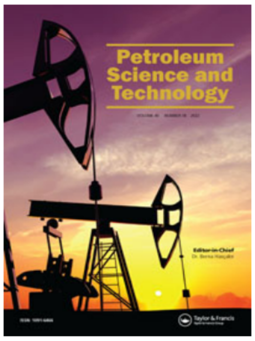

Taylor & Francis
Taylor & Francis Group

Petroleum Science and Technology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/lpet20

Neural network modeling for rigorous simulation of mid-pressure reciprocating expansion engines performance

Mahmood Farzaneh-Gord & Hamid Reza Rahbari

PETROLEUM SCIENCE AND TECHNOLOGY
https://doi.org/10.1080/10916466.2022.2094956

Neural network modeling for rigorous simulation of mid-pressure reciprocating expansion engines performance

Mahmood Farzaneh-Gord and Hamid Reza Rahbari

Faculty of Engineering, Mechanical Engineering Department, Ferdowsi University of Mashhad, Mashhad, Iran

ABSTRACT
In the Natural Gas (NG) distribution network, the town border stations are used to reduce NG pressure. Currently, pressure reduction is done by using throttling valves that cause a significant amount of physical exergy loss. Reciprocating Expansion Engine (REE) is a new tool to recover this pressure exergy. This study presents a thermodynamic evaluation to simulate the REE rigorously. The GERG-2008 equation of state (EOS) as an accurate model is used to calculate NG thermodynamic properties. As the utilization of GERG-2008 EOS requires specific inputs (pressure, temperature and mole fraction), the Try & Error method is utilized (while the inputs are density, specific internal energy, and NG composition). An Artificial Neural Network (ANN) method is also developed as an additional and alternative tool to overcome a basic limitation of the Try & Error method (knowing the NG composition). The validation results show that the error of the ANN and Try & Error methods for temperature, pressure calculation are reported 0.03%, 0.08%, and 0.04%, 0.9%, respectively. Also, the results show that the NG compositions have a significant impact on REE performance so that the indicated work for Khangiran and Bidboland NG mixtures are reported 165 and 143 kJ/kg, respectively.

KEYWORDS
GERG-2008 EOS; mathematical modeling; neural network; natural gas composition; reciprocating expansion engine; TBS station

1. Introduction

1.1. Motivation

In the NG industry, NG is transferred at high-pressure levels to reduce the pipeline size and also cut costs (Mokhatab and Poe 2012). The pressure of NG on these high-pressure pipelines is between 6 and 8 MPa. To supply the pressure required by consumers, the NG pressure is reduced to the desired consumer pressure at the City Gate Stations (CGS) and Town Border Stations (TBS). The NG pressure after pressure reduction at CGS reaches 1.7 MPa (supply pipeline). In the TBS, the NG pressure should be

CONTACT Mahmood Farzaneh-Gord m.farzanehgord@um.ac.ir Faculty of Engineering, Mechanical Engineering Department, Ferdowsi University of Mashhad, Mashhad, Iran.

reduced to 0.4 MPa (distribution pipeline) which is reasonable pressure for the consumers. The pressure reduction is usually performed by throttling valves at the TBSs (Mokhatab and Poe 2012). As a result of the throttling process, a large amount of latent energy of high-pressure NG is wasted during the pressure reduction process in the TBSs.

1.2. Literature review

As discussed above, researchers are always looking for ways to recover this enormous wasted energy (Rosen and Scott 1988; Chaczykowski, Osiadacz, and Uilhoorn 2011; He and Ju 2014). Expansion turbines (turbo expanders) are a common solution for recovering NG pressure energy. By using expansion turbines in parallel with TBS stations, in addition to reducing the gas pressure to the distribution pressure, the desired energy can also be recovered. The power obtained by expansion turbines can drive electrical generators, compressors, and other devices (Bisio 1995; Greeff et al. 2004; Poživil 2004; Kostowski and Usón 2013; Kostowski et al. 2014). A new method in this field is the use of the Reciprocating Expansion Engines (REE) for simultaneous pressure reduction and power generation. There are a few studies on using REE in pressure reduction stations such as CGSs and TBSs. For the first time, an REE was used to expand a mixture like NG to produce electrical power in the study of Tuma and Sekavcnik (Tuma and Sekavcnik 1997). The simulation of an REE for applying in CGSs based on ideal gas models was presented in the study of Farzaneh-Gord and Jannatabadi (2014). They surveyed the impact of physical parameters and thermodynamic properties on the REE performance. In another study were presented by this team of authors, the timing optimization of an REE based on exergy analysis is presented (Farzaneh-Gord and Jannatabadi 2015). Also, the optimization of the REE based on the AGA8 equation of state (EOS) is investigated in Farzaneh-Gord et al. (2015) and Farzaneh-Gord et al. (2015). In one recent study, Jannatabadi et al. (2018) investigated the energy and exergy analysis of an REE based on the value configurations. In their study, the impact of various valve configurations is studied on the optimization process of the REE.

The use of EOSs is the best way to calculate the thermodynamic properties of the NG mixture with high accuracy. There are two acceptable EOSs that are used in the NG industry include AGA8 EOS (AGA8-DC92 EoS 1992) and GERG-2008 EOS (Kunz and Wagner 2012). The accuracy of GERG-2008 EOS is higher than AGA8 EOS, therefore in this study, the thermodynamic properties of the NG mixture are calculated using GERG-2008 EOS (Mahmood Farzaneh-Gord et al. 2018). Temperature, pressure and mole fraction of the NG compositions are common input parameters of GERG-2008 EOS and then the thermodynamic properties are calculated by knowing these parameters. To calculate the thermodynamic properties using different inputs parameters which are mentioned above, the Try & Error method or the alternative methods should be applied. The Try and Error is the conventional method. Although the Try and Error method is a reasonable method and this method is applied by various researchers, this method does not have high accuracy. Therefore, in this case, the alternative methods which have high accuracy should be applied. Artificial intelligence (AI) methods such as artificial neural networks (ANN) are the new solutions for the calculation of thermodynamic properties with various input parameters and with high accuracy. AI methods were used by researchers in recent studies to calculate thermodynamic properties and simulate different processes. For example, the compressibility factor of NG was calculated using the ANN method (Al-Anazi et al. 2011). The NG density is estimated using the Fuzzy C-means algorithm in Kiomarsiyan and Sedaghat (2018). Sedaghat and Kiomarsiyan (2019) apply a method based on the ANN model to calculate gas density. Ajorkaran and Cheshmeh Sefidi (2019) presented a method based on the radial basis function of the ANN model to estimate NG density in different operational conditions. Farzaneh-Gord et al. (2020) simulated the throttling process of NG mixture to calculate pressure drop by using intelligence methods. The calculation of NG compressibility factor based on temperature, pressure, and speed of sound or Joule-Thomson coefficient using ANN methods are studied in Farzaneh-Gord and Rahbari (2020) and Farzaneh-Gord et al. (2021), respectively. The results of mentioned studies concluded that AI methods are explicit methods with high precision, therefore these methods could be applied for calculating thermodynamic properties of NG mixtures in the various NG industry processes.

