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Rigorous modeling of permeability impairment due to inorganic scale deposition in porous media

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ABSTRACT

Water flooding technique has widely been applied in oilfields aiming to augment the natural energy of the reservoir and displace the oil toward production wells. Deposition and accumulation of scaling minerals may occur in oilfields due to the incompatibility existing between foreign fluids injected into the medium and indigenous formation water. Deposition of these minerals in porous media may lead to severe permeability loss, formation damage and hydrocarbon production decline. This paper describes a modeling study representing permeability reduction due to scale deposition by employing an approach based on Least Squares Support Vector Machine (LSSVM) and Coupled Simulated Annealing (CSA), generally referred to as CSA–LSSVM. To this end, almost 1306 experimental data were assembled from the literature aiming to build a comprehensive and reliable model. Applicability of the CSA–LSSVM model was then evaluated in the range of data employed in this study and well accordance was observed between model predictions and experimental measurements yielding an overall correlation coefficient (R^2) 0.999. At the end, permeability reduction data gathered from the literature were analyzed for outlier diagnosis using the leverage statistical algorithm along with providing full details of the implemented method.

1. Introduction

Scaling problems have been accompanying the oil production since its early days of discovery and these issues have constantly been reported in oilfields around the globe. Owing to the importance of scaling phenomenon in petroleum industry and water treatment plants, several researchers have attempted to study the mechanism of scaling all aiming to predict, prevent or treat scale formation. Traditionally, scale deposition was looked upon as a problem occurring in valves, heaters, well tubing, surface and subsurface equipment (Yuan, 1989; Jamialahmadi and Muller-Steinhagen, 2008). In recent years, as water flooding techniques are being increasingly applied in petroleum industries, the incompatibility between injected water and indigenous formation water is being recognized as a menace to successful oil recovery. As a field example, incompatibility between commingling fluids in Iranian offshore Siri field caused a rapid depletion in injectivity of the reservoir from 9100 bbl/day to 2200 bbl/day in a six year period and finally water injection was terminated (Moghadasi et al., 2003b, 2002). Due to increasing demand of hydrocarbon production, there has been an upsurge of interest in understanding the mechanism of scaling and the permeability and porosity damage caused by scale deposition in oil reservoirs (Safari and Jamialahmadi, 2014b).

Water flooding is a popular oil recovery method used in oilfields aiming to augment natural energy of the reservoir and displace hydrocarbons toward production wells. During water flooding projects aqueous solutions, mostly sea water are introduced into underground reservoir, which contains hydrocarbons and excessive amount of brackish water. Sea water frequently contains sulfate and bicarbonate ions, while formation water holds an abundance of cationic components mostly calcium, barium and strontium ions. When these waters come into contact in the reservoir, precipitation of several inorganic minerals may occur as their sulfate and carbonate forms mainly due to

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Nomenclature

V_{inj}	volume of injected water, PV
$C_{Ba^{2+}}$	barium ion concentration in solution, ppm
$C_{Sr^{2+}}$	strontium ion concentration in solution, ppm
$C_{Ca^{2+}}$	calcium ion concentration in solution, ppm
$C_{SO_4^{2-}}$	sulfate ion concentration in solution, ppm
A^{η}	acceptance probability function
T_k^a	acceptance temperature
K_d	damage permeability, md
e_i	regression error
$K(x, x_i)$	kernel function
K_i	initial permeability, md
R^2	coefficient of determination
ΔP	differential pressure, psi
AARD	average absolute relative deviations, %
b	bias term
C	positive constant
CSA	Coupled Simulated Annealing
GA	genetic algorithm
H	Hat matrix
LSSVM	Least-Squares Supported Vector Machine
m	number of employed data
MSE	mean squared error
n	total number of model parameters
NO	number of training objects
PR	permeability ratio
Q	injection rate, cc/min
R	residual
RMSE	root mean square errors
S	set of all possible solutions
SA	simulated annealing
STD	standard deviation error
t	transpose
T	temperature, °C
w	nonlinear function
x	inputs
X	two dimensional matrix $(m \times n)$
y	outputs

