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Numerical simulation of foam flooding in porous media in the absence and presence of oleic phase

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A B S T R A C T

This paper presents a novel integrated approach for numerical simulation of foam core-flood experiments in the absence and presence of oil. The experiments consisted of the co-injection of gas and Alpha-Olefin Sulfonate (AOS) surfactant solution into Bentheimer sandstone samples initially saturated with the surfactant solution [see Simjoo & Zitha (2013)]. The foam model implemented is based on a local equilibrium and describes dependency of foam mobility reduction factor using several independent functions, such as liquid saturation, foam velocity, oil saturation and capillary number.

First, a series of numerical simulation was conducted to investigate the effect of surfactant concentration on pressure drop across the core for the foam flooding in the absence of oil. To this end, the dry-out and gas velocity functions in the foam model were determined from the experimental data obtained at low and high-quality regimes of foam flow at a constant injection velocity. Next, pressure drop profiles of foam flooding at two different surfactant concentrations were modelled to determine the parameters of the surfactant-dependent function in the foam model. The simulation results fit the experimental data of pressure drops very well. Then, the numerical simulations investigated the oil displacement, by foam where the main goal was to determine the foam model parameters dedicated to the oil saturation-dependent function. The pressure drop across the core, oil-cut, and oil recovery factor were modelled, and an excellent match was obtained between the pressure profile and the oil recovery obtained numerically compared with those obtained from the corresponding core-flood experiments.

1. Introduction

Gas injection for enhanced oil recovery (EOR) suffers from poor sweep efficiency. Three reasons are associated with this deficiency of gas flooding: 1) segregation and gravity override due to the lower density of gas compared to oil and/or water, 2) viscous fingering due to high mobility ratio between injected gas and oil and/or water, 3) channelling through high-permeability streaks or layers in heterogeneous and layered reservoir [21]. Although not all the gas injection methods essentially lead to the poor oil recovery efficiency. The recent method of the Gas-Assisted Gravity Drainage (GAGD) process has a good sweep efficiency and higher recovery than Continuous Gas Injection (CGI) and Water-Alternative Gas (WAG) processes, in both immiscible and miscible modes [1].

Foam can improve the volumetric sweep efficiency by reducing gas mobility, providing a favourable mobility ratio and contacting a larger fraction of the reservoir to mitigate the effect of heterogeneity, gas segregation and viscous instability [26,9,37]. Design of the foam EOR process for field-scale application requires accurate prediction and description of foam behaviour in porous media with and without the oleic phase. Modelling of foam flow in a porous media can be categorized into two major methods: the local equilibrium with implicit texture (LE-IT) foam model, and the population balance approach. The LE-IT foam model assumes that a local steady state of foam dynamics in terms of creation and destruction of foam is reached instantaneously wherever gas and surfactant (as a foaming agent) coexist in porous media [28,3,25]. This model implicitly takes into account the presence of foam generation and coalescence through a mobility interpolation factor which depends itself on water saturation, gas velocity and other factors [6]. Application of LE-IT foam model for the field scale requires

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Nomenclature

SI units are assumed for all parameters used in calculations.

$\overline{C}_{f,W}^{ref}$	reference surfactant concentration
e_c	exponent of capillary number function,
e_o	exponent of oil effect function
e_s	exponent of surfactant-dependent function
f_w	constant of driving foam evolution
f_g	foam quality
F_1	surfactant dependent function
F_2	water saturation dependent function
F_3	capillary number dependent function
F_4	oil saturation dependent function
k	absolute permeability of rock for water phase
k_{rg}^{gas}	gas relative permeability in absence of foam
k_{rg}^{foam}	gas relative permeability in presence of foam
k_{rw}^{0}	endpoint of water for water/gas relative permeability
k_{rg}^{0}	endpoint of gas for water/gas relative permeability
M_{ref}	reference foam mobility reduction factor
n_w	exponent of water for water/gas relative permeability
n_g	exponent of gas for water/gas relative permeability
N_c^{ref}	reference capillary number
P_c^*	limiting capillary pressure
q_g	flow rate of the gas phase
q_l	flow rate of the water phase
S_{wc}	connate water saturation
S_{gr}	residual gas saturation
S_w^*	critical water saturation
S_O^*	critical oil saturation
u	total superficial velocity
∇p	pressure gradient
φ	porosity of rock sample
μ_{app}	Apparent viscosity of displacing fluid (foam)
σ_{wg}	surface tension between gas and surfactant solution

dependency of the model parameters upon the variety of geological properties of the reservoir, in particular permeability, porosity or fracture geometry in each direction [10]. The LE-IT empirical foam model is unable to model the correct foam density as a function of foam quality where the foam quality can vary in thick reservoirs based upon various factors such as permeability, pore size distribution etc.

