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A new screening tool for evaluation of steamflooding performance in Naturally Fractured Carbonate Reservoirs

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HIGHLIGHTS

▶ Steamflooding is studied through field data, PSO–ANN, and statistical approaches.
▶ Predictive tools are developed to predict steamflooding performance in NFCRs.
▶ PSO–ANN combines local and global searching abilities of ANN and PSO, respectively.
▶ Fracture permeability has a significant impact on the steamflooding performance.
▶ Reasonable agreement is observed between the predictions and experimental data.

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ABSTRACT

Appropriate production method selection for Viscous Oil (e.g., Heavy Oil, Extra Heavy Oil, and Bitumen) Naturally Fractured Carbonate Reservoirs (VO NFCRs) mostly depends on the quality of the fluid and reservoir properties. Selection of a particular production method for a reservoir is generally evaluated through an exhaustive experimental, field pilot, and mathematical modeling approach. In the absence of robust and quick predictive tools, using connectionist techniques for performance prediction of a particular production method can be a valuable asset. In this study, a new screening tool is developed based on Artificial Neural Networks (ANNs) optimized with Particle Swarm Optimization (PSO) to assess the performance of steamflooding in VO NFCRs. As expected, Recovery Factor (RF) and Cumulative Steam to Oil Ratio (CSOR) during steamflooding are highly affected by the magnitudes of oil saturation and viscosity. The developed PSO–ANN model, conventional ANN and statistical correlations were examined using real data. Comparison of the predictions and real data implies the superiority of the proposed PSO–ANN model with an absolute average error percentage < 6.5%, a determination coefficient (R^2) > 0.98, and Mean Squared Error (MSE) < 0.06, in contrast with conventional ANN model and empirical correlations for prediction of RF and CSOR. This indicates a great potential for application of hybrid PSO–ANN models to screen Viscous Oil carbonate reservoirs for steamflooding.

1. Introduction

Different types of carbonate rocks, mostly naturally fractured make up about 30% of the sedimentary rocks on the earth's surface. Also, they contain around 40–45% of the world's present proven conventional oil reservoirs [1] and above 20% of the world's Viscous Oil (VO) endowment (including Heavy Oil, Extra Heavy Oil, and Bitumen) [2–4]. The presence of VO in NFCRs is reported in many countries including Iran, Canada, the USA, Brazil, Congo, Turkey, Egypt, Russia, Oman, Kuwait, Saudi Arabia, China, India, Cuba, Italy, France, Algeria, Libya, Congo, and Mexico [4].

According to the U.S. Energy Information Administration (EIA) in their 2011 International Energy Outlook report, the global demand for liquid fossil fuels will increase from 85.7×10^6 b/d in 2008 to 112.2×10^6 b/d in 2035, mainly because of the growing world population and development of industrial sectors. This increase in global energy demand will be led especially by rapidly developing economies such as China and India [5]. It is also expected that by 2035, VO will make up about 17% of the daily world oil production, and this includes VO from NFCRs, as well. The current contribution of VO to the world daily oil production is about $9–10 \times 10^6$ b/d, almost all from sandstones [4,5]. Large VO deposits in carbonates (Fig. 1) are far less common and of lower porosity (usually $\phi < 20\%$) than VO sandstones; nevertheless, carbonates host about 2×10^9 b of VO worldwide.

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Nomenclature

Acronyms and abbreviations

2D, 3D	two or three dimensional
AI	artificial intelligence
ANN	Artificial Neural Network
ANOVA	analysis of variance
BP	Back Propagation
CSOR	Cumulative Steam to Oil Ratio
EIA	Energy Information Administration
EOR	Enhanced Oil Recovery
HO NFCR	Heavy Oil Naturally Fractured Carbonate Reservoir
HO	Heavy Oil
MAPE	maximum absolute percentage error
MEAE	mean absolute error
MIPE	minimum absolute percentage error
MSE	Mean Squared Error
NFCR	Naturally Fractured Carbonate Reservoir
NN	neural network
OOIP	Oil Originally In Place
PSO	Particle Swarm Optimization
RF	Recovery Factor
SD	Steam Drive
SF	Steamflooding
VO NFCR	Viscous Oil Naturally Fractured Carbonate Reservoir
VO	Viscous Oil
XHO	Extra Heavy Oil