The ANN methods according to the high accuracy are used in various fields such as forecasting, optimizations, nanofluid, energy systems, etc. Various researchers investigated the ANN method in these fields of study in recent years. For example, Akhgar et al. (2019) used the ANN method to predict the thermal conductivity of a hybrid nanofluid. Toghraie et al. (2019) presented a method based on AI methods to predict the viscosity of Silver/Ethylene glycol nanofluid at various conditions. The viscosity of a type of hybrid nanofluid is predicted using the ANN method in Toghraie et al. (2020). The results of their study show that the viscosity could be predicted with a correlation of about 0.999837454 compared to experimental data. The prediction of thermal conductivity of a hybrid nanofluid using the ANN method is presented in Rostami et al. (2021). They concluded that the correlation coefficient of their proposed method compared to experimental data is 0.993861. In two recent studies, the thermal characteristics of engine oil-based nanofluids are predicted using the ANN method in the study of Soltani et al. (2021). Also, the thermal conductivity of a hybrid nanofluid is predicted by the ANN method in the study of Tian et al. (2021). The results of their study show that the ANN method could be predicted the thermal conductivity with an average of 1.67e − 6 for MSE and a correlation coefficient of 0.999.

1.3. Novelty

The above discussions are demonstrated that REEs have great potential to use in the TBSs for simultaneous pressure reduction and power generation. The simulation of the REEs operation under real conditions is useful to study the feasibility of its utilization. The main goal of the current study is the rigorous simulation of an REE for possible utilizing in TBSs based on the ANN methods. For this purpose, a thermodynamic simulation based on energy analysis is developed. The thermodynamic properties of NG are calculated using GERG-2008 EOS. As GERG-2008 EOS demands special input for calculating thermodynamic properties, the Try & Error method is also utilized for simulation. Then for rigorous simulation, the ANN method is presented to simulate the REE and study its performance. Eventually, the impact of NG compositions on the REEs' performance is investigated. An REE that could be used in the TBSs is represented schematically in Figure 1. As it can be seen, the pressure ratio of REE is 1.7 MPa (supply pipelines)/0.4 MPa (distribution pipelines).

2. Mathematical model for REE

Figure 2 represents the details of the REE geometry which is used in this study. NG enters the REE at medium pressure through the suction port and causes the cylinder to move downwards, then by reducing the pressure level to the distribution pressure, the NG leaves from the discharge port. The thermodynamic assumptions that are assumed to build the mathematical model are presented as follows:

- The behavior of NG is assumed real gas.
- The REE is an open control volume system.
- The process of inlet and outlet ports is assumed isentropic.
- The change in kinetic and potential energy is ignored.
- The circular velocity is assumed constant.
- There is no leakage in the engine.

According to the above assumptions, the mathematical modeling of the REE is presented as follows.

2.1. Energy analysis

In this study, the cylinder is assumed as a control volume. The first law of thermodynamics can be simplified by ignoring kinetic and potential energy (Moran and Shapiro 1993):

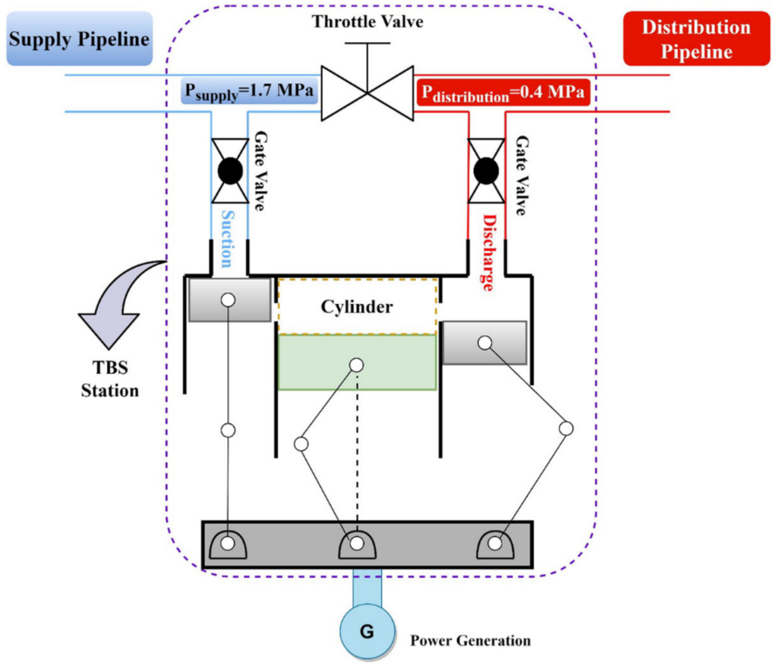

Figure 1. Schematic of an REE as the proposed system.

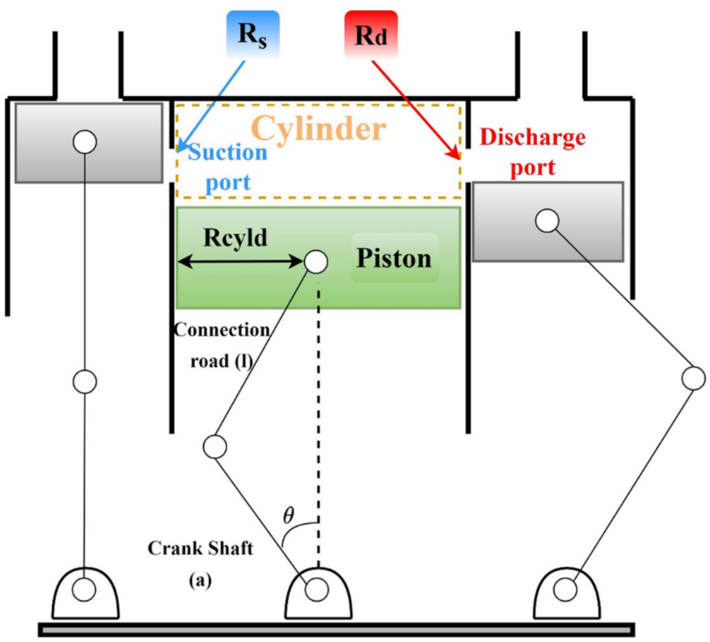

Figure 2. Schematic of a reciprocating expansion engine.

$$\frac{dQ_{cv}}{dt} + \frac{dm_s}{dt} h_s = \frac{dm_d}{dt} h_d + \frac{d}{dt}(mu)_{cv} + \frac{dW_{cv}}{dt} \tag{1}$$

In which, the subscripts cv, s, d refer to the control volume, suction, and discharge, respectively.

In which, the rate of control volume work can be defined as below (Moran and Shapiro 1993):

$$\frac{dW_{cv}}{dt} = P_{cv}\frac{dV_{cv}}{dt} \tag{2}$$

In which, P is pressure and V is volume.

The indicated work per in-cylinder mass is an important parameter of an REE which is calculated as follows (Lee 2013):

$$W_{indicated} = \frac{1}{m_{cv}}\int P.dV = \frac{1}{m_{cv}}\sum_{j=1}^{N}(P.dV)^{j} \tag{3}$$

In which, N is the number of time steps.

Piston displacement as a function of crankshaft angle and geometric characteristics can be given as follows (Sukhyung 1983):

$$x(\theta) = \frac{S}{2}\left[1 - \cos\theta + \frac{L}{a}\left(1 - \sqrt{\left(1 - \left(\frac{L}{a}\sin\theta\right)^{2}\right)}\right]\right. \tag{4}$$

In which, a is the length of the rod and L refers to the length of the crank. Also, The instantaneous volume of the cylinder is defined as below (Sukhyung 1983):

$$V_{cv} = A_{cv} \times s(\theta) + V_0 \tag{5}$$

Where V_0 is the dead volume.

