGSs while there is no information about the natural gas mixture compositions. Firstly, this work presents a new correlation for molecular weight calculation as a functional of three easy measurable thermodynamic properties including temperature, pressure and JT coefficient of the gas mixture. The JT coefficient is calculated by measuring pressure and temperature drop during pressure reduction process. Finally

natural gas mixture density is calculated using the thermodynamic equations (Farzaneh-Gord and Rahbari, 2011). Note that, the presented method could be combined with any volume flow meters to calculate natural gas mass flow rate. Not only the presented method could be considered as another new method of natural gas mass flow metering, but also it includes some superiorities relative to the previous common methods and instruments such as a very simple construction, high accuracy, being isolated from drift problem and not being restricted by any operating specification.

2. The proposed system and methodology

2.1. The current method of mass flow metering

CGS is a place near cities in which high pressure natural gas, originated from refineries, must be expanded to much lower pressure, usually from about 6800 kPa to 1700 kPa, to be appropriate for usage by its consumers (Farzaneh-Gord et al., 2011, 2012). CGSs are one of main places in the natural gas transmission industry in which the natural gas flow metering also should be carried out. In Iran's CGSs, currently, the natural gas measurement is carried out by a Volume Flow Meter (VFM) which is usually a turbine flow meter (TFM), an ultrasonic flow meter or an orifice flow meter (Gallagher, 2006). Fig. 1 illustrates a schematic diagram of a common CGS. It also shows how the natural gas mass flow rate is currently being measured in Iran's CGSs using a VFM along with the other required devices.

Considering the above figure, the volume corrector receives information about the volume flow rate (from VFM), temperature and pressure (from sensors) and gas compositions (from appropriated devices or just a report from gas refinery) to calculate the passing natural gas mass flow rate. Based on the received values and the AGA8 standard (Farzaneh-Gord and Rahbari, 2011), it produces a correction factor to convert the volume flow rate measured by the volume flow meter to the volume flow rate at standard condition ($T = 298$ K and $P = 101.325$ kPa). The main problem with this method of calculation is error in the density value. The density value is usually calculated by reported compositions generated yearly or each six months by the gas refinery. Therefore, as long as the experimental instruments or online density meter instruments are available, natural gas density could be calculated accurately; otherwise, the mass flow rate measurement would not be precise enough. Currently, no CGS within Iran is equipped with a real time density measurement. Therefore, the necessity of another simple and accurate real time method of calculating natural gas density is well sense in CGSs.

Note that, in the above figure the heater and the throttling valve are not parts of flow measurement system. As it was explained before, a CGS is a place in which the natural gas pressure should be fallen to lower levels. This task is done by the throttling valve. The heater also warms up the natural gas stream before the pressure reduction process to avoid gas hydrate forming in the natural gas stream (Arabkoohsar et al., 2015; Farzaneh-Gord et al., 2015b; Arabkoohsar et al., 2014).

2.2. The proposed solution method

As it was claimed before, the main goal of this work is to estimate the natural gas molecular weight (subsequently, the natural gas density) by using some real time and easy measurable parameters such as the temperature, pressure and JT coefficient of natural gas. The method could be combined with any VFM (e.g. turbine flow meter, ultrasonic flow meter or orifice flow meter) to calculate mass flow rate.

The most important question which may arise here is that how

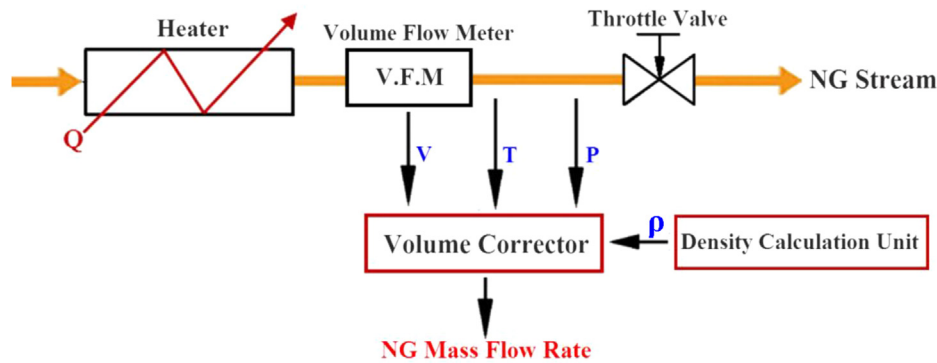


Fig. 1. The calculation process of the natural gas mass flow rate in a CGS.

one can define the molecular weight as a functional of such parameters as it is only a function of the natural gas mixture compositions.

$$MW = f(\text{compositions}) \quad (1)$$

Actually, it is intended to find a strong relationship between these four variables i.e. the molecular weight, temperature, pressure and JT coefficient of natural gas mixture employing a huge available database based upon the data mining approach and curve fitting. In this case, one correlation could be developed in which the molecular weight could be defined as a functional of the natural gas temperature, pressure and JT coefficient. Based on this technique, a precise and accurate relation has been fitted between the three aforementioned parameters and the molecular weight and released in the form of a novel correlation.

It's worth mentioning that the correlation development and its validation have been carried out based on the AGA8 EOS (Farzaneh-Gord and Rahbari, 2011) and a large database including 6 main natural gas fields of Iran (three of them for developing the correlation and the other three for investigating the developed correlation accuracy).

One has to be noted is that the estimated value of the molecular weight by this correlation operates as a figural molecular weight (MW_f) which changes by variation of the temperature, pressure and JT coefficient rates as:

$$MW_f = f(T, P, \mu) \quad (2)$$

where, T , P and μ refer to the temperature, pressure and JT coefficient of the natural gas stream, respectively. By employing this figural molecular weight, one could calculate the natural gas density by the AGA8 EOS thoroughly discussed in (Buonanno et al., 1998). Based upon this EOS, the density of a natural gas (ρ) mixture is defined as a functional of the molecular weight (compositions), temperature and pressure of natural gas:

$$\rho = g(T, P, MW_f) \quad (3)$$

Having this value, one could calculate the natural gas mass flow rate (\dot{m}) as below:

$$\dot{m} = \rho VS \quad (4)$$

where, V refers to the velocity of natural gas stream and S is the sectional area of pipe. Fig. 2 illustrates the schematic diagram of proposed method of the natural gas mass flow rate calculation.

As Fig. 2 shows, not only the experimental facilities and density calculator instruments are eliminated from the system, but there is also no need to estimate the natural gas density like before and a

simple processor which employs the presented correlation to estimate a figural molecular weight, and subsequently the density, has been added instead. It should be noted that the novel correlation input data are only the JT coefficient, temperature and pressure.

As the main objective of the work is to introduce an approach as easy as possible, and according to the fact that the equation with fewer numbers of variables is easier to be solved, the authors tried to define as few parameters as possible in the correlation (three parameters). The other inquiry may arise is that why these three properties (T , P and JT) have been chosen as the main variables of the correlation?

In fact, by employing the same curve fitting and data mining approach, the correlation could be defined as a functional of every properties of natural gas provided that the required database on the given properties is available. In this work, however, as temperature, pressure and JT coefficient are among the easiest properties to be measured, they were chosen as the main variables of the correlation.

For measuring the temperature and pressure, common gauges can be easily hired. In addition, having the temperatures and pressures of the gas stream at both sides of the throttling valve in the CGS, one could calculate the JT coefficient of the gas mixture as follow (Farzaneh-Gord and Rahbari, 2012):

$$\mu = \left(\frac{\partial T}{\partial P} \right)_h \approx \left(\frac{\Delta T}{\Delta P} \right)_h \quad (5)$$

where, the subscription h refers to the constant enthalpy process through the throttling valve. There is also another possible method of calculation for this parameter using porous plug which causes a minor pressure drop in the natural gas stream and measures the temperature and pressure of the natural gas before and after the pressure reduction process. Therefore, the JT coefficient could be calculated. However, as the available temperature sensors are not able to report the exact values of temperature, therefore the pressure reduction should be high enough to attenuate the effects of deviation in temperature measurements. Regarding this fact, the application of porous plugs could not be considered as an effective method here.

Fig. 3 illustrates the proposed system schematic for the calculation of natural gas mass flow rate including the JT coefficient calculation process.

Regarding the figure, this time, the volume corrector receives the volume flow rate value from the volume flow meter as well as the calculated density after doing the required calculation process employing the presented molecular weight calculator correlation, so that the volume corrector could present accurate values of

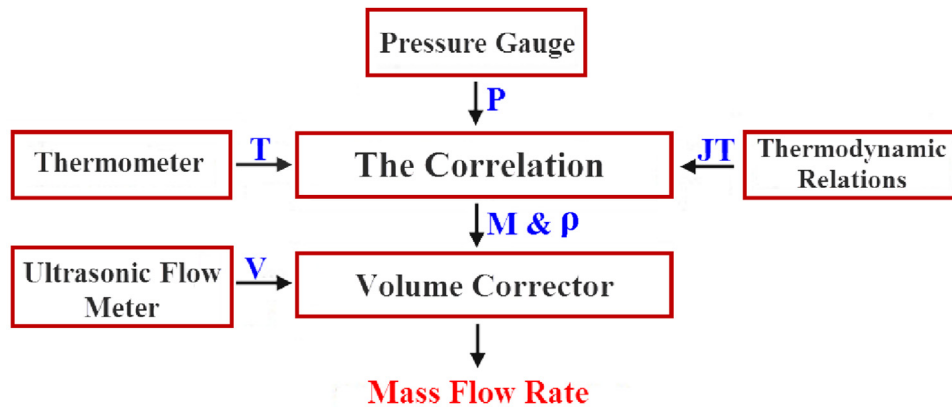


Fig. 2. The proposed system schematic diagram.

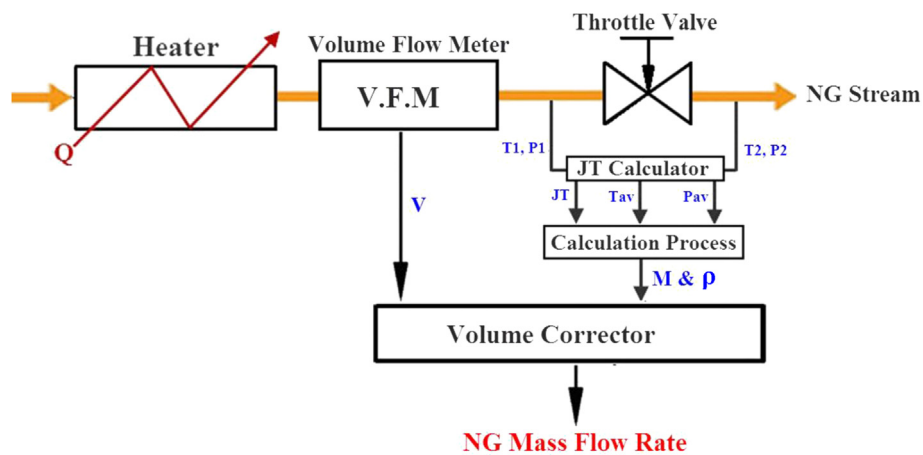


Fig. 3. The proposed system schematic.

natural gas mass flow rate. As the figure shows, a simple processor is required to calculate the JT coefficient of the stream receiving the amounts of the temperatures and pressures before and after the throttling valve in the CGS. Then, the average temperature and pressure as well as the calculated value of the JT coefficient are employed as the input data of the presented correlation. Therefore, a simple processor supported by the presented correlation is used to calculate the molecular weight and subsequently the density of the natural gas stream. Finally, this value for the density and the measured value for the volume flow rate of the stream enter the volume corrector to calculate the natural gas mass flow rate of the natural gas passing the CGS.

3. The new developed correlation

In this section, a step by step instruction for developing the novel correlation based on the natural gas temperature, pressure and JT coefficient is presented. As respects all these properties are real time measurable; thus, the calculation of real time figural molecular weight would be possible. The existing database includes the natural gas physical properties such as the temperature, pressure, JT coefficient and molecular weight for 6 main natural gas fields of Iran namely Khangiran, Shurjeh, Gonbadly, Torkman, Pars and Kangan. Table 1 reports the compositions of these 6 fields in which the first three are used to develop the target correlation and the last three are employed to evaluate the accuracy of the extracted correlation. Note that the selection of these fields was

totally intentional to cover all possible ranges of molecular weight in natural gas mixtures. Khangiran gas field represents the lowest possible of molecular weight as it is mainly constituted by Methane. Pure Methane molecular weight is 16.04 kg/kmol. On the other hand, Pars represents the highest value molecular weight among all the considered mixtures. It is worth mentioning that the database related to the understudy natural gas fields includes the actual data in pressure and temperature ranges which are widely occurred in Iran's CGSs, i.e. 0.1 MPa < P < 1.8 MPa, 250 K < T < 350 K. The observations on the actual database show that, overall, decreasing

Table 1

The compositions and actual molecular weight of different natural gas fields of Iran employed in this work.