Variables

P_g^t	best ever particle position of particle *i*
P_i^t	global best position in the swarm until iteration t
V_i^t	velocity vector at iteration t
°C	degrees celsius
°F	degrees fahrenheit
b	barrel of oil
c_1, c_2	acceleration coefficients (Eqs. (2)–(4))
D	Darcy
F	Produceability factor – kh/μ (mD-m/cP)
G	number of training samples
H	reservoir thickness
k	current iteration (Eqs. (2)–(4))
k	permeability (milliDarcy or Darcy)
K_f	fracture permeability (mD or D)
k_v, k_h	Permeability in Darcies, vertical, horizontal
m	meters
m	number of output nodes
mD	milliDarcy
MPa	mega pascal
n	number of samples
r_1, r_2	two random variables varying between 0 and 1 (Eqs. (2)–(4))
R^2	coefficient of determination
S_o	oil saturation (% or fraction)
S_w	water saturation (% or fraction)
T	temperature in °F or °C
T_j (*k*)	actual output
w_k	inertia weight (Eqs. (2)–(4))
X_i	position of the *i*-th particle
x_l, x_g	local best position and global best particle position (Eqs. (2)–(4))
x_s	steam quality (% or fraction)
Y_j (*k*)	expected output
z	depth in meters
z_i	overall composition of component *i*
λ	limiting factor (Eqs. (2)–(4))
v^k, x^k	vectors of real velocity and position, respectively (Eqs. (2)–(4))

Greek letters

ω	inertia weight
μ	dynamic viscosity (kg m/s or cP)
Δ	difference operator
ϕ	porosity

Subscripts

i	particle *i*
max	maximum
min	minimum

Superscripts

M	measured
net	Network
P	Predicted

Metric conversion factors

°F	(°C × 1.8) + 32
1 barrel oil	0.159 m^3
1 psi	6.8947 kPa
1 psi/ft	22.62 kPa/m or 22.62 MPa/km

In this paper, VO is defined as all types of oil with viscosity greater than 100 cP *in situ*. The crude oil is called Heavy Oil (HO) when the viscosity is in the range of 100–10,000 cP *in situ*, whereas Extra Heavy Oil (XHO) is crude oil with viscosity higher than 10,000 cP at thermodynamic reservoir conditions, but with a density over 1.0 g/cm^3. Finally, all crude oils having a viscosity higher than 10,000 cP *in situ* are referred to as Bitumen [2,6]. There is no universal definition for VO in the literature. For other definitions see Dusseault and Shafiei [6].

A quick look at the worldwide Enhanced Oil Recovery (EOR) surveys published in the Oil and Gas Journal during the last two decades shows that steam injection is the only commercialized viscosity reduction approach. Over 70% of the current VO production worldwide involves steam injection, and this dominance will continue into the foreseeable future [7–14]. Technologies required for economical VO production in NFCRs, particularly XHO and Bitumen, have major differences compared to conventional oil recovery methods. It is usually necessary to reduce the viscosity; in practice, this can be achieved by heating, diluting, reducing the molecular weight (usually pyrolytically), or a combination of these methods. Despite the immense resource size, a full-field commercial thermal production operation in VO NFCRs has not yet been reported. The application of thermal processes to VO NFCRs remains limited to very few vertical well steamflooding and cyclic steam stimulation field pilots in Canada, France, Italy, Turkey, China, the USA, Egypt, Syria, Congo, Kuwait, and Saudi Arabia [4]. To date, only primary cold production (e.g., Oman, Iran, Iraq, Kuwait, Saudi Arabia, Turkey, France, Italy, Cuba, Brazil, China, Russia, Congo, and Mexico) and CO_2 flooding (e.g., Turkey) have achieved some commercial success in accessing this immense energy resource [4].

Several experimental and mathematical models are reported for performance prediction of steamflooding processes in VO sandstones, and some of these are briefly mentioned here. For instance,