Fluid Phase Equilibria 399 (2015) 30–39

Contents lists available at ScienceDirect

Fluid Phase Equilibria

journal homepage: www.elsevier.com/locate/fluid

A rigorous approach to predict nitrogen-crude oil minimum miscibility pressure of pure and nitrogen mixtures

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ARTICLE INFO

Article history:
Received 22 February 2015
Received in revised form 5 April 2015
Accepted 6 April 2015
Available online 9 April 2015

Keywords:
Minimum miscibility pressure
Nitrogen
Lean gas
Genetic programming
Constrained multivariable search methods

ABSTRACT

Nitrogen has been appeared as a competitive gas injection alternative for gas-based enhanced oil recovery (EOR) processes. Minimum miscibility pressure (MMP) is the most important parameter to successfully design N_2 flooding, which is traditionally measured through time consuming, expensive and cumbersome experiments. In this communication, genetic programming (GP) and constrained multivariable search methods have been combined to create a simple correlation for accurate determination of the MMP of N_2-crude oil, based on the explicit functionality of reservoir temperature as well as thermodynamic properties of crude oil and injection gas. The parameters of the developed correlation include reservoir temperature, average critical temperature of injection gas, volatile and intermediate fractions of reservoir oil and heptane plus-fraction molecular weight of crude oil. A set of experimental data pool from the literature was collected to evaluate and compare the results of the developed correlation with pre-existing correlations through statistical and graphical error analyses. The results of this study illustrate that the proposed correlation is more reliable and accurate than the pre-existing models in a wide range of thermodynamic and process conditions. The proposed correlation predicts the total data set (93 MMP data of pure and N_2 mixture streams as well as lean gases) with an average absolute relative error of 10.02%. Finally, by employing the relevancy factor, it was found that the intermediate components of crude oil have the most significant impact on the nitrogen MMP estimation.

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1. Introduction

The reduction of oil production through primary stage has led to rapid development of variety of techniques and enhanced oil recovery (EOR) processes to extract the residual oil prior to abandonment of the reservoir [1]. Generally, EOR techniques are classified into thermal (such as steam or hot water injection) and non-thermal techniques (including water flooding, gas injection and chemical flooding). The former is primarily intended for heavy oils, while the latter is normally applied in light oil reservoirs [2]. Non thermal EOR techniques promote recovery by three main mechanisms: (i) achieving or approaching miscibility by solvent extraction (ii) interfacial tension (IFT) reduction between the displacing and displaced phases (iii) viscosity change of displacing and/or displaced phase. Some of the non-thermal enhanced oil recovery methods, such as polymer flooding, alkaline-surfactant-polymer (ASP) and alkaline flooding are expensive, and are also subjected to some operational restrictions, such as reservoir temperature and formation permeability [3].

Gas injection on the other hand, can improve oil recovery by oil viscosity reduction, oil swelling, interfacial tension reduction by mass transfer between displacing and displaced phases during condensing/vaporizing gas drive [4,5] (this phenomenon causes capillary force alleviation), and re-pressurization of reservoir. Gas injection technique in various forms consisting of hydrocarbon gas injection (including natural gas, enriched natural gas and a liquefied petroleum slug driven by natural gas) and non-hydrocarbon gas injection (such as carbon dioxide, nitrogen and flue gas) is widely used to diminish the residual oil saturation [3]. CO_2 injection is more preferred as it applies for two different purposes; improving oil recovery and CO_2 sequestration for reducing the greenhouse gases emissions. Different problems such as corrosion in the production wells and surface facilities, CO_2 separation from the saleable hydrocarbons, large requirement of CO_2 per incremental barrel, and asphaltene precipitation which causes formation damage and wettability alteration, etc., have been reported for CO_2 injection process [6–11].

Nitrogen or N_2-contaminated lean hydrocarbon gases injection are appropriate EOR processes for deep, high pressure reservoirs,

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http://dx.doi.org/10.1016/j.fluid.2015.04.003
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Nomenclature

E_i	Relative error, percent
E_a	Average absolute percent relative error, percent
E_r	Average percent relative error, percent
Interm	Intermediate component in crude oil including C2-C6, H_2S and CO_2, fraction
Max APRE	Maximum absolute percent relative error, percent
Min APRE	Minimum absolute percent relative error, percent
$MW_{C7}+$	Heptane plus fraction molecular weight
MMP	Minimum miscibility pressure, MPa
RMSE	Root mean square error
SD	Standard deviation
T	Reservoir temperature, K
T_{CM}	Average critical temperature of the injection gas, K
Vol	Volatile component in crude oil including C1 and N_2, fraction

with light or volatile oil that are rich in light and intermediate hydrocarbon components (C_2–C_5) due to their miscible displacement potential. The low cost, abundance and availability of Nitrogen are the most reported advantages for N_2 injection. Nitrogen is produced by cryogenic processes from air for a long time [12]. Nitrogen injection process is performed miscible or immiscible, depending on the injection pressure at reservoir temperature and oil composition. Miscibility is theoretically defined as the conditions at which there is no interface between displacing phase and reservoir oil [4]. In other words, two phases are miscible when a single phase fluid is produced after intermingling two fluids with each other at any ratio. The lowest operating pressure, at reservoir temperature, at which miscibility is achieved between injection gas and reservoir fluid is termed as the minimum miscibility pressure (MMP) [13]. One of the vital parameters to design an effective injection process is the minimum miscibility pressure. The MMP can be determined whether experimentally or theoretically. Slim tube, rising bubble apparatus (RBA) and the vanishing interfacial tension (VIT) technique are the most proposed experimental methods for the MMP determination, which are time consuming and expensive [14,15].

