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Rigorous prognostication of permeability of heterogeneous carbonate oil reservoirs: Smart modeling and correlation development

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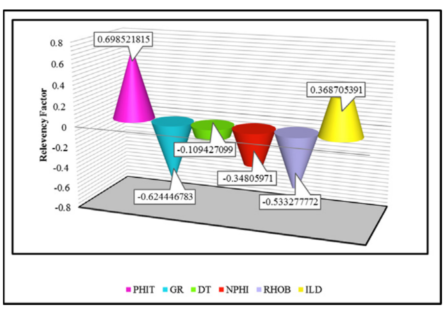
GRAPHICAL ABSTRACT



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ABSTRACT

Permeability estimation has a major role in mapping quality of the reservoir, reservoir engineering calculation, reserve estimation, numerical reservoir simulation and planning for the drilling operations. In carbonate formations, it is of great challenge to predict permeability by reason of natural heterogeneity, nonuniformity of rock, complexity and nonlinearity of parameters. Various approaches have been developed for measuring/predicting this parameter, which are associated with high expenditures, time consuming processes and low accuracy. In this study, comprehensive efforts have been made to the development of radial basis function neural network (RBF-ANN), multilayer perceptron neural network (MLP-ANN), least square support vector machine (LSSVM), adaptive neuro-fuzzy inference system (ANFIS), genetic programming (GP), and committee machine intelligent system (CMIS). For this purpose, a widespread databank of 701 core permeability datapoints as a function of well log data was adopted from the open literature for heterogonous formations. Moreover, several optimization techniques like genetic algorithm (GA), particle swarm optimization (PSO), and levenberg marquardt (LM) were employed to enhance the prediction capability of the proposed tools in this study. For assessing the models efficiency, several tools like crossplot and error distribution diagram were applied in association with statistical calculation. As a result, the CMIS model is identified as the most accurate model with the highest determination coefficient (R^2 near to unity) and the lowest root mean square error (RMSE near to zero). As a result of GP mathematical strategy, a new user-friendly empirically-derived correlation was developed for rapid and accurate estimation of reservoir permeability. The outcome of outlier detection shows the validity of

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dataset used for modeling, and the effective porosity is perceived to be the most affecting parameter on the permeability estimation in terms of sensitivity analysis. The main novelty of this modeling study was the proposal of CMIS and GP-based empirically-derived models for the first time in literature. To this end, the outcome of this study can be of great value for reservoir engineers dealing with simulation and characterization of the heterogonous carbonate reservoirs.

1. Introduction

Permeability as a petrophysical property is of crucial significance in evaluation of the hydrocarbon reservoirs. This valuable property indicates the quantitative potential of the porous media allowing the fluid to flow through it [1]. The concept behind permeability is necessary in accurate simulation and description of the reservoir [2]. In detail, this parameter is required for planning injection patterns and conditions during enhanced oil recovery (EOR), improving perforation and well completion design, and reservoir development and management so as to select the optimal production rate and drainage points [2]. Thus, determining permeability is vital earlier to any calculation or modeling study [3]. Analyzing core samples in laboratory is the most accurate technique for permeability determination by using Darcy's law, which needs long-time experiments and high expenditures [4,5]. Well test is also another alternative approach to predict the reservoir permeability, though it has the aforementioned disadvantages of the laboratory measurements as well as it represents an average value for the reservoir instead of giving a permeability profile [6].

For solving these issues, a number of techniques have been developed by many researchers among which establishing an appropriate relationship between the well log data and core permeability is the oldest approach [4]. In sandstone reservoirs, application of empirical correlations has been reported to be successful [7]; however, permeability estimates in heterogeneous formations by such correlations have resulted in considerable errors because of non-linearity and non-uniformity in permeability, complexity, and natural heterogeneity [8]. Availability and continuity of well log data [9] along the wellbore have encouraged the researchers to estimate permeability from them especially by applying smart computational techniques due to their incredible robustness, low cost, and widespread applicability in approximating any function effectively [2,10].