	Khangiran	Shurjeh	Gonbadly	Torkman	Pars	Kangan
CH ₄	98.66	90.04	88.05	94.38	86.93	90.04
C ₂ H ₆	0.59	3.69	1.4	2.25	5.40	3.69
C ₃ H ₈	0.09	0.93	0.34	0.53	1.70	0.93
I-C ₄ H ₁₀	0.02	0.20	0.09	0.36	0.30	0.20
N-C ₄ H ₁₀	0.04	0.29	0.13	0.00	0.45	0.29
I-C ₅ H ₁₂	0.02	0.14	0.07	0.26	0.13	0.14
N-C ₅ H ₁₂	0.02	0.08	0.06	0.00	0.11	0.08
C ₇ H ₁₆	0.00	0.01	0.03	0.18	0.03	0.01
N ₂	0.56	4.48	7.85	1.90	3.10	4.48
CO ₂	0.00	0.00	0.35	0.14	1.85	0.00
H ₂ S	0.00	0.00	1.63	0.00	0.00	0.14
MW	16.31	17.79	18.17	17.34	18.7	18.54

the temperature in a specific pressure increases the JT coefficient of all the natural gas fields constantly and significantly (almost doubles the JT coefficient value in the considered temperature range) while pressure drop from the maximum level to its minimum level in the considered range in a constant temperature reduces the JT coefficient value mildly. Therefore, the highest value of JT coefficient is related to the minimum temperature (250 K) and pressure (0.1 MPa) and evidently, its minimum value can be observed in the maximum temperature (350 K) and pressure (1.8 MPa) for all the natural gas fields. The maximum JT coefficient of Khangiran, Shurjeh, Gonbadly, Torkman, Pars and Kangan are 5.73, 6.14, 6.97, 6.10, 6.60 and 6.15 K/Pa and the minimum JT coefficients are 2.95, 3.13, 3.57, 3.12, 3.34 and 3.13 K/Pa, respectively.

Knowing the natural gas compositions, one could make the molecular weight calculable. Then it is possible to have a large database of the natural gas JT coefficient for various temperatures, pressures and molecular weights. Based on this database, the natural gas mixture figural molecular weight could be defined as a functional of the temperature, pressure and JT coefficient variations. It is noteworthy here that finding the relation of figural molecular weight changes versus the other parameters could be done by doing curve fittings on the existent practical database.

As the first step of formulation, the figural molecular weight should be defined as a functional of the gas mixture JT coefficient. For this purpose, an accurate curve fitting should be implemented on the JT coefficients of different natural gas mixtures with their corresponding molecular weights in the specific temperatures and pressures. The curve fitting show that the natural gas figural molecular weight could be defined as a quadratic functional of the JT coefficient as below.

$$MW_f = A\mu^2 + B\mu + C \quad (6)$$

where, A, B and C are the constant coefficients of the correlation for different temperatures and pressures. Determining the figural molecular weight of natural gas mixture variations versus its pressure is the second step of formulation for which the constant coefficients in equation (6) should be found as a functional of the pressure. Doing another curve fitting on different A, B and Cs of various pressures reveals that a quadratic function of pressure for each of the constant coefficients could make an exact estimation for the figural molecular weight variation versus the pressure. Thus, the constant coefficients in equation 6 should be defined as below:

$$\begin{aligned} A &= A_2P^2 + A_1P + A_0 \\ B &= B_2P^2 + B_1P + B_0 \\ C &= C_2P^2 + C_1P + C_0 \end{aligned} \quad (7)$$

where P refers to the mixture pressure and $A_2, A_1, A_0, B_2, B_1, B_0$ and C_2, C_1, C_0 are constant coefficients for different temperatures. Considering these constants, equation (6) could be re-written as below:

$$MW_f = (A_2P^2 + A_1P + A_0)\mu^2 + (B_2P^2 + B_1P + B_0)\mu + (C_2P^2 + C_1P + C_0) \quad (8)$$

Based on equation (6), the figural molecular weight of natural gas mixture at a specific temperature can be calculated. The only remaining step is to find how this item varies by the temperature changes. Finally, as the last step of formulation, while there are nine constant coefficients in each specific temperature, the third curve fitting should be done on the constant coefficients and temperature values to reveal the figural molecular weight of natural gas mixture dependence on its temperature. However this time, a cubic

dependency on the temperature for the natural gas mixture figural molecular weight was found. Naturally, the nine constant coefficients in the above equation could be re-written as below:

$$\begin{aligned} A_2 &= A_{23}T^3 + A_{22}T^2 + A_{21}T + A_{20} \\ A_1 &= A_{13}T^3 + A_{12}T^2 + A_{11}T + A_{10} \\ A_0 &= A_{03}T^3 + A_{02}T^2 + A_{01}T + A_{00} \\ B_2 &= B_{23}T^3 + B_{22}T^2 + B_{21}T + B_{20} \\ B_1 &= B_{13}T^3 + B_{12}T^2 + B_{11}T + B_{10} \\ B_0 &= B_{03}T^3 + B_{02}T^2 + B_{01}T + B_{00} \\ C_2 &= C_{23}T^3 + C_{22}T^2 + C_{21}T + C_{20} \\ C_1 &= C_{13}T^3 + C_{12}T^2 + C_{11}T + C_{10} \\ C_0 &= C_{03}T^3 + C_{02}T^2 + C_{01}T + C_{00} \end{aligned} \quad (9)$$

The final correlation by which the figural molecular weight of every arbitrary natural gas mixture can be calculated as a functional of its temperature, pressure and JT coefficient, could be written as follow:

$$\begin{aligned} MW_f = & [(A_{23}T^3 + A_{22}T^2 + A_{21}T + A_{20})P^2 + (A_{13}T^3 + A_{12}T^2 \\ & + A_{11}T + A_{10})P + (A_{03}T^3 + A_{02}T^2 + A_{01}T + A_{00})]\mu^2 \\ & + [(B_{23}T^3 + B_{22}T^2 + B_{21}T + B_{20})P^2 + (B_{13}T^3 + B_{12}T^2 \\ & + B_{11}T + B_{10})P + (B_{03}T^3 + B_{02}T^2 + B_{01}T + B_{00})]\mu \\ & + [(C_{23}T^3 + C_{22}T^2 + C_{21}T + C_{20})P^2 + (C_{13}T^3 + C_{12}T^2 \\ & + C_{11}T + C_{10})P + (C_{03}T^3 + C_{02}T^2 + C_{01}T + C_{00})] \end{aligned} \quad (10)$$

Table 2 lists the values of all the coefficients in the above equation.

4. The validation of presented novel correlation

Here, to validate the novel method, the value of density is obtained in two ways: one is named actual value; the other is named calculated value. The actual value is determined by assuming the natural gas mixture compositions to be known and using the AGA8 EOS (Farzaneh-Gord and Rahbari, 2011); the calculated value is determined by assuming a value for pressure drop, knowing the compositions and using the AGA8 EOS (AGA8, 1992), thermodynamic relations and employing the proposed method. Finally, the calculated and actual values of density are compared.

