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Rigorous prognostication of natural gas viscosity: Smart modeling and comparative study

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ABSTRACT

The current study plays a major role in modeling natural gas viscosity in terms of several operating parameters including pseudo-reduced properties and molecular weight through radial basis function neural network (RBFNN), least-squares support vector machine (LSSVM), and multilayer perceptron neural network (MLPFNN). As it known, an important feature of any comprehensive modeling is the application of a large database for model development. Therefore, more than 3800 gas viscosity data points were used for modeling. For upgrading the efficiency of the abovementioned predictive tools, four optimization algorithms including levenberg-marquardt (LM), coupled simulating annealing (CSA), Bayesian regularization (BR), and scaled conjugate gradient (SCG), were integrated with them to find the optimal models' parameters during prediction analysis. Consequently, it was understood that among the all suggested tools in this study, the MLP-LM and then MLP-BR are the most accurate models for estimating gas viscosity with root mean square error (RMSE) of 0.001 and 0.002, respectively. Comparison of the MLP-LM and MLP-BR with previously published models in literature demonstrates their higher prediction capability, with less numbers of input parameters (without needing any density data), than the existing literature models. Based on the sensitivity analysis, it is concluded that the molecular weight is the most affecting variable on the viscosity prediction. Finally, the suggested tools in this study can be of great value for effective estimation of gas viscosity in simulating both upstream and downstream natural gas processes.

1. Introduction

Natural gas resources have been increasingly gaining lots of worldwide attentions owing to their clean burning, availability and versatility for the aim of private and industrial consumptions in comparison with other sources of energy [1–3]. This type of energy is mainly composed of methane, ethane, propane, butane as hydrocarbon constituents, and hydrogen sulfide, carbon dioxide, helium and nitrogen as impure constituents [4,5]. Gas and oil reservoirs are considered as the chief hydrocarbon reserves for natural gases. For gas recovery purposes, optimal equipment design including separators, inside well instruments and wellhead facilities, relies on the properties of the reservoir fluids; thereby, it is inevitable to be completely educated about the natural gas thermophysical properties [6]. Moreover, a large number of researches have been conducted to investigate the impact of storage of CO_2 as an important natural gas on enhanced oil recovery (EOR) by co-optimization of both recovery and storage processes on the basis of various experimental and modeling studies [7–14].

One of the main transport and thermophysical properties of natural gases is known as viscosity. Viscosity of pure light hydrocarbons and impure natural gases is highly important in effective assessment of optimum gas consumption, gas reserves, reservoir simulation, reservoir transportation and characterization [15,16]. For obtaining the natural gas viscosity, several methodologies have been introduced in the literature; experimental measurements, soft computation approaches, empirical correlations and equations of state (EOSs) [15,17]. Experimental means such as capillary tube, vibrating and falling body viscometers, almost always give precise and trustworthy results; even though monotonous test condition, large variety of operational conditions and natural gas mixtures, and high expenses inhibit the widespread applicability of such measurements for determining the viscosity [4,6,15,18–20]. Consequently, proper estimation/calculation of natural gas viscosity has been understood to be critically significant in a number of gas engineering processes including phase behavior analysis,

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gas metering, surface facilities, gas compression, gas wells' pressure gradient estimation, pipeline designation, and optimal exploitation [21–25]. Up to now, the two main categories have been proposed for viscosity prediction by existing models in literature; the first type of modeling is EOS-base that uses the reduced/critical properties and composition of fluid. Moreover, the second kind of models applies the molecular weight, temperature, density and pressure which are obtained through the field measurements. The earlier category may result in low accuracy when dealing with mixtures of gases, whereas the latter includes single- or two-step techniques [26].

In accordance with the bulk of literature investigations concerning on the potential application of EOSs for calculating PVT behavior of reservoir fluid [27–29], the inefficient estimates of the gas mixtures volumetric property have been understood via EOS application [30]. Under different thermophysical conditions, a number of corresponding state methods and empirically derived correlations have been extended to predict the viscosity of natural gases [24,25,31–36]. Alongside the complicated form of these models, they are applicable for a specific range of data, in which applying them out of the establishment range may lead to noticeable deviations from actual viscosity value [37,38]. Therefore, there is still a large gap between the accurate estimate of natural gas viscosity and the literature models proposed for this goal.

To overcome the existing challenges integrated with the large numbers of reservoir parameters including fuzziness, nonlinearity, uncertainty as well as complexity, it is crucial to apply strong predictive methods [39,40]. Soft computations have been recently attained widespread applications in different areas of petroleum and chemical engineering leading to the acceptable prediction of the several complex problems [15,39,41–44]. Such type of calculation strategy includes various predictive frameworks including support vector machine (SVM) [45,46], adaptive neuro-fuzzy inference system (ANFIS) [47,48], artificial neural network techniques (ANN) [49] and their hybrid with other optimization techniques. Several researches have been conducted on the application of ANN and SVM- based intelligent methods including estimation of breakthrough time [50], asphaltene precipitation [51–53], and wax deposition rate [54].