In recent years, soft computation methods have been developed successfully in wide varieties of chemical and petroleum engineering subjects [11–30]. They are also extremely powerful in finding optimum mathematical equations between the input and output data than the statistical and classical regression techniques [2]. One of the preliminary approaches is called artificial neural network (ANN) which has been performed to solve classification and highly nonlinear problems leading to the fast generalization and estimation, after training the network [31]. It has been proved that formation permeability can be estimated with good accuracy as a function of petrophysical data by means of ANN in heterogeneous formations [32,33]. Nevertheless, during ANN learning/training stage, limited size of the used databank establishes the problem of overfitting, which may lead to inefficient performance for generalization, applicability, and capability [34]. Moreover, substantial amount of effort and time is required to achieve the optimal network structure by reason of iterative and time-consuming procedure [35,36].

Another useful approach is known as fuzzy inference system (FIS). During FIS modeling, linguistic fuzzy information will be distributed by membership function, and the theory of classical set will be developed progressively [37]. This meta-heuristics algorithm can simulate nonlinear and complicated phenomena, like multi-dimensional input and output systems. High uncertainties and not clearly determined disciplines are the key features associated with geoscience systems [2]; thus, FIS could be used to effectively estimate the reservoir permeability [38,39]. Adaptive neuro-fuzzy inference system (ANFIS) is a more powerful technique which uses the joined effect of ANN learning power, and explicit information illustration of FIS [40]. Gedeon et al. [41] and Kaydani et al. [42] utilized ANFIS calculation strategy for improving permeability prediction.

Latest efforts on soft computation schemes have directed to the development of support vector machine (SVM) as a supervised machine learning methodology, in which data analysis and pattern recognition will be applied by its associated learning technique [43]. Due to the tremendous performance of SVM machine learning in dealing with hard regression and classifications problems, it has achieved lots of universal admiration [44]. The application of SVM has been found to be in wide variety areas of engineering and science but not restricted to recognition of lithology, permeability and porosity prognostication by well log data, computation of reservoir fluid properties, detection of speech and text, and identification of pattern in medical science [45–49]. El-Sebakhy [50] conducted SVM modeling in order to estimate the PVT behavior of reservoir fluid system handling the shortcomings of the classical neural network. By comparing SVM technique with literature empirical correlations, nonlinear regression, and neural network, the authors demonstrated that SVM is the most accurate model leaving behind the existing literature correlations. Using newer version of SVM known as, least square SVM (LSSVM), quantitative determination of asphaltene precipitation by a new scaling equation was carried out by Chamkalani et al. [51] resulting in remarkably acceptable results. Another generation of smart mathematical strategies is called genetic programming (GP). In this type of calculation strategy, a precise equation can be developed between the input and output data without assuming any specific format of correlation. Many researchers have developed more powerful GP-based empirically-derived equations in various fields of petroleum and chemical engineering successfully in comparison with the existing published correlations which were derived by the use of traditional regression approaches [12,13,52,53].

In this study, a comprehensive modeling was carried out by applying intelligent techniques, including multilayer perceptron neural network (MLPNN), radial basis function neural network (RBFNN), LSSVM, GP, ANFIS, and committee machine intelligent system (CMIS) for estimation of absolute permeability. For this purpose, a wide-ranging databank was collected from the open literature [44] for the heterogeneous carbonate oil reservoirs located in Saudi Arabia including 701 permeability datapoints as function of well log data. Then, about 75% and 25% of the whole databank were split into, respectively, two groups of training and test sets. Moreover, a newly developed empirically-derived correlation was developed via GP mathematical strategy

Table 1
Specification of the databank used for modeling.

Parameter	Symbol	Unit	Min.	Avg.	Max.	STDEV[a]
Total porosity	PHIT	percent	5.70	26.74	36.30	6.57
Gamma ray	GR	API	7.64	27.90	83.02	15.50
Sonic compression transit time	DT	μs/ft	64.40	93.24	109.30	4.68
Thermal neutron apparent porosity	NPHI	p.u.	0.21	0.30	0.48	0.04
Bulk Density	RHOB	gr/cm^3	1.87	2.23	2.68	0.11
Deep induction log	ILD	ohm.m	0.17	73.19	2000	294.50
Permeability	K	Darcy	0.10	2.28086	9.92961	2.20082

[a] STDEV refers to the standard deviation which can be calculated as follows: