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# New correlations for predicting pure and impure natural gas viscosity

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ABSTRACT

Accurate determination of natural gas viscosity is important for successful design of production, transportation, and gas storage systems. However, most of available models/correlations suffer from complexity, robustness, and inadequate accuracy especially when wide range of pressure and temperature is applied. Present study illustrates development of two novel models for predicting natural gas viscosity for pure natural gas ($CH_4$) as well as natural gas containing impurities. For this purpose, 6484 data points have been gathered and analyzed from the open literature covering wide range of pressure, temperature, and specific gravity levels, temperature ranges from −262.39 to 620.33 °F (109.6 to 600 K), pressure ranges from 1.4508 to 29,000 psi (0.0100−199.94801 MPa), and gas specific gravity ranges from 0.553 to 1.5741. Sensitivity analysis on the collected data points through design of experiments algorithm showed that pseudo reduced pressure and pseudo reduced temperature are the most effective parameters as the inputs of the models. The Leverage Value Statistics is applied and doubtful data points are determined.

The average absolute relative error and the coefficient of determination of the proposed models for predicting pure/impure natural gas viscosity on a wide range of conditions are 5.67% and 1.87%, 0.9826 and 0.9953, respectively. Reliable accuracy of proposed models in comparison to eight commonly used correlations makes them attractive for possible implementing in natural gas simulation/modeling applications.



## 1. Introduction

Abundance, easily accessible, wide usage and clean burning of natural gas make its demand increasing in the world (Wang and Economides, 2013). The human needs to extract this vital fuel from the underground reservoir to the location of usage. It is worth bearing in mind that the most dominant portion of natural gas is constructed from methane (McCain, 1990). Through single-phase and multiphase flow in gas and oil reservoirs, wellbore, separator, turbine, compressor, surface operation devices and transportation pipelines, the knowledge of the thermo-physical properties of natural gas is indispensable (Kamari et al., 2013), which is covered in various fields of study such as gas production, gas injection, and carbon dioxide injection in oil wells (AlQuraishi and Shokir, 2011; Carr et al., 1954; Fayazi et al., 2013; Iverson and Denlinger, 2001; Shams et al., 2015). Natural gas is composed of complex mixtures of light hydrocarbons, heavy hydrocarbons with low viscosity and density and a minor amount of inorganic/non-hydrocarbon components such as hydrogen sulfide, carbon dioxide and nitrogen. Natural gas is a subcategory of petroleum fluids but its specifications are different from that of liquid hydrocarbon. Natural gas physical properties vary widely with pressure, temperature and composition (Davani et al., 2013; McCain, 1990).

One of the most used properties of natural gas is viscosity. Viscosity is the measure of fluid flow resistance (Carr et al., 1954; Geertsma, 1974). It plays an important role in the study of dynamics of fluids flow processes such that described above and in simulation application especially in porous spaces in chemical and petroleum engineering (Iverson and Denlinger, 2001). According to Newton's expression, viscosity is a constant proportional parameter (μ) which is used in following expression:

$$\tau = \mu \frac{\partial v}{\partial y} \tag{1.1}$$

τ is shear stress between bordering layers of fluid, $\frac{\partial v}{\partial y}$ is velocity gradient, perpendicular to layers direction. Practically, there is no

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exact theory that explains viscosity as a function of pressure, temperature and composition (Vesovic, 2001). Hence, one who needs to calculate accurate gas viscosity at desirable conditions should design an experiment, using apparatus such as vibrating wire viscometer (Wilhelm and Vogel, 2000), rolling-ball viscometer (Heidaryan et al., 2011), falling-body viscometer (Chan and Jackson, 1985; Heidaryan et al., 2010b), capillary tube viscometer (Jarrahian et al., 2015; Yusibani et al., 2011) or oscillating-piston viscometer (Davani et al., 2013). In addition, the gas viscosity is much more difficult to measure compared to the oil viscosity (AlQuraishi and Shokir, 2011).

A suitable viscosity model for implementation in simulators must: 1. trace the viscosity for full range condition of operation 2. be accurate, simple and fast; 3. forecast both pure component and mixture viscosities; 4. be reliable across the critical point.

The best of our knowledge, accurate experimental procedure needs to satisfy above conditions in measurement of viscosity. As well as, the various possible mixtures of natural gas and different operating conditions of interest hind acquisition of the pertinent data by experimental means alone. In addition, accurate measurement of natural gas viscosity is difficult and is necessary to optimize the number of wells in gas reservoirs, especially in high pressure/high temperature condition (Hu, 2013).

Consequently, in the absence of experimentally measured viscosity, it is essential to determine the viscosity from equations of state (EOSs), empirically derived correlations, and novel soft computing techniques.

