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Modeling and analysis of the thermal conductivities of air saturated sandstone, quartz and limestone using computational intelligence

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ABSTRACT

Accurate experimental determination of the effective thermal conductivity (ETC) of porous reservoir rocks (especially under high temperature and pressure conditions) is a difficult problem and often a time-consuming and costly process. This study firstly examines the ability of the theoretical and empirical correlations for estimating the air saturated sandstone, quartz and limestone ETCs based on the models available in the literature. Optimal values of constant parameters of these correlations are found using the genetic algorithm (GA) technique. Empirical correlations have acceptable accuracy; however, they are not applicable in wide ranges of temperature and/or pressure. Also, each equation is dependent on the composition of the porous rock. In other words, they are not generalized correlations. The ability of artificial neural networks (ANN) and adaptive neuro-fuzzy inference system (ANFIS) as two generalized models are also investigated utilizing 872 experimental data points for a wide range of pressure and temperature. Temperature, pressure, porosity and bulk density are considered as the inputs of the mentioned models. An optimal topology of multi-layer perceptron neural network model (MLPNN) is determined via 10-fold cross-validation method. The total average absolute relative deviation (AARD (%)) of the developed ANN and ANFIS models for estimation of ETC are obtained 2.91% and 3.80%, respectively. The results show that the optimal ANN model is able to estimate ETC with the higher accuracy than the other correlations.

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1. Introduction

One of the thermo-physical properties of material which describes the ability of a bulk/body to conduct heat is thermal conductivity (λ). Effective thermal conductivity (λ_{eff}) is one of the significant parameters in porous media (for instance, petroleum and natural gas bearing reservoirs) which plays an undeniable role in analysis of heat conduction, evaluation of heat transfer rate and estimation of temperature distribution. λ_{eff} is also necessary for assessment of the thermal enhanced oil recovery processes efficiency as well as the calculation of heat lost using mathematical modeling and simulations. It should be noted that the magnitude of λ_{eff} for reservoir rocks, is a significant factor affecting the effectiveness of thermally recovery processes such as hot steam injection [1].

Estimation of the λ_{eff} of fluid saturated reservoir rocks is also useful in petroleum and natural gas reservoirs engineering for calculation and analysis of heat transfer, determination of optimal operating conditions for thermal oil and gas recovery enhancement, and investigation of phase behavior in fluid saturated porous media [2].

The λ_{eff} of fluid saturated porous rocks is a complicated function of various main and corrective parameters such as: temperature, pressure, porosity, density, mineralogical composition, fractional content of the components, grain size and shape, degree of cementation and thermal conductivity of solid matrix and orientation of crystals and their fragments [3]. The λ_{eff} of various porous materials are measured and reported by several research groups [4]. A number of experimental approaches and laboratory methods have been proposed for measurement of λ_{eff} [4,5] such as needle-probe; divided-bar; guarded hot plate; hotwire; optical scanning and parallel-plate methods. Also there are many burgeoning techniques for the determination of effective properties of porous materials; for instance, the use of 3D scanning (either destructive or non-destructive) and reconstruction methods which allow direct simulation of the effective thermal conductivity as a function of each individual phase properties [6]. Also, there have been many attempts to develop expressions for thermal conductivity of gravels and soils based on liquid content in granular media [7,8].

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Nomenclature

A	constant number
b_j	jth neuron bias
B	constant number
C	constant number
c	constant/Gaussian MFs center
D	constant number
E	constant number
F	constant number
g	activation (transfer) function
k	constant number
N	number of data points
n	number of hidden layer neurons
P	pressure (MPa)
T	temperature (K)
z_j	output from jth neuron
x_i	output signal from ith to jth neuron

Subscripts

eff	effective
f	fluid phase
intermed	intermediate
lat	lattice
max	maximum
min	minimum
rad	radiative
s	solid phase

Superscripts

Ave	average
Exp	experimental
Pred	predicted

Greek symbols

Ω	bulk density (g cm^{-3})
σ	constant/Gaussian MFs width
ρ	density (kg m^{-3})
φ	porosity
λ	thermal conductivity (W/m K)