The continuity equation for natural gas in the expansion engine can be presented as follows (Moran and Shapiro 1993):

$$\frac{dm_{cv}}{d\theta} = \frac{dm_s}{d\theta} - \frac{dm_d}{d\theta} \tag{6}$$

In which, $\frac{dm_s}{d0}$ and $\frac{dm_d}{d0}$ refer to the suction and discharge mass flow rate. Equations (7) and (8) are defined as the suction and discharge mass flow rate, respectively (Sukhyung 1983):

$$\dot{m}_s = \begin{cases} \rho_s A_s\sqrt{\dfrac{2(P_s - P_c)}{\rho_s}} & for\ P_s > P_c\ and\ x_s > 0 \\ \rho_s A_s\sqrt{\dfrac{2(P_c - P_s)}{\rho_s}} & for\ P_s < P_c\ and\ x_s > 0 \end{cases} \tag{7}$$

$$\dot{m}_d = \begin{cases} \rho_s A_d \sqrt{\frac{2(P_d - P_c)}{\rho_d}} & for\ P_d > P_c\ and\ x_d > 0 \\ \rho_s A_d \sqrt{\frac{2(P_c - P_d)}{\rho_d}} & for\ P_d < P_c\ and\ x_d > 0 \end{cases} \tag{8}$$

In Eqs. (7) and (8), A_s and A_d are the suction and discharge port areas that take place from the cylinder, respectively.

Suction and discharge ports are rotated by crankshaft force. This motion is simulated as sinusoidal motion as follows (Saad 1985):

$$A = A_{\max} \sin\left(\frac{\theta - \theta_{\text{open}}}{\theta_{\text{close}} - \theta_{\text{open}}} \pi\right) \tag{9}$$

In which, θ_{open} and θ_{close} are the angles at which the ports open and close, respectively.

The heat transfer between the expansion engine and the surrounding can be calculated as (Annand and Pinfold 1980):

$$Q = UA_0(T_0 - T_{amb}) \tag{10}$$

In which, U is the overall heat transfer coefficient, A_0 is the heat transfer surface, and T_0, T_{amb} refer to in-cylinder temperature and the ambient temperature, respectively.

The overall heat transfer coefficient could be defined as follow (Annand and Pinfold 1980):

$$U = \frac{1}{A_{Ref} \sum R_j} \tag{11}$$

In which $\sum R_j$ represents the total heat resistance that can be written as following equation (Annand and Pinfold 1980):

$$\sum R_j = \frac{1}{2\pi r_i X_0 h_i} + \frac{\log\left(\frac{r_o}{r_i}\right)}{2\pi K_i X_0} + \frac{1}{2\pi r_o X_0 h_o} \tag{12}$$

The ambient heat coefficient can be defined by the following equation (Annand and Pinfold 1980):

$$Nu = \frac{\alpha D}{K} = \left(\frac{Gr \times Pr_f^{\,2}}{2.435 + 4.884\sqrt{Pr_f} + 4.953 Pr_f}\right)^{0.25} \tag{13}$$

In which, $Pr = \frac{Cp.\mu}{K}$ and the subscript f refers to the film temperature which is defined as below (Bergman et al. 2011):

$$T_f = \frac{T_w + T_{amb}}{2} \tag{14}$$

The Grashov number is written as (Bergman et al. 2011):

$$Gr = \frac{\left(\frac{\pi D}{2}\right)^3 g \left(\frac{T_{amb} - T_w}{T_0}\right)}{\nu^2} \tag{15}$$

In which, T_0 represents the wall temperature of the cylinder. The coefficient of thermal conductivity of the cylinder wall is considered to be equal to 50 W/(m K), assuming the steel material and at ambient temperature.

Hassan's equation is applied to calculate the Nusselt number (Annand and Pinfold 1980):

$$Nu = \frac{\alpha_i D}{K} = 0.023 Re^{0.8} \tag{16}$$

Here $Re = \frac{C_m D}{\nu}$ is Reynolds number and $C_m = \frac{2sN}{60}$ is mean piston speed with the rotational speed of N.

3. Thermodynamic properties calculation

To determine the thermodynamic properties of the NG inside the cylinder (i.e., temperature and pressure), we need to know two independent thermodynamic properties. Here, the density which is calculated from the continuity equation, and the internal energy which is calculated from the energy equation, are two independent thermodynamic properties.

The first law of thermodynamic (i.e., energy equation) and continuity equations are discretized to calculate internal energy and density of NG inside of cylinder:

$$\frac{u^{j+1} - u^j}{\Delta\theta} = \frac{1}{m_{cv}}\left(\left(\frac{\Delta Q}{\Delta\theta}\right)^j + h_s\left(\frac{\Delta m_s}{\Delta\theta}\right)^j - P_{cv}\left(\frac{\Delta V}{\Delta\theta}\right)^j - h_d\left(\frac{\Delta m_d}{\Delta\theta}\right)^j - \omega\left(\frac{\Delta m_{cv}}{\Delta\theta}\right)u^j\right) \tag{17}$$

$$\frac{\Delta m_{cv}}{\Delta\theta} = \frac{\dot{m}_s - \dot{m}_d}{\omega} \tag{18}$$

The two above differential equations are solved by applying the Runge-Kutta method for each crank angle to calculate internal energy and in-cylinder mass. Then, the density at each crank angle is calculated as follow:

$$\rho_{(\theta)} = \frac{m_{cv(\theta)}}{V_{cv(\theta)}} \tag{19}$$

In which, m_{cv} and V_{cv} are the in-cylinder mass and volume of the cylinder, respectively.

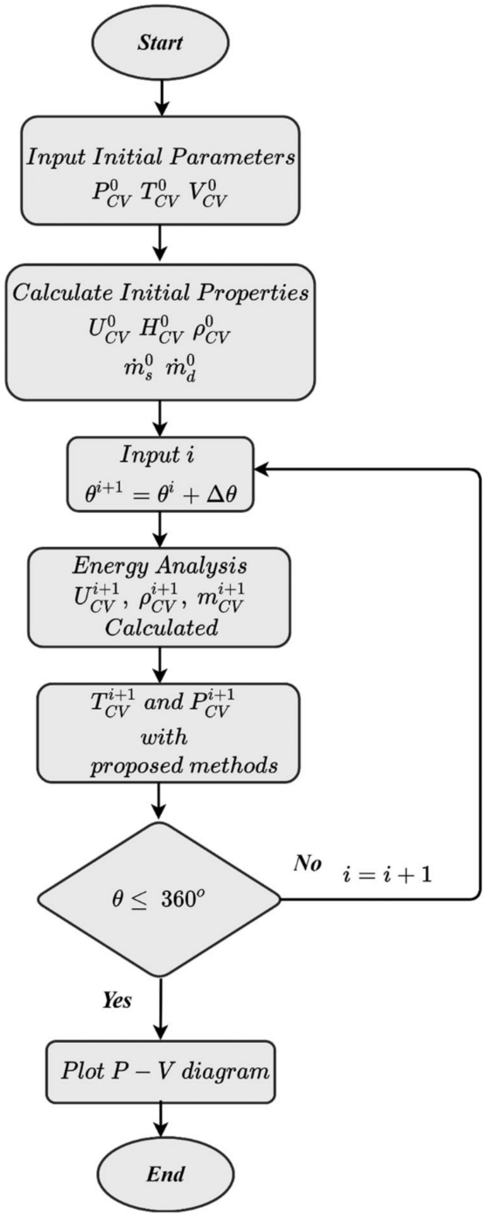

Figure 3. Flowchart of the simulation procedure.