It should be reminded that for developing and verifying the proficiency of the presented correlations a huge database including the practical data of 6 selected main natural gas fields of Iran was used. In fact, 50% of the available experimental data (three fields) have been used to develop the correlation and the remaining 50% (the other three fields) were used in accuracy assessment step.

As a common and simple method of deviation assessment in such proposals, the error is reported in percent relative to the reference value. This error value in each state could be given by the following equation:

$$Er = \frac{|\text{Calculated Value} - \text{Actual Value}|}{\text{Actual Value}} \times 100 \quad (11)$$

For the aim of more professional assessment also, two basic metrics, the MAE (mean absolute error) and STD (standard deviation of absolute error), presented in the following equations, are used to compare and validate the performance of presented correlation (Arabkoohsar et al., 2015; Kusiak et al., 2009).

Table 2
The values of coefficients of the presented correlation.

	A ₂				A ₁				A ₀			
	A ₂₃	A ₂₂	A ₂₁	A ₂₀	A ₁₃	A ₁₂	A ₁₁	A ₁₀	A ₀₃	A ₀₂	A ₀₁	A ₀₀
A	1.602e-007	-1.277e-005	0.001052	0.02687	4.639e-008	1.911e-005	0.004047	-0.0506	2.425e-006	0.001096	0.1117	5.664
B	-5.882e-007	8.409e-005	-0.006389	-0.1845	-2.429e-006	0.0003978	-0.03682	0.9233	2.176e-005	-0.004723	-0.7628	-61.83
C	2.186e-006	-0.0002841	0.01132	0.2646	7.991e-006	-0.00146	0.08695	-3.641	-4.198e-005	0.0008735	0.8403	186.2

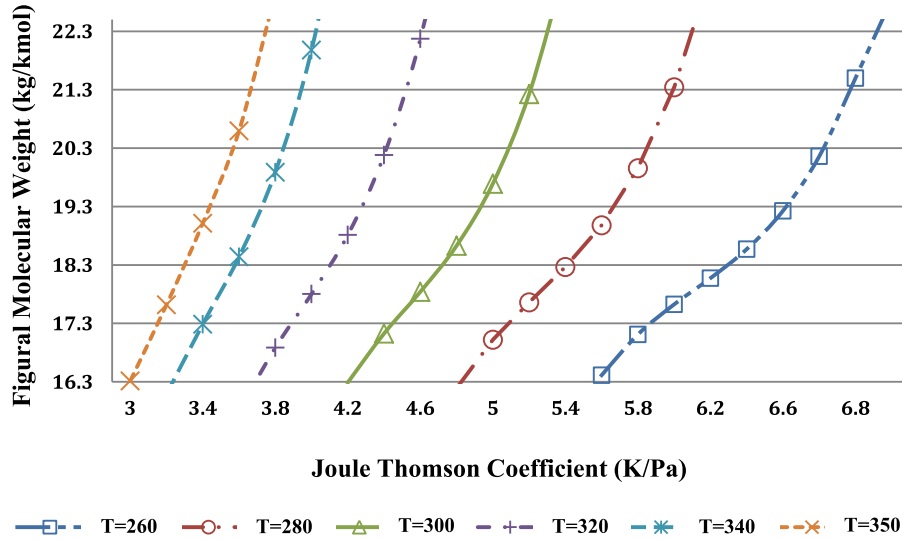


Fig. 4. The variation figural molecular weight by changing the JT coefficient in different temperatures when P = 0.8 MPa.

$$MAE = \frac{\sum_{i=1}^N AE(i)}{N}$$

$$STD = \sqrt{\frac{\sum_{i=1}^N (AE(i) - MAE)^2}{N - 1}}$$
(12)

where N is the number of test data points used to validate the performance of the correlation; \bar{y} is the predicted value of a variable, and y is the observed value of a variable, i.e., the calculated and actual density. The AE also refers to absolute error which should be obtained as:

$$AE = |\bar{y} - y|$$
(13)

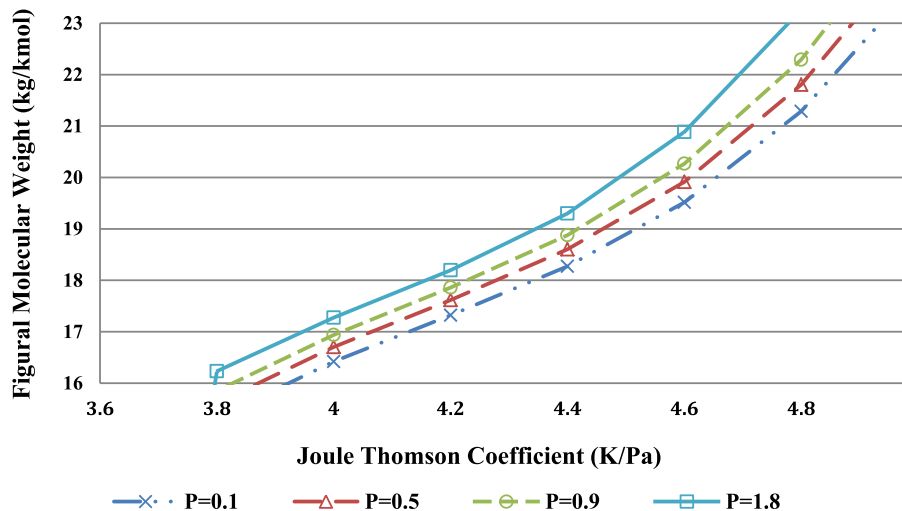


Fig. 5. The variation of figural molecular weight by changing the JT coefficient in different pressures when T = 320 K.

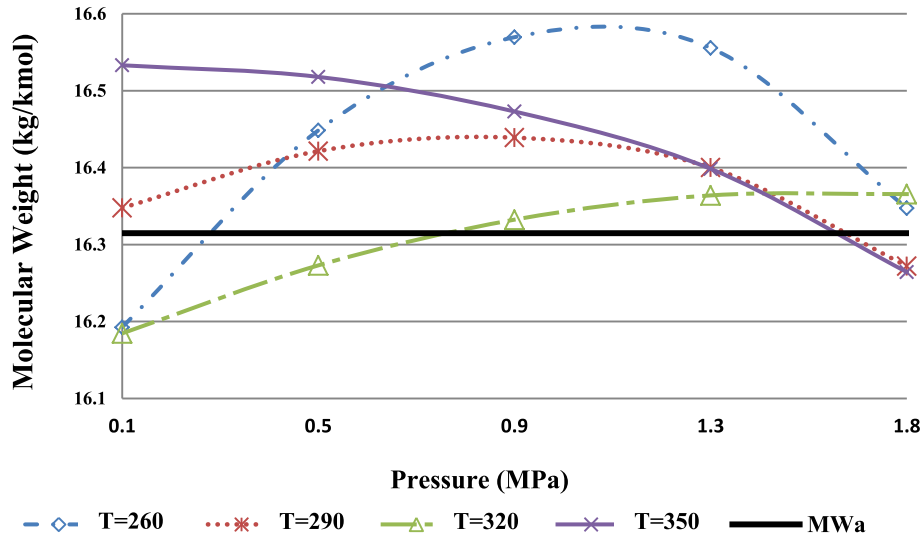


Fig. 6. Comparing actual and figural molecular weights for Khangiran in different pressure and temperatures.