Acronyms

AARD	average absolute relative deviation
ANN	artificial neural network
ANFIS	adaptive neuro-fuzzy inference system
BR	Bayesian regularization back-propagation
CGB	conjugate gradient back-propagation
ETC	effective thermal conductivity
GA	genetic Algorithm
GDA	gradient descent with adaptive learning rate back-propagation
MRE	mean relative error
MLPNN	multi-layer perceptron neural network
LM	Levenberg–Marquardt

Precise measurement of the λ_{eff} for porous saturated reservoir rocks in a laboratory is too difficult. It is also a time-consuming and costly problem especially under high temperature and pressure conditions. On one hand, the irregularity of the microstructure of porous media leads to complex mechanisms of heat transfer phenomena. On the other hand, even considering the same porous rock type, the reported λ_{eff} data available in the literature, may be varying over a remarkable range (up to 200% disparity) [3]. Therefore, finding an accurate method for estimation of λ_{eff} for porous reservoir rocks would be a significant valuable effort.

Extensive studies have been carried out for derivation of accurate correlations to calculate λ_{eff} as a function of more easily measurable properties of porous rock systems. These efforts have been conducted through three main approaches;

1.1. Mixing law models

The porosity of rocks is one of the most important factors, which significantly affects their mechanical and thermal properties. The relationship between λ_{eff} and porosity is not always completely understood. Mixing law models offer λ_{eff} as a function of solid thermal conductivity (λ_s), fluid thermal conductivity (λ_f) and porosity (ϕ) [9–17]. The detailed review of the correlating and estimating approaches for approximation of the λ_{eff} of gas and fluid saturated porous rocks dependent on porosity at constant temperature and pressure is available in Refs. [18,19]. Three basic forms of the mixing law models are listed in Table 1.

The Maxwell model [21] as the best modified form of these three basic formulations has been proposed as follows;

$$\lambda_{eff} = \lambda_f \left[\frac{2\phi\lambda_f + (3-2\phi)\lambda_s}{(3-\phi)\lambda_f + \phi\lambda_s}\right] \tag{1}$$

1.2. Full theoretical models

The full theoretical models have been developed based on the mechanisms of heat transfer and simplified geometries [4,18]. Thermal conductivity can be divided into two main branches; lattice conductivity and radiative conductivity. Lattice conductivity is produced by the propagation of thermal vibrations in a crystalline lattice and tends to be inversely proportional to temperature $\lambda_{lat}\ \alpha\ T^{-1}$ [22]. Several researchers have proposed $\lambda_{lat}\ \alpha\ T^{-5/4}$ for structurally perfect isotropic single crystals [23]. Rocks have different compositions. A large number of rocks are composed of crystal mixtures. Therefore, their lattice conductivity tends to decrease less than $\lambda_{lat}\ \alpha\ T^{-1}$ [4]. Radiative conductivity is produced by infrared electromagnetic waves and tends to be proportional to the cube of the temperature ($\lambda_{rad}\ \alpha\ T^3$) [22]. It should be noted that at temperatures below 880–980 K, radiative conductivity is negligible in comparison to lattice one [22].

Eq. (2) is proposed by Seipold (1998) for crystalline rocks [24];

$$\lambda_{eff} = (A + BT)^{-1} + CT^3 \tag{2}$$

The cubic term (CT^3) is considered to account the contributions of electromagnetic radiation [24]. Thermal conductivity of amorphous materials is proportional to absolute temperature ($\lambda\ \alpha\ T$) [25]. The following formula is suggested by Eucken [26] for λ_{eff} of mixtures of mixed crystals and amorphous substances;

Table 1
Basic mixing law models used for the correlation of the fluid saturated porous materials.

Mathematical forms of the models	References
$\lambda_{max} = \lambda_f\phi + \lambda_s(1-\phi)$; Arithmetic mean	[19]
$\lambda_{min} = [\phi/\lambda_f + (1-\phi)/\lambda_s]^{-1}$; Harmonic mean	[20]
$\lambda_{intermed} = \lambda_f^{\phi}\lambda_s^{(1-\phi)}$; Geometric mean	[20]

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