The final purpose of REE simulation is to calculate in-cylinder temperature and pressure by applying the mathematical model. The procedure of these calculations is shown in Figure 3. As it can be seen, the calculations are performed for a complete crankshaft rotation, and in each step using two methods of Trial & Error and MLP-ANN the pressure and temperature inside the cylinder are calculated using specific input parameters.

3.1. Try & error method

As discussed earlier, the temperature and pressure inside the cylinder at each angle of the crankshaft should be calculated by specifying the density, internal energy, and composition of natural gas. The Try & Error method is a common method for this purpose. The density and internal energy of NG are calculated by the GERG-2008 EOS by guessing the temperature and pressure and knowing the NG compositions. These values are compared with the value of density and internal energy obtained from the continuity and energy equations, respectively. Therefore, the Try & Error method demands density, internal energy, and molar fraction of the NG components. Measuring NG composition is a costly and complex process. As a result, the use of Try & Error will have a basic limitation. To overcome this limitation, the ANN method is also employed in this study.

3.2. Ann method

The ANN method as the alternative tool is proposed in this study to calculate the in-cylinder temperature and pressure. The ANN method demands density at standard condition, internal energy, and standard density of NG. Measuring the standard density of NG, unlike NG compositions, is a simple process. As a result, the temperature and pressure of NG inside the cylinder are calculated using an explicit method. The multilayer perceptron (MLP) which is a class of feedforward artificial neural networks (FFANN) (Hagan, Demuth, and Beale 2002) is used to calculate in-cylinder temperature and pressure.

The performance of the proposed ANN method is calculated for training, validation, test, and all data sets which is used in the ANN method. The percentage of data used for train, validation, and test data is 70, 15, and 15%, respectively. The coefficient of determination for the ANN is 0.99996, 0.99996, 099996, and 0.99996 for training, validation, test, and all data, respectively. These values demonstrate that the proposed ANN has high accuracy to calculate the temperature and pressure of NG mixture by using internal energy, density, and density at standard conditions as three input parameters.

Table 1 gives the design parameters of the proposed ANN method that is applied in this study.

4. Calculation procedure

The final purpose of REE simulation is to calculate in-cylinder temperature and pressure by applying the mathematical model. The calculations are performed for a complete crankshaft rotation, and in each step using two

Table 1. Design parameters of the applied ANN method.

Parameters	Value/comment
Number of input parameters	3
Number of output parameters	1
Total data	50,000
Number of hidden layers	3
Number of neurons in each hidden layer	10
Transfer function of hidden layers	tansig
Transfer function of the output layer	purelin
Division of data for training	70%
Division of data for validation	15%
Division of data for test	15%
Performance function	MSE
Training function algorithm	Levenberg-Marquardt
Coefficient of determination for outputs	0.99996
Best validation performance at Epoch	463

Table 2. The basic design parameters of the expansion engine.

Parameter	Symbol	Value	Unit
Diameter of cylinder	D_{cyld}	18	cm
Stroke	S	12	cm
Radius of suction port	R_s	3	cm
Radius of discharge port	R_d	4	cm
Rotational speed	ω	1000	rpm
Suction temperature	T_s	300	K
Suction pressure	P_s	1.7	MPa
Discharge pressure	P_d	0.4	MPa
Pressure ratio	$\frac{P_s}{P_d}$	4.16	–

methods of Trial & Error and ANN the pressure and temperature inside the cylinder are calculated using specific input parameters. The basic design of the expansion engine includes the geometric properties and thermodynamic properties that are required for modeling an expansion engine are listed in Table 2.

Figure 4 represents the procedure of thermodynamic properties which is used in this study.

5. Results and discussion

The methods of temperature and pressure calculation are compared to the study of Setzmann and Wagner (1991) for pure methane. Figure 5 shows the in-cylinder pressure versus volume which is calculated with these two proposed methods. As can be seen, the in-cylinder pressure profile which is calculated using the MLP-ANN method has good agreement with Setzmann and Wagner's study (Setzmann and Wagner 1991). There is a significant error compared to Setzmann and Wagner's study (Setzmann and Wagner 1991) when the Try & Error method is applied to compute the in-cylinder pressure.

The average absolute percent deviation (AAPD) of in-cylinder pressure calculation is 0.08 and 0.92% for the ANN method and Try & Error

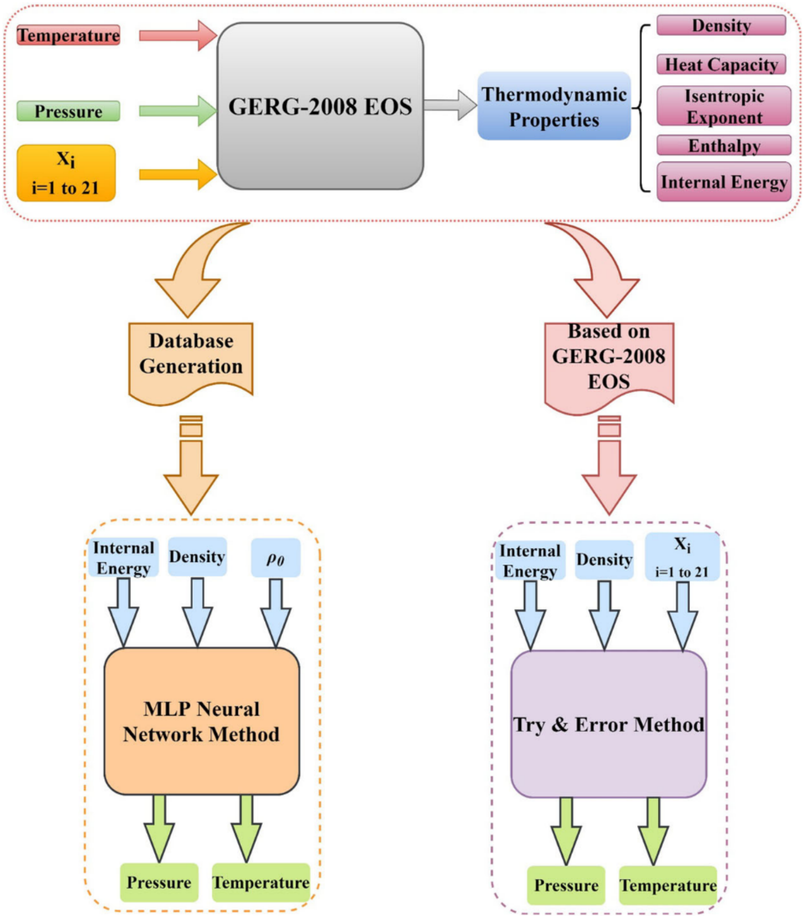

Figure 4. Procedure of thermodynamic properties calculation.

method, respectively. The AAPD of in-cylinder temperature calculation is 0.03% for the ANN method and 0.04% for the Try & Error method. Since the ANN method is a simple and explicit method with high accuracy, this method is used for the following results.