Greek letters

σ^2	squared bandwidth
ψ	coupling term
η	subset of all possible solutions
α, β	Lagrange multipliers
μ	relative weight of the summation of the regression errors
ξ	slack variable
$\phi(x)$	mapping function

super-saturation in the media. Of all the scaling minerals widely encountered in oilfields, $CaCO_3$ and $BaSO_4$ have frequently been reported in North Sea offshore operations (Mitchell et al., 1980; Yuan, 1989). $BaSO_4$ and $SrSO_4$ are also known to form a completely complex mixture in the reservoir when the concentrations of both barium and strontium are high in formation water (Mitchell et al., 1980; Yuan, 1989; Todd and Yuan, 1992). Despite carbonate scales which are highly dependent on PH alterations and pressure changes, sulfate scaling minerals mostly occur as a result of temperature changes and incompatibility between commingling fluids (Safari and Jamialahmadi, 2014a, 2014b). A schematic view of an oilfield undergoing water flooding process is shown in Fig. 1.

A number of investigators conducted some laboratory experiments in an attempt to examine the effect of fluids incompatibility on scale deposition. Since this study is devoted to theoretical investigation of permeability loss and formation damage caused by scale deposition, some important experimental and theoretical studies are reviewed in the following, putting more stress on theoretical studies conducted so far.

1.1. Experimental studies

The earliest study on scale formation in subsurface environments was carried out by Weintritt and Cowan (1967). In their experiment, water was injected into a core previously saturated with formation water, but almost no deposition was found in the rock core after termination of the experiment (Yuan, 1989). This result was confirmed by Mitchell et al. (1980), and Yuan (1989) attributed their observation to the small amount of formation water mixed with injected sea water.

Effect of incompatibility of injected fluid and formation water on scale deposition was further investigated by Mitchell et al. (1980) and Read and Ringen (1982) through mixing artificial sea water and formation water in aluminum core plugs at 70 °C. Mitchell et al. (1980) conducted some laboratory experiments through mixing artificial North Sea water with formation water of Forties field using a core with six injectors at one end and one outlet at the other end attempting to simulate a production well. Deposition of scale and resultant permeability damage was reported in their work; however, the nature of scale deposits was not mentioned. Read and Ringen (1982) mixed sea water and North Sea formation water both in glass and in porous media to investigate the formation damage due to incompatibility of commingling fluids. The core samples were then examined by scanning electron microscopy (SEM) in order to find the nature of scaling crystals formed on rock surface. $(Ba,Sr)SO_4$ and $CaCO_3$ formation was confirmed by Read and Ringen (1982) in their experimental studies.

Further, Lindlof and Stoffer (1983) carried out some laboratory tests to investigate $SrSO_4$ and $CaSO_4$ salt formation in Arab-D oil reservoir, nevertheless, no measureable reduction in permeability was observed due to incompatibility effects and the only precipitate was found to be strontium sulfate under various mixing conditions. The $(Ba,Sr)SO_4$ solid solution scale formation was fully described by Yuan (1989) through conducting some laboratory experiments in bakers and multi-pressured tap cores at room temperature and at 70 °C. Several artificial formation and sea waters differing in their super-saturations of barium and strontium sulfate salt were mixed under both static and dynamic conditions. SEM was further carried out to investigate the morphology of the formed crystals and to identify the type of solid precipitates.

A comprehensive study of scale formation and formation damage was performed by Moghadasi et al. (2003b). They investigated the effect of incompatibility of mixing fluids on formation of calcium sulfate and carbonate scale in porous media. In their experiments, two solutions, one rich in calcium ion and the other rich in carbonate or sulfate ion were mixed under specified thermodynamic conditions. Further, theoretical and experimental studies were conducted by Moghadasi et al. (2004b) on permeability reduction due to deposition of $CaSO_4$ and $CaCO_3$ in porous media by mixing incompatible calcium rich and sulfate/carbonate rich solutions.

In recent years, Binmerdhah (2007) comprehensively studied the deterioration of permeability in sandstone cores as a result of