The small values of the MAE and STD imply superior performance of the corresponding correlation.

5. Results and discussion

The results have been divided into two parts. In the first part, the variation of figural molecular weight values versus the pressure, temperature and JT coefficient is presented. Fig. 4 shows the figural molecular weight value variations versus the JT coefficient at different temperatures for a constant pressure (P = 0.8 MPa) for an arbitrary natural gas mixture. Fig. 5 also depicts the variation of figural molecular weight value versus the JT coefficient for different pressures at a constant temperature (T = 320 K) for an arbitrary natural gas mixture. It should be noted that the correlation performance is illustrated only for a constant pressure and a constant temperature in order to avoid presenting numerous similar figures.

According to Fig. 4, the figural molecular weight value increases by the JT coefficient growth in a constant temperature. The temperature growth in a constant JT coefficient also leads to higher

values of figural molecular weight values. As Fig. 4 doesn't reveal any information about the variation of figural molecular weight value versus the pressure changes, Fig. 5 is presented to show this issue in a constant temperature.

According to Fig. 5, the figural molecular weight value increases by the JT coefficient growth in specific pressures, whereas the predicted molecular weight by the correlation has more values at higher pressures at the same temperature and JT coefficients. Comparing Figs. 4 and 5, it also could be found out that the dependency of the extracted correlation on the pressure variations is not as strong as the temperature variations because small changes in temperatures result to significant changes in the figural molecular weight values, while this remarkable change in the figural molecular weight values could not be seen against the pressure variations. Comparing the figural molecular weights at different temperatures, pressures and JT coefficients with the actual values in the reference database reveals that the presented correlation is considerably reliable. To prove this reliability the following figures are presented. Figs. 6–11 are presented in order for making a

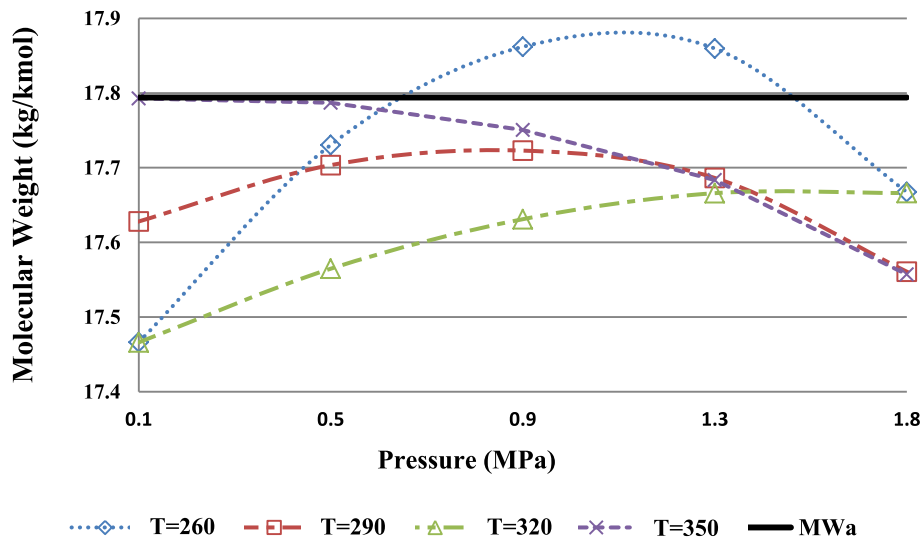


Fig. 7. Comparing the actual and figural molecular weights for Shurjeh in different pressure and temperatures.

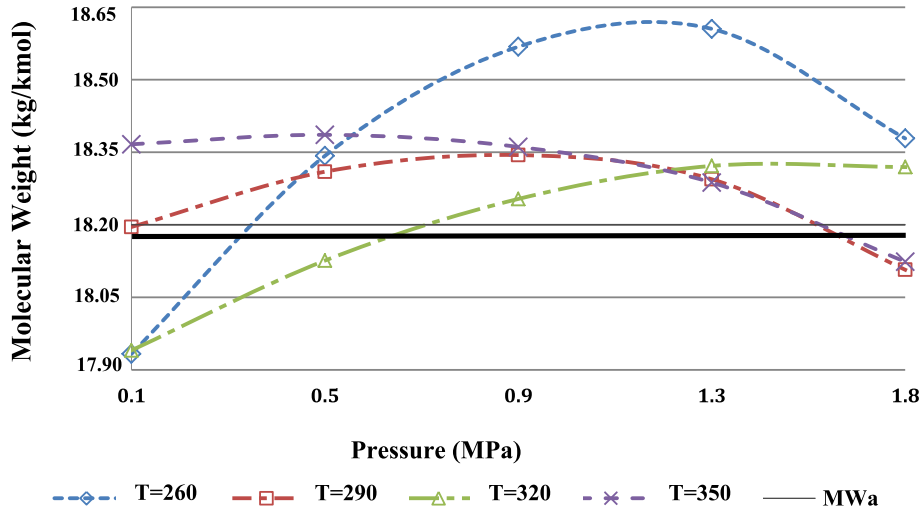


Fig. 8. Comparing the actual and figural molecular weights for Gonbadly in different pressure and temperatures.

comparison between the actual molecular weights (calculated based on its compositions) and the figural molecular weight (calculated by the novel correlation) for the three natural gas mixtures which were used to develop the considered correlation (Khangiran, Shurjeh and Gonbadly) as well as the other three natural gas mixtures which are used to evaluate the correlation performance (Torkman, Kangan and Pars). The black solid lines in the following figures refer to the actual molecular weight values of corresponding natural gas fields.

Fig. 6 shows that in almost all pressures, the correlation estimates upper values than the actual molecular weight of Khangiran field. Not only the maximum deviation calculation from the reference value doesn't exceed 0.25, but also the deviation decreases by the pressure increase and the temperature decrease.