In 2013, an intelligent model called as least-squares SVM (LSSVM) was introduced by Fayazi et al. [15] for estimating viscosity of natural gas in terms of gas composition, pressure, molecular weight and temperature. They used a databank of 2485 data points for model development, and reported the total estimation error of 0.26% for their suggested model. In another investigation, Yousefi et al. [4] used the LSSVM model for gas viscosity prediction of more than 3800 data points as a function of the molecular weight, density, the pseudo-reduced pressure and pseudo-reduced temperature of gases. As a consequence, the authors achieved the prediction error of less than 2%, in which their model performed much better than the available literature correlations. Afterwards, Hajirezaie et al. [18] applied a powerful technique named as, gene expression programming (GEP), in order to construct an empirical correlation by this smart strategy. Using the same databank mentioned above, the authors assigned the total error of 4.9% for the GEP-based model which was a function of molecular weight, density, the pseudo-reduced pressure and pseudo-reduced temperature of gases. More recently, a new type of ANN modeling known as group method of data handling (GMDH) was extended in relation with density, pseudo reduced temperature, molecular weight, and pseudo reduced pressure in the work of Dargahi-Zarandi et al. [6]. They compared GMDH tool with 13 literature models, and concluded the superior performance of their model. In most of the existing models density of gas is an input for viscosity prediction. This parameter should be measured experimentally for using in viscosity models which is expensive and time consuming. Otherwise, density should be estimated by equations of state or empirical correlations which have their own disadvantages such as high error in some conditions. In this paper, this property is not considered as an input parameter of the viscosity models to directly calculate the viscosity of gas with the minimum number of inputs.

In the current study, three types of smart intelligent strategies integrated with four optimization algorithms, were utilized for modeling the viscosity of natural gases. The proposed tools in this study were developed by considering just three parameters of pseudo-reduced temperature, pseudo-reduced pressure, and molecular weight. In other words, the proposed methods in this study require less numbers of input data for estimating gas viscosity. For the reason that, a dataset of more than 3800 data points were adopted from the open literature for training and testing the models estimation capability. Then, by applying a number of illustrations and statistical parameters, the better performance of the developed tools in this study was proven as compared with existing literature models. By conducting the so-called technique of sensitivity analysis, the influence of each input variable on the estimate of natural gas viscosity was examined.

2. Data collection

Previous researches have proven that the comprehensive databank is of significant value for construction of a global and generalized model [37,38,41,42,55–61]. Hence more than 3800 gas viscosity data points in association with three parameters of pseudo-reduced temperature and pressure, and molecular weight were taken from the various open source literatures estimating viscosity of the pure and impure natural gases in this study [62–65]. Table 1 indicates the detailed characteristics of the used datasets for modeling in this study. Skewness indicates the degree of property asymmetry in comparison to its mean value. Normal distribution has zero skewness. When the probable distribution is not normal, this parameter can be both positive and negative values. The skewness becomes a positive value when the population of small values is more than the large values; even though it is negative when the large values have higher frequency. The other important property is termed as kurtosis, which describes the data distribution in relation to the shape of normal probability. Similar to skewness, the kurtosis is equal to zero for normal distribution. Moreover, the positive and negative kurtosis values will occur, respectively, at the time of more peaked and flatter distribution manners than the normal distribution. Fig. S1 shows the schematic distribution of the input and output parameters used in this study.

3. Intelligent model development

3.1. Predictive techniques

3.1.1. Least squares support vector machine (LSSVM)

Latest efforts on the machine leaning theory have led to development of the so-called predictive tool of support vector machine (SVM) aiming for regression analysis and problem classification [42,66–72]. The key benefits of SVM-based methods over ANN-based techniques are less occurrence of overfitting problem, less numbers of tuning coefficients, more generalization performance, no requirement for specifying network topology and insignificant alteration in convergence condition [42]. However, handling a quadratic programming problem in a large-scale has been considered as the main shortcoming of the SVM modeling [73]. As a result, the newer form of SVM approach termed as least-

Table 1
Statistical description of the selected inputs and output properties of the models.

	MW, g/mol	Tpr	Ppr	Viscosity, cP
Mean	36.490	1.430	5.934	0.080
Median	27.265	1.440	4.207	0.027
Mode	16.040	1.782	0.022	0.018
Kurtosis	3.675	0.181	0.939	12.787
Skewness	2.073	0.244	1.151	3.331
Minimum	16.040	0.541	0.021	0.009
Maximum	129.661	2.682	29.298	1.174