The impact of NG compositions on the expansion engine performance is presented and discussed in the following results. For this purpose, the various NG mixture is selected from different Iran's region. Table 3 gives the mole fraction of the NG component for the NG mixtures which is used in this study.

The variation of in-cylinder pressure relative to cylinder volume for different NG mixtures is shown in Figure 6. It is assumed that the inlet and outlet pressures to the expansion engine are constant. As can be seen, the suction and discharge processes are constant pressure evolution. Also, the expansion process and compression of the residual mass process are polytrophic constant volume processes, respectively. According to the figure,

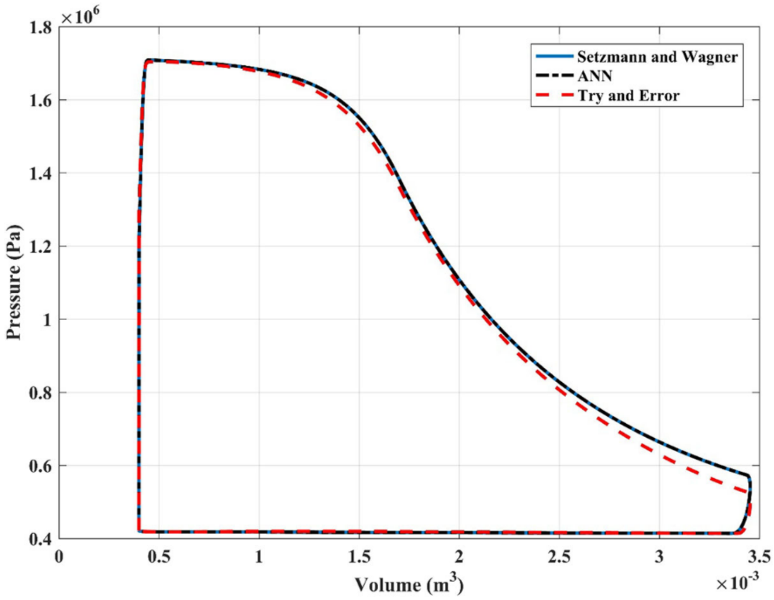

Figure 5. In-cylinder pressure vs. volume for several proposed methods.

Table 3. NG compositions of different Iran's region ("National Iran Gas Company Official Website.").

	CH4	Khangiran	Shorijeh	Bidboland
Methane	100	98.548	90.04	85.01
Nitrogen	0	0.5	4.48	0.44
Carbon dioxide	0	0	0	0.41
Ethane	0	0.647	3.69	9.38
Propane	0	0.069	0.93	3.49
Isobutane	0	0.018	0.2	0.34
n-Butane	0	0.039	0.29	0.65
Isopentane	0	0.018	0.14	0.1
n-Pentane	0	0.021	0.08	0.09
n-Hexane	0	0.14	0.14	0.09
n-Heptane	0	0	0.01	0
n-Octane	0	0	0	0
n-Nonane	0	0	0	0
n-Decane	0	0	0	0
Hydrogen	0	0	0	0
Oxygen	0	0	0	0
Carbon monoxide	0	0	0	0
Water	0	0	0	0
Hydrogen sulfide	0	0	0	0
Helium	0	0	0	0
Argon	0	0	0	0
Molecular weight (kg/kmol)	16.042	16.356	17.793	19.091
Density at standard conditions (kg/m^3)	0.6798	0.6932	0.7542	0.8097

the area enclosed in the pressure–volume diagram decreased if the NG with high molecular weight is used. This area represents the indicated work of the expansion engine in one crankshaft period. As a result, the amount of indicated work for NG with higher molecular weight is lower than other NG mixtures. Furthermore, at a specific angle of the crankshaft, the

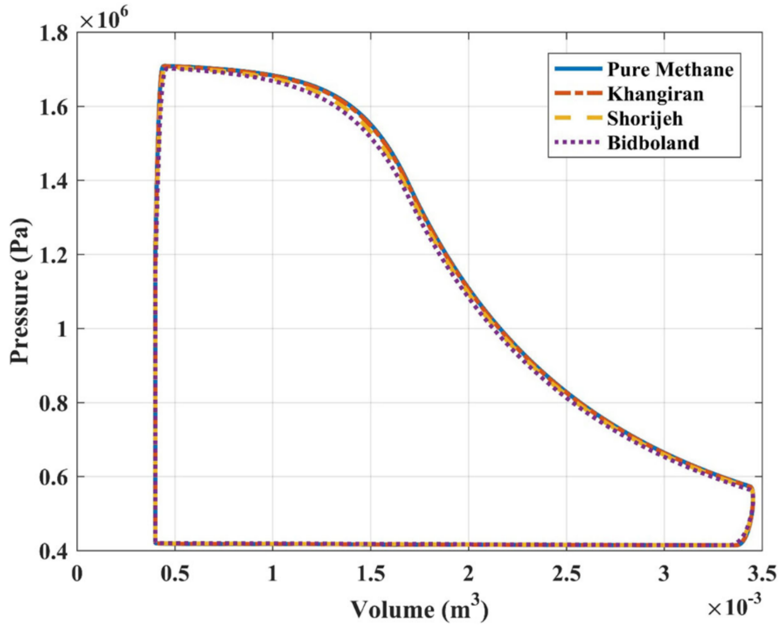

Figure 6. Pressure–volume profiles for different NG mixtures.

amount of in-cylinder pressure for the Bidboland NG mixture is less than the amount of in-cylinder pressure for the Khangiran NG mixture. It can be concluded that the amount of pressure inside the cylinder is lower for NG mixtures with higher molecular weight.

Figure 7 demonstrates the temperature change inside the cylinder relative to the cylinder volume and for different NG mixtures. As can be seen, the temperature increases at the beginning of the process due to the mass arrival at the high temperature. As long as the cycle reaches its half, the downtrend continues. The decrease in specific volume is the main reason for temperature reduction in the suction process. The pressure and temperature drop in the expansion process at the same time. In the discharge process, the pressure is constant but the temperature increases due to the decrease in NG density. According to the figure, the impact of NG compositions on temperature profiles is significant.

The impact of NG composition on temperature profile is much greater than the impact of NG composition on pressure profile. For a certain amount of crankshaft angle, the temperature is higher for the NG mixtures with high molecular weight. The amount of maximum temperature in the discharging and residential mass compression process is higher for the heavier NG Mixture (i.e., high molecular weight)

Figure 8 reveals the variation of suction (7a) and discharge (7b) mass flow rates versus the crankshaft angle and for different NG mixtures during the expansion process. According to the optimization results, the suction

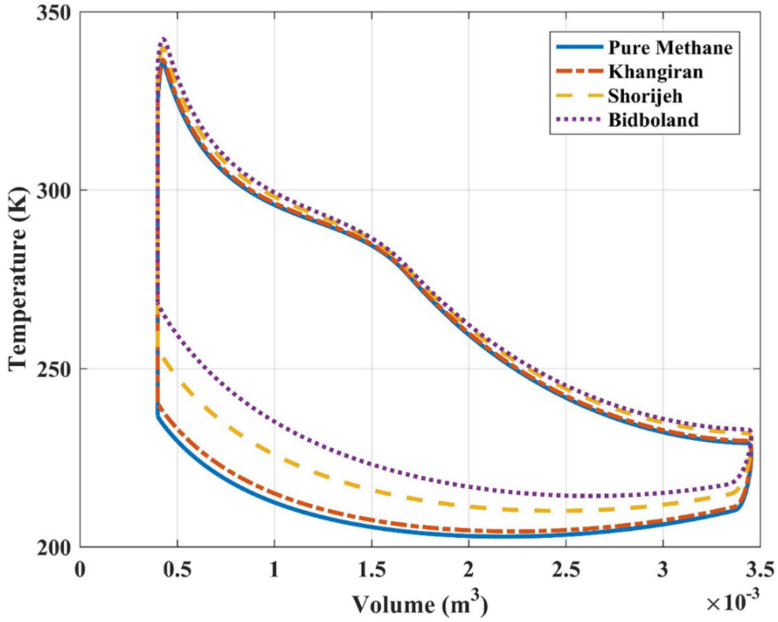

Figure 7. In-cylinder temperature profiles vs. volume for various NG compositions.

port is open from the beginning of the crankshaft movement and then closes at an angle of 73° (Farzaneh-Gord et al. 2015). Also, the discharge port opens at 170° and closes at 359° of the crankshaft (Farzaneh-Gord et al. 2015). Based on the information are given by Figure 7a, the sudden entry of mass at the suction process beginning is due to the large difference between the pressure inside the cylinder and the suction pressure. On the other hand, as molecular weight increases, the suction mass flow rates will be slightly increased. According to Figure 7b, the discharge mass flow rate will be significantly increased if the molecular weight of NG increased. The reason for this is that the NG mixtures with higher molecular weight have higher density.

Figure 9 shows the variation of in-cylinder mass relative to the crankshaft angles for different NG mixtures. The increase in the amount of NG in the cylinder occurs due to the opening of the suction port. Then mass flow rates stay constant for each NG mixture during the expansion process. A sudden discharge happens at the beginning when the discharge port opens, but it continues with a smoother rate afterward. Based on the expected results, the in-cylinder mass for pure methane is lower than the other NG mixture. Therefore, it can be concluded that the amount of in-cylinder mass will be increased if the heavier NG Mixture (i.e., high molecular weight) is used.

As is evident from the in-cylinder pressure profile, the production work per cycle in the same condition for NG with lower molecular weight is

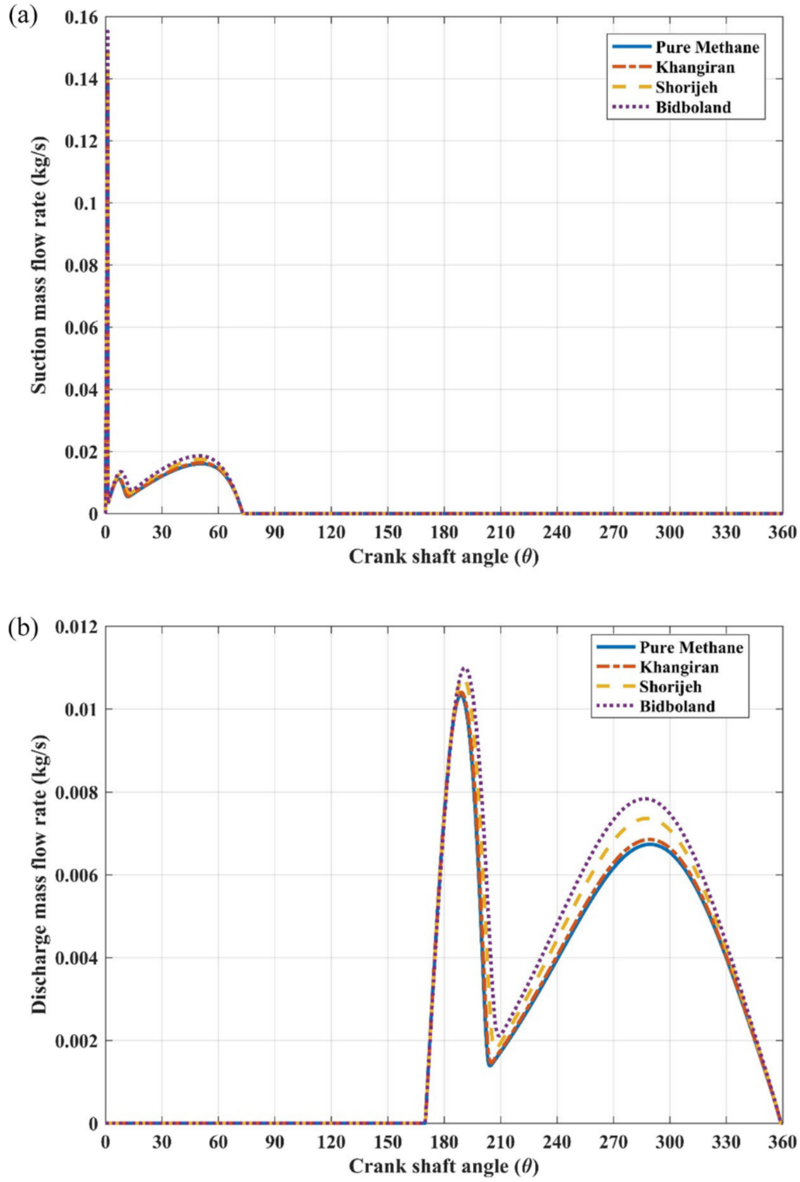

Figure 8. Mass flow rates vs. crank angle for different NG mixtures: (a) suction and (b) discharge.

significantly greater than the NG with higher molecular weight. Figure 10 gives the impact of NG compositions on the work produced in each cycle and for different NG mixtures. For example, the indicated work per cycle is 165 kJ/kg and 143 kJ/kg for Khangiran (i.e., Mw = 16.356) and Bidboland (i.e., Mw = 19.091) NG mixture, respectively. According to the results obtained, due to the increase in-cylinder mass with increasing molecular weight, also, since the pressure inside the cylinder does not

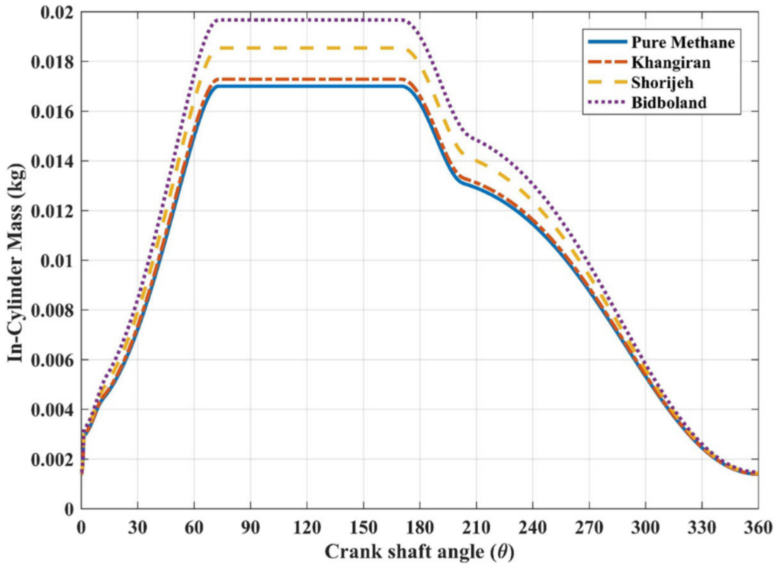

Figure 9. Mass of NG inside the cylinder vs. crank angle for different NG mixtures.

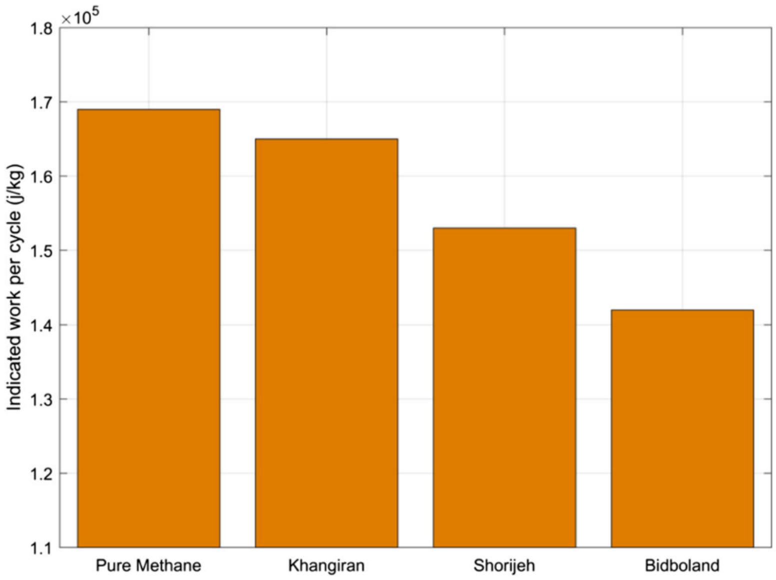

Figure 10. The amount of indicated production work for different NG mixtures.

significantly change for various NG mixtures, the indicated production work per unit mass increases when the NG molecular weight increased.

6. Conclusion

The pressure reduction at the natural gas (NG) pressure reduction stations is always one of the main issues in natural gas industries. The use of

Reciprocating expansion engines (REE) in the pressure reduction stations is a new tool to produce a significant amount of power as well as pressure reduction in these stations. The main objective of the current study is to simulate the REE rigorously based on thermodynamic analysis to optimize the REE performance. The NG is assumed as real gas and thermodynamic properties of the NG mixture are calculated based on the GERG-2008 equation of state (EOS). Try & Error and artificial neural network (ANN) methods are used in the simulation process of the REE. The ANN method is proposed as an alternative tool in the REE simulation process due to is not required NG composition. The measurement of NG composition is a costly and complex process therefore the proposed ANN method is efficient and rigorous. Eventually, the impact of natural gas composition on the performance of the expansion engines is surveyed. The main findings which are concluded from this study can be summarized as follows:

1. Comparison of ANN method and Try & Error method shows that the accuracy of neural network for calculating the in-cylinder pressure and temperature compared to experimental data is equal to 0.08 and 0.03%, respectively, while this value for Try & Error method is equal to 0.92 and 0.04%.
2. It can be concluded that the use of the ANN causes the precise simulation of the expansion engine even without knowing the mole fraction of NG components.
3. The NG compositions have a significant impact on the in-cylinder temperature, mass, and mass flow rate while having a slight impact on the in-cylinder pressure.
4. The output work of each cycle, in the same condition, is 168 kJ/kg for pure methane, 165 kJ/kg for Khangiran NG, and 143 kJ/kg for Bidboland NG mixtures.
5. The result concluded that the indicated work is higher for NG with lower molecular weight.

Funding

This research is supported by the Ferdowsi University of Mashhad. The second author would like to thank the support from the Ferdowsi University of Mashhad.

References

"National Iran Gas Company Official Website." https://nigc.ir/.

AGA8-DC92 EoS. 1992. Compressibility and Super Compressibility for Natural Gas and Other Hydrocarbon Gases. Transmission Measurement Committee Report.

Ajorkaran, F., and A. Cheshmeh Sefidi. 2019. Application of RBF-ANN in prediction of natural gas density in different operational conditions. *Petroleum Science and Technology* 37 (22):2246–51. doi:10.1080/10916466.2018.1476888.

Akhgar, A., D. Toghraie, N. Sina, and M. Afrand. 2019. Developing dissimilar artificial neural networks (ANNs) to prediction the thermal conductivity of MWCNT-TiO_2/water-ethylene glycol hybrid nanofluid. *Powder Technology* 355:602–10. (October). Elsevier: doi:10.1016/j.powtec.2019.07.086.

Al-Anazi, B. D., G. R. Pazuki, M. Nikookar, and A. F. Al-Anazi. 2011. The prediction of the compressibility factor of sour and natural gas by an artificial neural network system. *Petroleum Science and Technology* 29 (4):325–36. Taylor & Francis Group doi:10.1080/10916460903330080.

Annand, W. J, and D. Pinfold. 1980. Heat transfer in the cylinder of a motored reciprocating engine. In SAE Technical Papers, 173:973–990. doi:10.4271/800457.

Bergman, T. L., F. P. Incropera, D. P.Dewitt and A. S. Lavine. 2011. *Fundamentals of heat and mass transfer*. John Wiley & Sons.

Bisio, G. 1995. Thermodynamic analysis of the use of pressure exergy of natural gas. *Energy* 20 (2):161–7. doi:10.1016/0360-5442(94)00074-D.

Chaczykowski, M., A. J. Osiadacz, and F. E. Uilhoorn. 2011. Exergy-based analysis of gas transmission system with application to Yamal-Europe pipeline. *Applied Energy* 88 (6): 2219–30. Elsevier Ltd doi:10.1016/j.apenergy.2010.12.045.

Farzaneh-Gord, M., S. Izadi, M. Deymi-Dashtebayaz, S. I. Pishbin, and H. Sheikhani. 2015. Optimizing natural gas reciprocating expansion engines for town border pressure reduction stations based on AGA8 equation of state. *Journal of Natural Gas Science and Engineering* 26:6–17. doi:10.1016/j.jngse.2015.05.025.

Farzaneh-Gord, M., S. Izadi, S. I. Pishbin, H. Sheikhani, and M. Deymi-Dashtebayaz. 2015. Thermodynamic analysis of medium pressure reciprocating natural gas expansion engines. *Polish Journal of Chemical Technology* 17 (2):119–25. doi:10.1515/pjct-2015-0039.

Farzaneh-Gord, M., and M. Jannatabadi. 2014. Simulation of single acting natural gas reciprocating expansion engine based on ideal gas model. *Journal of Natural Gas Science and Engineering* 21:669–79. doi:10.1016/j.jngse.2014.09.031.

Farzaneh-Gord, M., and M. Jannatabadi. 2015. Timing optimization of single-stage single-acting reciprocating expansion engine based on exergy analysis. *Energy Conversion and Management* 105:518–29. doi:10.1016/j.enconman.2015.08.012.