Fig. 7 represents the correlation performance for Shurjeh. According to Fig. 7, in contrast with Khangiran, the correlation almost always underestimates the molecular weight values rather than the reference value. The maximum prediction deviation is about 0.3 in the lowest temperature and the lowest pressure and the deviation

decreases even to zero in the middle temperatures and pressures. Overall, it could be said that the prediction accuracy is more in higher pressures for Shurjeh.

Fig. 8 shows the correlation performance for Gonbadly. Based upon this figure, the calculation deviation even comes up to almost 0.5 in the lowest temperature (T = 250 K); however, in other circumstances the deviation falls down considerably and the accuracy gets much better.

Fig. 9 presents a comparison between the actual molecular weight value and the calculated molecular weight values for Pars. For Pars also the calculation deviation varies up to 0.25 in a few points, while overall performance is completely satisfactory.

As Fig. 10 shows the predicted values of molecular weight for Torkman field is totally acceptable with maximum prediction error of 0.35 in the middle pressures and the lowest temperature (T = 250 K). The deviation calculation decreases to smaller values in higher pressures.

Fig. 11 shows this factor for Kangan. According to the figure, the correlation underestimates the molecular weight for this field in

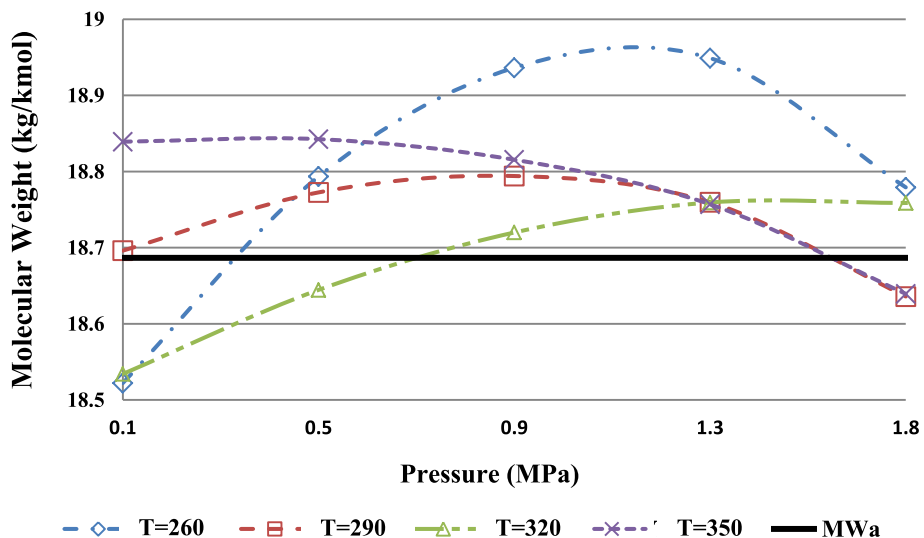


Fig. 9. Comparing the actual and figural molecular weights for Pars in different pressure and temperatures.

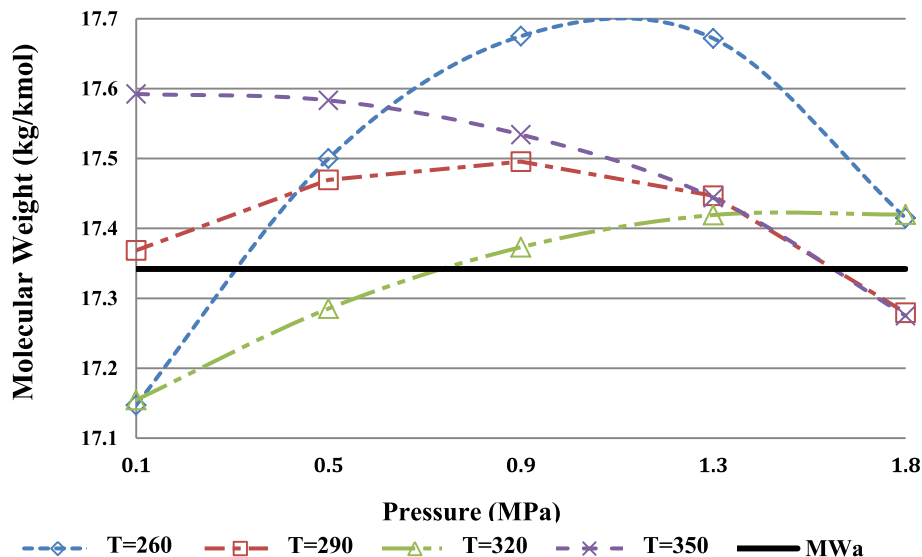


Fig. 10. Comparing the actual and figural molecular weights for Torkman in different pressure and temperatures.

almost all cases; however the prediction accuracy is satisfactory with average deviations less than 0.2.

As a whole, it could be seen that more accurate results of prediction could be acquired from the correlation at higher pressures and higher temperatures, though this statement could be violated in a few cases.

Since the main goal of this work is to calculate the natural gas mass flow rate, the equation adequacy should be assessed in density prediction directly. Figs. 12 and 13 depict the actual density of different natural gas mixtures calculated by AGA8 EOS (Farzaneh-Gord and Rahbari, 2012) versus the calculated values of density for the corresponding natural gas mixture. In this figure, the black dash line refers to the actual value of density of each natural gas field and the red marker (X) shows the calculated value of density by the correlation.

As the figure demonstrates, although some minor deviations in the molecular weight calculation stage were observed, the effects of such deviations on the density calculation are negligible. In other

words, the presented correlation results to such accurate values of molecular weight that the calculated density values almost match the actual values. It is noticeable that the horizontal axis of all the graphs depicted in Figs. 12 and 13 refer to the both temperature and pressure, i.e. five different pressure values (0.1, 0.5, 0.9, 1.3 and 1.8 MPa) in four specific temperatures (260, 290, 320 and 350 K).

Although, the super accuracy of the proposed system is easily observable from the graphs presented in Figs. 12 and 13 and having a glance on the density comparison graphs reveals this fact, however, presenting an error reporter graph as a common method for accuracy evaluation seems to be inevitable. For this aim, the Fig. 14 exhibits the density prediction error by the proposed correlation relative to the actual densities of different natural gas fields for three temperatures (low, medium and high) from the lowest possible pressure to the highest levels of pressure in CGSs. As the figure shows, the error doesn't exceed 1.2% anywhere, while for more than 70% of the states the deviation is even less than 0.6% and even the average error is less than 0.4%.