As a result, using the EOSs to calculate the PVT properties of hydrocarbon fluids (Benedict et al., 1940) show that EOSs have poor capability to estimate the volumetric-properties of natural gas mixtures (Danesh et al., 1991; Elsharkawy, 2004; Younglove and Ely, 1987). As a standard approach, two steps are required to derive gas viscosity, the first step is to calculate gas viscosity at atmospheric condition then by using a graph, determine viscosity at desired condition (McCain, 1990). Up to now, several corresponding state models and empirical correlations have been introduced for calculating the gas viscosity under various pressure, temperature and composition. Some models that are used to predict the viscosity are under limited operating condition and sometimes have significant deviation and error, Some other are too complex and difficult to use (Danesh et al., 1991; Elsharkawy, 2004; Farasat et al., 2013; Younglove and Ely, 1987). Other category is soft computing methods. These models are based on black boxes, such as LS-SVM and ANN based models. In black box models (AlQuraishi and Shokir, 2011; Fayazi et al., 2013), there is no visual relationship between inputs and outputs. In order to use these models we should utilize a toolbox which maybe it is not easy to use in several cases, because the user usually need other software, which are not conventional.

Consequently, as one of several efforts by authors to present viscosity correlation for pure natural gas and mixtures, the main objective of the current work is to develop a useful, fast, accurate and simple viscosity correlation as a function of pressure, temperature and composition (Bicher Jr and Katz, 1943). In this study two correlations have been developed, one for pure ($CH_4$) natural gases and one for impure (sour (with $H_2S$) and sweet (without $H_2S$)) natural gases, respectively.

To achieve these objectives, we accomplish following steps: Review several existing open literature, which contain a wide range of natural gas compositions, experimental conditions and viscosity data. Finally gather them as a comprehensive data bank. Investigate accuracy of gathered data by implementing Leverage Value Statistics. Build a new, exact, and trustworthy correlation for estimating the natural gas viscosity using the obtained data set. Investigate the reliability, performance and preciseness of the developed correlations by statistical parameters and visual error examination. To reach this aim, we use several impressiveness criteria such as the coefficient of determination ($R^2$), average relative error (ARE %) and average absolute relative error (AARE %). Confirm validity of the constructed correlation by comparison with widely used correlations.

## 2. Review on previous studies

There are numerous correlations, which are developed to predict natural gas viscosity. It is suitable to introduce and investigate the eight well-known empirical correlations to be aware of effectiveness and accuracy of newly proposed correlations. In a characteristic manner, these correlations are functions of pressure, temperature and gas composition. For quickness view only, essential factors of these eight correlations are demonstrated as follows.

### 2.1. Jossi–Stiel–Thodos (JST), 1962

Jossi et al. (1962) developed following equation based on the relationship between pseudo reduced density $\rho_r$ and a pseudo viscosity term,$(\mu_g-\mu^0)\zeta$, it should be mentioned that this equation is applicable for $\rho_r \le 2$(Jossi et al., 1962):

$$\left[\left(\mu_g-\mu^0\right)\zeta+10^{-4}\right]^{0.25}=0.1023+0.023364\rho_r+0.058533\rho_r^2-0.040758\rho_r^3+0.0093324\rho_r^4 \tag{1.2}$$

where $\mu_g$ is gas viscosity. Further explanations about the parameters are available in Appendix A.

### 2.2. Dean-Stiel (DS), 1965

Dean and Stiel (1965) developed a correlation for the determination of the viscosity of nonpolar gas mixtures. Their equation can be used at moderate (2.94–73.5 psia) pressures and high pressures up to 11,240 psia. They develop their equation by modify the pure gas viscosity equation:

$$\mu_g=\mu^0+\frac{(10.8*10^{-5})(exp(1.439\rho_r)-exp(-1.111\rho_r^{1.858}))}{\zeta} \tag{1.3}$$

Criteria for defining the $\mu^0$ is described in Appendix A.

### 2.3. Lee–Gonzalez–Eakin (LGE), 1966

Lee et al. (1966) presented experimental measurements of viscosity for several natural gas mixtures. Based on the theory of viscosity presented by Born and Green (Born and Green, 1946), Starling and Ellington (Starling and Ellington, 1964) developed an expression for gas viscosity. Lee et al. modified Starling and Ellington equation and offered a better correlation. The new correlation has is shown below:

$$\mu_g=10^{-4}K\exp\left(X\rho_g^Y\right) \tag{1.4}$$

where K, X and Y are defined in Appendix A.

### 2.4. Sutton (S), 2007

Sutton (2007) combines gas viscosity presented by Lucas (Lucas, 1981), nonlinear regression and Lee et al. equation to develop a new