Farzaneh-Gord, M., B. Mohseni-Gharyehsafa, A. Toikka, and I. Zvereva. 2018. Sensitivity of natural gas flow measurement to AGA8 or GERG2008 equation of state utilization. *Journal of Natural Gas Science and Engineering* 57:305–21. doi:10.1016/j.jngse.2018.07.014.

Farzaneh-Gord, M., and H. R. Rahbari. 2020. An intelligent approach for calculating natural gas compressibility factor and its application in ultrasonic flow meters. *Flow Measurement and Instrumentation* 76:101833. (December). Elsevier Ltd: 101833. doi:10.1016/j.flowmeasinst.2020.101833.

Farzaneh-Gord, M., H. R. Rahbari, B. Mohseni-Gharesafa, A. Toikka, and I. Zvereva. 2021. Accurate determination of natural gas compressibility factor by measuring temperature, pressure and Joule-Thomson coefficient: artificial neural network approach. *Journal of Petroleum Science and Engineering* 202:108427. January. Elsevier B.V., 108427. doi:10.1016/j.petrol.2021.108427.

Farzaneh-Gord, M., H. R. Rahbari, B. Mohseni-Gharyehsafa, A. Toikka, and I. Zvereva. 2020. Machine learning methods for precise calculation of temperature drop during a throttling process. *Journal of Thermal Analysis and Calorimetry* 140 (6):2765–78. Springer Netherlands doi:10.1007/s10973-019-09029-3.

Greeff, I. L., J. A. Visser, K. J. Ptasinski, and F. J. Janssen. 2004. Using turbine expanders to recover exothermic reaction heat - flow sheet development for typical chemical processes. *Energy* 29 (12–15):2045–60. doi:10.1016/j.energy.2004.03.048.

Hagan, M. T., H. B. Demuth, and M. H. Beale. 2002. *Neural Network Design.*

He, T. B., and Y. L. Ju. 2014. A novel process for small-scale pipeline natural gas liquefaction. *Applied Energy* 115:17–24. (February). Elsevier Ltd: doi:10.1016/j.apenergy.2013.11.016.

Jannatabadi, M., M. Farzaneh-Gord, H. R. Rahbari, and A. Nersi. 2018. Energy and exergy analysis of reciprocating natural gas expansion engine based on valve configurations. *Energy* 158:986–1000. doi:10.1016/j.energy.2018.06.103.

Kiomarsiyan, A., and M. Sedaghat. 2018. Application of fuzzy C-means algorithm as a novel approach to forecast gas density in different conditions. *Petroleum Science and Technology* 36 (17):1368–73. Taylor & Francis doi:10.1080/10916466.2018.1471498.

Kostowski, W. J., and S. Usón. 2013. Thermoeconomic assessment of a natural gas expansion system integrated with a co-generation unit. *Applied Energy* 101:58–66. doi:10.1016/j.apenergy.2012.04.002.

Kostowski, W. J., S. Usón, W. Stanek, and P. Bargiel. 2014. Thermoecological cost of electricity production in the natural gas pressure reduction process. *Energy* 76:10–8. doi:10.1016/j.energy.2014.01.045.

Kunz, O., and W. Wagner. 2012. The GERG-2008 wide-range equation of state for natural gases and other mixtures: An expansion of GERG-2004. *Journal of Chemical & Engineering Data* 57 (11):3032–91. doi:10.1021/je300655b.

Lee, S. 2013. First law analysis of unsteady processes with application to a charging process and a reciprocating compressor. https://etd.ohiolink.edu/apexprod/rws_etd/send_file/send?accession=osu1208791610&disposition=inline.

Mokhatab, S, and W. Poe. 2012. *Handbook of natural gas transmission and processing.* .Gulf Professional Publishing, Elsevier Inc, USA. doi:10.1016/C2010-0-66115-3.

Moran, M. J., and H. N. Shapiro. 1993. *Fundamentals of engineering thermodynamics, second edition*. Chichester: Wiley. doi:10.1080/03043799308928176.

Poživil, J. 2004. Use of expansion turbines in natural gas pressure reduction stations. *Acta Montanistica Slovaca* 9 (3):258–60. https://core.ac.uk/download/pdf/27232521.pdf.

Rosen, M. A., and D. S. Scott. 1988. Energy and exergy analyses of a production process for methanol from natural gas. *International Journal of Hydrogen Energy* 13 (10):617–23. doi:10.1016/0360-3199(88)90010-9.

Rostami, S., D. Toghraie, M. Ahmadi Esfahani, M. Hekmatifar, and N. Sina. 2021. Predict the thermal conductivity of SiO_2/water–ethylene glycol (50:50) hybrid nanofluid using artificial neural network. *Journal of Thermal Analysis and Calorimetry 2020 143:2*143 (2): 1119–28. Springer doi:10.1007/s10973-020-09426-z.

Saad, M. A. 1985. Compressible fluid flow, USA: Englewood Cliffs. doi:10.1017/cbo9781316134030.009.

Sedaghat, M., and A. Kiomarsiyan. 2019. Applying MLP-ANN as a novel and accurate method to estimate gas density. *Petroleum Science and Technology* 37 (20):2128–33. Taylor & Francis doi:10.1080/10916466.2018.1482324.

Setzmann, U., and W. Wagner. 1991. A new equation of state and tables of thermodynamic properties for methane covering the range from the melting line to 625 K at pressures up to 100 MPa. *Journal of Physical and Chemical Reference Data* 20 (6):1061–155. doi:10.1063/1.555898.

Soltani, F., M. Hajian, D. Toghraie, A. Gheisari, N. Sina, and A. Alizadeh. 2021. Applying artificial neural networks (ANNs) for prediction of the thermal characteristics of engine oil -based nanofluids containing tungsten oxide -MWCNTs. *Case Studies in Thermal Engineering* 26:101122. doi:10.1016/j.csite.2021.101122.

Sukhyung, L. 1983. "First Law Analysis of Unsteady Process with Application to a Charging Process and a Reciprocating Compressor." https://etd.ohiolink.edu/apexprod/rws_etd/send_file/send?accession=osu1208791610&disposition=inline.

Tian, S., N. I. Arshad, D. Toghraie, S. A. Eftekhari, and M. Hekmatifar. 2021. Using Perceptron feed-forward artificial neural network (ANN) for predicting the thermal conductivity of graphene oxide-Al_2O_3/water-ethylene glycol hybrid nanofluid. *Case Studies in Thermal Engineering* 26:101055. doi:10.1016/j.csite.2021.101055.

Toghraie, D., M. Hasan Aghahadi, N. Sina, and F. Soltani. 2020. Application of artificial neural networks (ANNs) for predicting the viscosity of tungsten oxide (WO3)-MWCNTs/engine oil hybrid nanofluid. *International Journal of Thermophysics* 41(12): 1–17. Springer: doi:10.1007/s10765-020-02749-x.

Toghraie, D., N. Sina, N. A. Jolfaei, M. Hajian, and M. Afrand. 2019. Designing an artificial neural network (ANN) to predict the viscosity of silver/ethylene glycol nanofluid at different temperatures and volume fraction of nanoparticles. *Physica A: Statistical Mechanics and Its Applications* 534:122142. (November). North-Holland: 122142. doi:10.1016/j.physa.2019.122142.

Tuma, M., and M. Sekavcnik. 1997. Power generation by natural gas expansion engines. *Fuel and Energy Abstracts* 38:177.