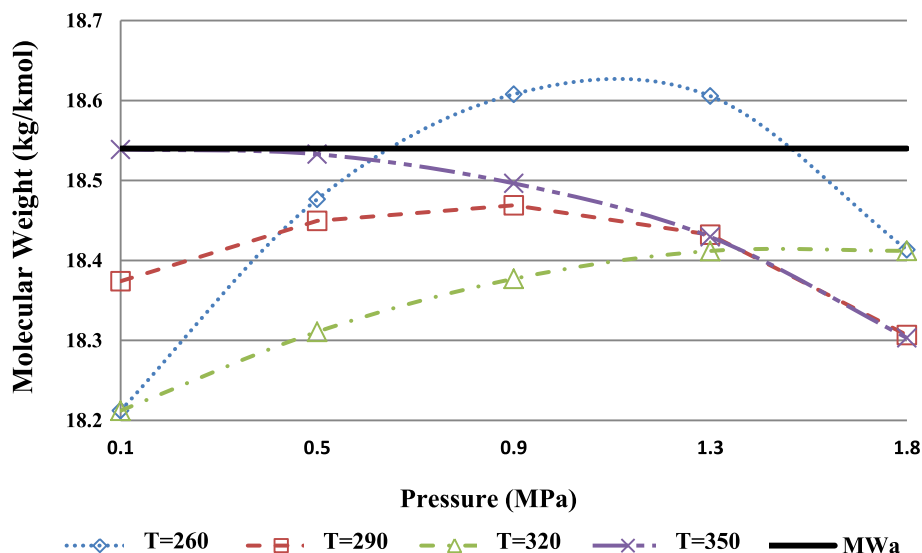


Fig. 11. Comparing the actual and figural molecular weights for Kangan in different pressure and temperatures.

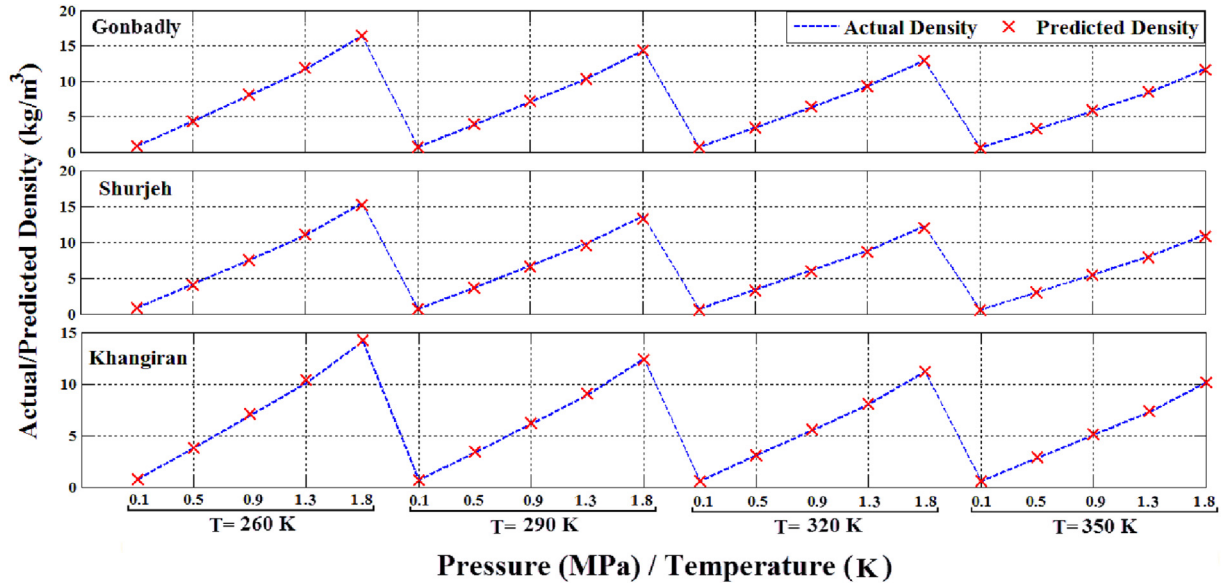


Fig. 12. Comparing the actual density values and predicted density values in different temperatures and pressures for Khangiran/Shurjeh/Gonbadly.

As another method of proficiency evaluation, two criterions were used to illustrate the correlation prediction accuracy. Figs. 15 and 16 illustrate the MAE and STD analysis on the proposed system performance, respectively. The following figures show the correlation MAE and STD for the six considered natural gas fields in a wide range of pressure variations (from 0.1 MPa to 1.8 MPa) and the JT coefficients variations (from 3 to 7) in four specific temperatures (260, 290, 320 and 350 K).

According to the figure, overall, it could be seen that the highest values of MAE belong to Gonbadly except in $T = 320$ K and the least MAEs could be attributed to Pars. The average MAE for all the considered fields in all the temperatures is almost 0.057 which implies the high accuracy of the correlation.

Fig. 16 also shows the STD for the correlation performance in different temperatures for all of the considered natural gas fields resulted from comparing the predicted values with the actual

values of density in a wide range of pressures and JT coefficients.

According to Fig. 16 and confirming the MAE graph, the worst performance of correlation is for Gonbadly while the best is for Pars and Khangiran.

The results extracting from the above figures prove that the correlation performance is completely reliable for an arbitrary natural gas mixture in every range of the temperatures, pressures and JT coefficients common in CGSs.

6. Conclusion

Accurate prediction of thermodynamic properties for natural gas is an essential requirement in optimum design and operation of most process equipment involved in petrochemical production, transportation, and processing. Particularly for mass flow metering in the natural gas industry, although there are some devices or

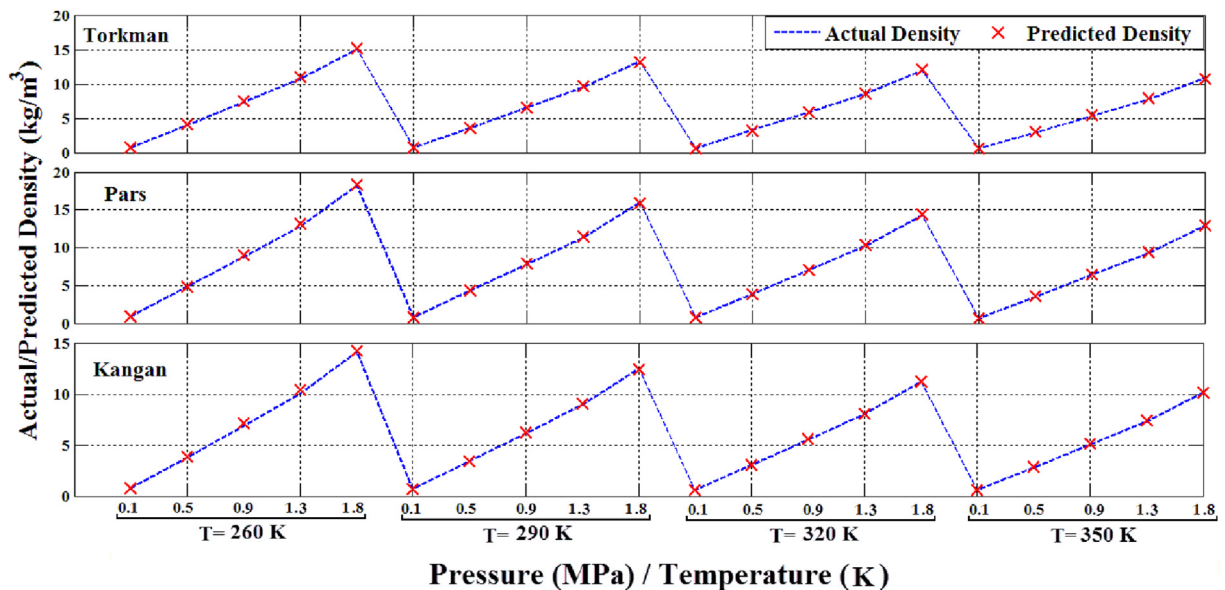


Fig. 13. Comparing the actual density values and predicted density values in different temperatures and pressures for Kangan/Pars/Torkman.

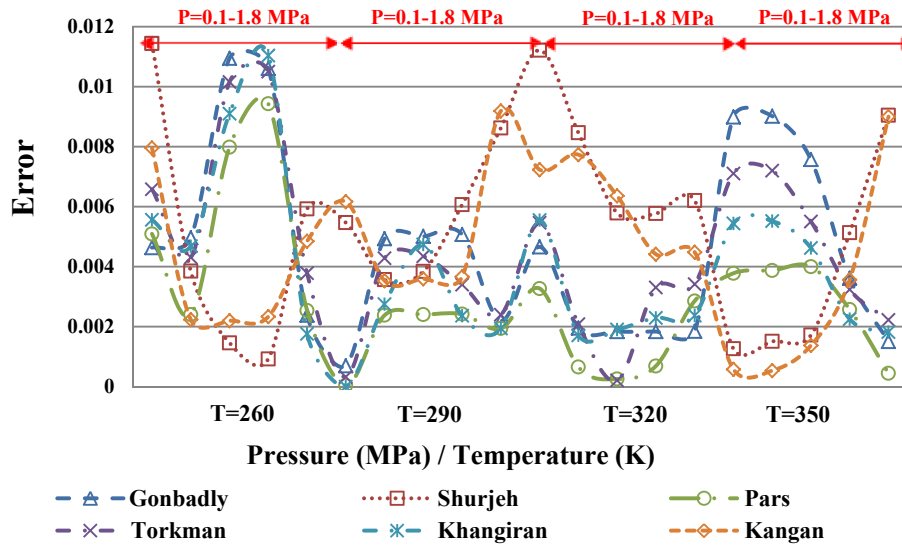


Fig. 14. The error values in density calculation process by the proposed method.

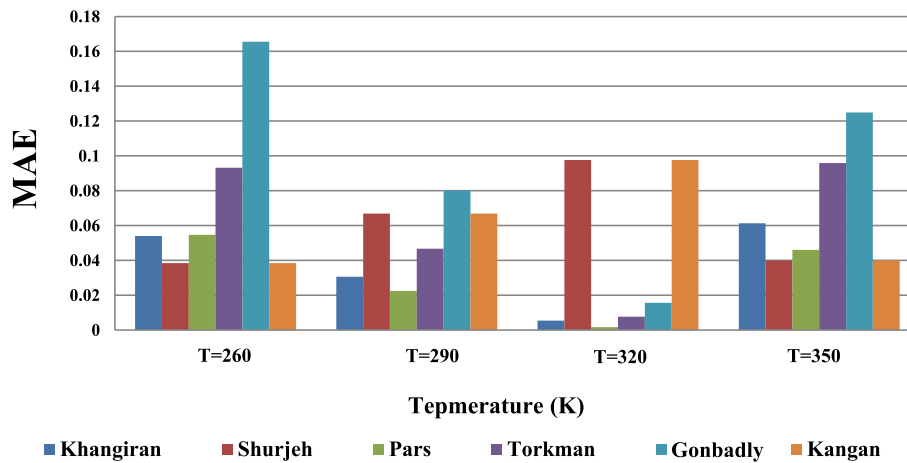


Fig. 15. The MAE values for the novel correlation in various temperatures, pressures and JT coefficients.

methods that could afford it, however, there are some limitation and disadvantages with each of them that makes necessity the existence of alternative and novel methods of mass flow metering.

In this work, a novel correlation was presented for calculating the real time density of natural gas, when no information about its compositions is available, as a functional of temperatures and

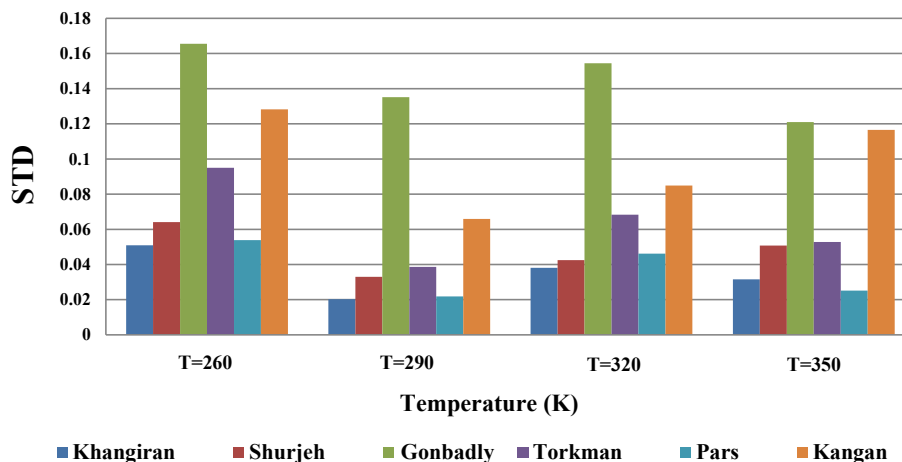


Fig. 16. The STD values for the novel correlation in various temperatures pressures and JT coefficients.

pressures across a throttle valve. For developing and verifying the proficiency of the presented correlations a huge database including the practical data of 6 selected main natural gas fields of Iran was used. In fact, 50% of the available experimental data (three fields) have been used to develop the correlation and the remaining 50% (the other three fields) were used in accuracy assessment step.

The investigations on the correlation performance show that the average error in prediction of density value is almost 0.4% and the maximum error, which occurs rarely, is less than 1.2%. The average MAE for all the considered natural gas fields in the studied temperature and pressure range is almost 0.057 which implies the high accuracy of the correlation. The other metric employed for verification of the correlation accuracy, i.e. STD also show satisfactory results for the system performance in density calculation process.

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