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Modeling and analysis of effective thermal conductivity of sandstone at high pressure and temperature using optimal artificial neural networks

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ABSTRACT

Thermal conductivity (TC) is among the most important characteristics of porous media for hydrocarbon reservoir thermal simulation and evaluating the efficiency of the thermal enhanced oil recovery process. In this study a two-layer artificial neural network (ANN) approach is proposed for estimating the effective TCs of dry and oil saturated sandstone at a wide range of environmental conditions. Temperature, pressure, porosity, bulk density of rock, fluid density and oil saturation are employed as independent variables for prediction of effective TCs of sandstone. Various types of ANN such as multi-layer perceptron (MLP), radial basis function, generalized regression and cascade-forward neural network have been examined and their predictive capabilities are compared. Statistical errors analysis confirms that a two-layer MLP network with seven and 15 hidden neurons are optimal topologies for modeling of TC of oil saturated and dry sandstone, respectively. The predictive capabilities of the optimal MLP models are validated by conventional recommended correlation and a large number of experimental data which were collected from various literatures. The predicted effective TC values have a good agreement with the experimental TC data, i.e., an absolute average relative deviation percent of 2.73% and 3.81% for the overall experimental dataset of oil saturated and dry sandstone, respectively. The results justify the superiority of the optimal MLP networks over the other considered models in simulation of the experimental effective TCs of dry and oil saturated sandstones.

1. Introduction

The effective thermal conductivity is one of the most important thermo-physical properties of porous media which is often required for analysis of heat transfer in oil and gas bearing reservoirs. Heat transfer in porous media is concerned with three different phenomena: (1) thermal conduction through the solid as well as liquid bulks, (2) radiation across the pore spaces and (3) convection through the pore spaces. Importance of TCs data is essentially revealed during mathematical modeling and computer analysis of heat transfer through porous media, especially for reservoir thermal simulation. It can be said that the thermal conductivities have undeniable effects on the efficiency of the thermal recovery process. Importance of the effective thermal conductivities of dry as well as fluid-saturated porous materials in various scientific disciplines, e.g. petroleum and natural gas geology (Stalkup and Fred, 1983), underground thermal energy sources (Sasaki et al., 1987) and composite substances (Staicu et al., 2001; Gruescu et al., 2007), have been widely investigated.

Thermal conductivities of fluid-saturated sandstones often measure on remolded or reconstituted oil sand cores in normal environmental conditions, i.e. room temperature and atmospheric pressure. A designed transient state thermal test cell by Seto (1985) has been widely used to estimate the thermal conductivity of oil-saturated sandstone samples as a function of temperature, pressure and fluid saturation. Interested readers can obtain more detailed information about this apparatus and its analysis procedures in the works of Scott and Seto (1986) and Hepler and Hsi (1989). The transient state thermal conductivity cell has greatly reduced the undesired effects of thermal convection on the thermal conductivity and led to its more precise measurement.

Accurate measurement of the thermal conductivity of sandstones is a more time-consuming and difficult process. Moreover, the cost and expense of conducting properly replicated experiments prohibit the measurement of the thermal conductivity of a given rock over all of the desired temperature and pressure conditions. While accurate measurements of the thermal conductivity of sandstones are difficult, a number of attempts have been made in deriving some theoretical/empirical correlations to relate

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Nomenclature

AD	average deviation
AAD	average absolute deviation
ARD%	average relative deviation percent
AARD%	average absolute relative deviation percent
ANN	artificial neural network
b_j	bias of jth neuron
CFBNN	cascade-forward back-propagation neural network
CV	coefficient of variation
F	transfer function
$f(net_j)$	output of the neuron
GRNN	generalized regression neural network
k	effective thermal conductivity (W m^{-1} K^{-1})
$\bar{k}$	average value of the experimental effective TCs data (W m^{-1} K^{-1})
$k_i^{cal.}$	predicted effective TCs of the developed ANN model (W m^{-1} K^{-1})
$k_i^{exp.}$	ith experimental value of the effective TCs (W m^{-1} K^{-1})
Max (D)	maximum deviation
Min (D)	minimum deviation
MLP	multi-layers perceptron
MLPNN	multi-layers perceptron neural network
MSE	mean square error
N	number of experimental data points
n_j	output of jth neuron
P	pressure (Mpa)
RBFNN	radial basis function neural network
R^2	correlation coefficients
R^2_{adj}	adjusted determination coefficient
SD	standard deviation
T	temperature (K)
v	number of independent variables
x_r	entry information of each neuron
w_{jr}	weight from neuron r to neuron j
ρ	density of sandstone (g cm^{-3})
φ	porosity of sandstone (%)

thermal conductivity to more easily measured properties of the rock/fluid system.

The correlations which are proposed for modeling the thermal conductivity of sandstones can be categorized into two general types: (1) some of the empirical models are derived in such ways which relate thermal conductivity to other more easily measured physical properties through regression analysis of experimental data and (2) general theoretical models which have been developed based on the fundamental mechanisms of heat transfer through simplified geometries. Somerton (1992) has extensively reviewed these types of models and others have performed researches in these areas.

Similar to the laboratory measurements, the above-mentioned theoretical/empirical methods have also some drawbacks. These developed models may be appropriate only to a specific region of rocks being investigated and their application to different suites of rocks can lead to substantial errors (Zehner and Schlunder, 1970; Roufosse and Klemens, 1974; Özbek, 1976). Moreover various types of simplifications which are assumed in order to obtain a theoretical correlation often introduce some errors (Zehner and Schlunder, 1970; Roufosse and Klemens, 1974; Özbek, 1976).

It can be said that deriving a reliable and precise analytical correlation that can explain highly non-linear behaviors of effective thermal conductivity among more easily measured properties of the rock/fluid systems are often difficult and sometimes impossible.

In such cases where precise analytical or semi-experimental correlations are not available, other fast and more accurate black box models – which are generally based on the artificial intelligence techniques – such as artificial neural network seem very attractive. ANNs are popular and receive considerable interest because of their non-linearity, massive parallel connections, multiple input–output variables handling, no assumptions about the function form of the model and also their tolerance against noisy data (Hagan et al., 1996). In addition, the greatest advantage of an ANN approach is the elimination of complex equations and replacing them with some matrix and transfer functions (Vaferi et al., 2013).

Therefore in the present work a good deal of effort has gone into developing a systematic procedure based on ANN for the prediction of effective thermal conductivity of oil saturated and dry sandstone from more easily measured properties of the rock/fluid system, i.e. temperature, pressure, porosity, bulk density of rock, fluid density and oil saturation.

2. Artificial neural networks

Artificial neural networks are nonlinear learning mathematical approach which was widely utilized for data processing, process analysis and control, fault detection and pattern recognition (Hagan et al., 1996). ANN models were designed in the second half of the 20th century by mathematical simulation of the procedures on which the human nervous system works (Hagan et al., 1996). ANNs are generally categorized by feed-forward networks (Perceptron network), competitive networks (Hamming network) and recurrent networks (Hopfield network) (Haykin, 1999; Darwish et al., 2007).

The most widely used type of ANNs for solving the regression problem is the feed-forward network, particularly radial basis functions neural network (RBFNN), generalized regression neural network (GRNN), cascade-forward back-propagation neural network (CFBNN) and MLP (Petriciolet et al., 2010; Prasad et al., 2010; Elsayed and Lacor, 2012), which have been extensively used in various fields of science and engineering to date (Lashkarbolooki et al., 2011, 2012; Vaferi et al., 2011, 2013).

Broomhead and Lowe (1988) proposed the radial basis function network model. This network has a fast training process and can create a model with zero error on training vectors. The drawback of RBFNN is that it produces a network in which the number of its hidden neurons is equal to the number of its input vectors, and often introduces relatively high error in prediction of the testing dataset. A GRNN has a radial basis layer and a special linear layer and often used for function approximation. It has been shown that, given a sufficient number of neurons in the hidden layer, GRNN similar to RBFNN can also theoretically approximate a continuous function with a desirable precision (Marquez and Hill, 1993). Interested readers can find more details about RBFNN and GRNN in the work by Zhao and Su (2010).

CFBNN is a special type of back-propagation network which has more connections compared to the traditional feed-forward network. The first layer of this network has a weighted link coming only from the input layer whereas all of the other subsequent