Generalized MMP correlations can be used for screening the gas injection projects before expensive experimental tests. Although there are several correlations for MMP estimation of pure and impure CO_2 injection, few correlations exist for N_2 and its mixtures. The accuracy of any MMP correlation strongly depends on the quality and range of independent parameters used to develop the correlation. Wisely selection of independent parameters (such as temperature, injecting gas properties, etc.) is the main factor to develop every MMP correlation.

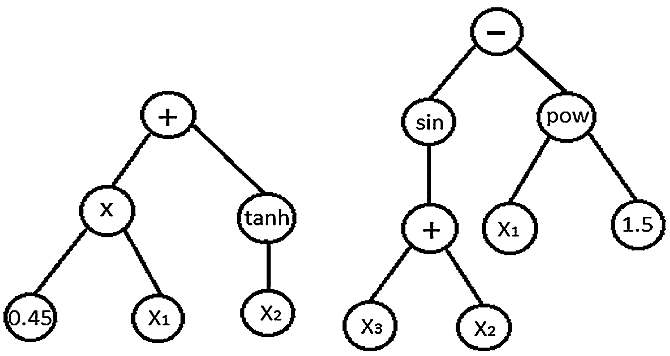

Fig. 1. Tree structure of a multi-gene symbolic model.

There are several correlations for MMP prediction of N_2 and lean gas flooding, including Glaso [16], Hudgins et al. [17], Hanssen [18], Sebastian and Lawrence [19], and Firoozabadi and Khalid [20], which have been developed based on the limited data points (less than 35 data sets) in a narrow range of reservoir temperature and crude oil composition. In addition, some of them (including: Hudgins et al. [17] and Sebastian and Lawrence [19] correlations) were developed for MMP estimation of pure N_2 injection which is not recommended for the real cases of impure N_2 or lean gases.

Artificial intelligent techniques have been widely used in chemical and petroleum industries to provide accurate estimation for the interested properties [21–25]. However, these intelligent models are black box and do not provide a clear relationship between the output of the model and affecting factors. Recently, genetic programming (GP), which produces a correlation (mathematical equation) between the output and influential factors, has been used in petroleum and chemical engineering to model some important properties [26–28]. To the best of the authors' knowledge, this methodology has not yet been employed for predicting MMP of pure and impure N_2 streams.

This work is aimed to develop a more accurate MMP correlation for pure and impure N_2 injection based on a comprehensive data bank, including 93 MMP data that covers a wide range of thermodynamic conditions and crude oil compositions. Previously published N_2 MMP models have been developed by a simple regression; however, in this study genetic programing approach is employed in order to find a good mathematical format for the MMP model. Since GP is time consuming, some other techniques can be utilized in order to speed up the model. Very recently, constrained multivariable search methods have been successfully applied to develop simple and accurate models for prediction of crude oil viscosity and PVT properties of crude oil systems [29,30]. However, in those models, the primary formats of the developed models have been obtained by a trial and error procedure. In the present

Table 1
Data sources and ranges used for developing MMP correlation in this study.

Reference	MWC_7^+	T (K)	T_{CM} (K)	Vol (fraction)	Interm (fraction)	MMP (MPa)
[20]	183.6–250	333.2–444.3	126.1–225.3	0.13–0.571	0.219–0.463	23.44–43.44
[16]	142–232	333.2–410.2	126.1	0.094–0.576	0.119–0.455	25–61.7
[17]	140	380.4–422	126.1	0–0.386	0.1167–0.1272	33.44–64.81
[19]	215–261	380.4–422.1	126.1	0.237–0.352	0.281–0.361	37.92–48.26
[31]	142–244	373.2–404	126.1–190.56	0.546–0.606	0.14–0.278	24.7–55
[35]	282	380.4–422.1	126.1	0.174	0.148	33.44–62.05
[32]	282	328.8–369.8	214.5–236.3	0.174	0.148	21.55–26.75
[33]	237–290	349.3–365.4	240.1–268.7	0.265–0.274	0.148	26.3–31.03
[34]	205.3–260.4	372.1–394.3	209-263	0.073–0.481	0.2412–0.6376	22.1–37.9
Total	140–290	328.8–444.3	126.1–268.7	0–0.606	0.1167–0.6376	21.55–64.81

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