The population balance approach describes the dynamics of foam generation and destruction where the foam mobility reduction is based on the bubble size and bubble density (foam texture) [19,18]. Although population balance model provides a comprehensive mechanistic description of foam flow in porous media, it requires many physical parameters which are not easy to determine for the field application. On the other hand, the empirical LE-IT model is more pragmatic and simpler for the field-scale simulation as it requires fewer simulation parameters and numerical difficulties and lower computational cost compared to the population balance model [16,27].

Much work in the literature has focused on the simulation of foam flooding in the absence of an oleic phase. Simjoo and Zitha [33] studied the transient foam flow in an oil-free porous media by using the stochastic bubble population model. The premise of this model is that foam flow in porous media is a complex fluid and bubble generation is a stochastic process. They obtained a good match between the numerically calculated fluid saturation and pressure data with those obtained from the experiments at which foam was generated by co-injecting nitrogen and alpha olefin sulfonate surfactant in Bentheimer sandstone. Boeije and Rossen [4] proposed a method to calculate the parameters of the water-saturation-dependent function and also shear-thinning function from the foam pressure gradient data at low and high-quality regimes at fixed total velocity. This method can provide the initial estimates for the foam model physical parameters to be used in the reservoir simulator for foam simulation at a large scale. Ma et al. [24] estimated the parameters of the water-saturation-dependent function to describe the dry-out effect in the absence of the oil phase. In their approach, shear-thinning behaviour at the low-quality regime of foam flooding was ignored.

Effect of permeability variation of porous media on the behaviour of foam flow in the absence of oil was studied experimentally and theoretically by Kapetas et al. [39]. They showed permeability can have a significant impact on the critical foam saturation such that the higher permeability layer exhibits lower critical water saturation (S_w^*). However, they did not come up with a robust correlation between the permeability and transition abruptness characteristic of the LE-IT foam model for the foam quality-scan experiments at different foam-flow regimes. Jones et al. [14] fitted the core-flood results of foam flooding without oil, for different surfactant concentration by the LE-IT foam model. To be able to predict the effect of the concentration on the foam apparent viscosity, they extend the model such that five foam parameters vary with surfactant concentration.

Lotfollahi et al. [23] presented a numerical model to simulate foam flooding in the presence of micro-emulsion phase. However, in this work no validation was given with respect to the experimental data. Similarly, Lashgari et al. [22] applied the black-oil model system coupled with the micro-emulsion phase behaviour model for simulation of low-tension gas flooding. They used the interfacial tension (IFT) reduction as the main factor to control the incremental oil recovery even though this mechanism in foam flooding does not always function. Therefore, most of the works in the literature have modelled foam flow in porous media either in the absence or the presence of oleic phase. On the other hand, many experimental data of foam flooding for EOR purposes have been reported [38].

Thus, this study aimed to investigate the application of LE-IT foam model for numerical modelling of foam flow in the sandstone rock for both in the absence and presence of an oleic phase. The foam model of Puma-Flow reservoir simulator (IFP Energies nouvelles) was used, which is similar to the foam model in CMG-STARS simulator (Computer Modelling Group Ltd., 2007). To this end, first the parameters of the dry-out and gas velocity functions in the foam model were determined by a least-square matching of the model to the experimental data obtained at low and high-quality regimes at a constant superficial velocity. Then, numerical simulations were conducted to investigate the effect of surfactant concentration on the pressure drop across the core sample for the core-flood laboratory data of foam flooding in the absence of oil. Thereafter, the effect of oil on the modelling of foam flooding was elaborated by fitting foam parameters to experimental data of the foam flooding in the presence of oil. The structure of this paper is as follows. First, we describe the main features of the foam model used in this study. Next we present an overview of the experimental study on foam flooding in sandstone porous media with and without oleic phase. The paper proceeds with the simulation results obtained from numerical modelling of the experimental data, and finally the main conclusions are drawn.

2. Theoretical description of LE-IT foam model

Features of local equilibrium and implicit-texture (LE-IT) foam model, in the PumaFlow simulator (in-house reservoir simulator of IFPEN), are described as follows. Reduction of gas mobility due to presence of a foaming agent is assigned to the relative permeability function, while gas-phase viscosity is assumed unchanged no matter whether a foaming agent is present or not. The relative permeability