



Uncertainty Quantification of Buckley Leverett Equation with Oil Viscosity as Random Variable

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Reservoir simulation is an important but tough task in the petroleum sector. Reservoir properties (rocks and fluids) exhibit uncertainties in their values thus, quantification of uncertainty of reservoir prediction models becomes a necessity. In this paper, an application of uncertainty quantification has been carried out using the Buckley Leverett model for two-phase immiscible flow in porous media considering the randomness of oil viscosity in the model. Based on the Monte Carlo method for uncertainty quantification, we use a finite volume scheme to obtain the deterministic solution. Our solutions revealed that water saturation during water flooding process for secondary oil recovery can be affected by randomness of oil viscosity.

Keywords: Buckley leverett; uncertainty quantification; monte carlo; finite volume.

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1 Introduction

Scientific computer simulations help to design complex engineering systems and saves time and money when compared to building prototype models for the study of such systems. Some areas of application include automobile engines, aerospace engines and reservoir systems. This advanced technology has played a major role in the oil and gas sector. The petroleum sector for example has enjoyed the application of computer simulation in the discovery and recovery of petroleum resources in subsurface reservoirs. But, the possibility of predicting the performance of complex systems through computer simulations with 100% certainty is not obtainable [1] thus, there is the need to carry out uncertainty quantification of prediction models to improve on the prediction confidence of such models.

Uncertainty quantification is the science of quantitative characterization and reduction of uncertainties in mathematical models and real-world systems. Uncertainty quantification characterizes the proximity between predictions and observations of real systems through methods that connects computational models and their true physical systems simulated by the models [2]. This area of study deals mostly with detailed complex models of physical systems with limited experimental or observed data [3]. A well defined problem in uncertainty quantification must have a system's mathematical model with special interest in a given quantity subject to uncertainties from the model parameters, boundary values, initial values or both boundary values and initial values which are handled probabilistically in most cases. Uncertainty quantification has being applied in many real world systems with random behaviours, some of these include space weather predictions with atmospheric drag as the main source of uncertainty [4]. Atmospheric weather and climate prediction where initial condition and model formulations are seen as main sources of uncertainties, [5]. Climate modelling and projection [6]. Building performance simulation of structural engineering systems with uncertainties in input parameters of model [7], Building energy assessment with both model form and parameter uncertainties [8], aircraft structures [9]. Machine learning for space weather prediction with uncertainty in dataset and input parameters [10], stock and bond market with uncertainties in stock volatility and abnormal stock turnover [11]. Cardiovascular application models in Medical sciences, [12] as well as Reservoir models with uncertainties in permeability and other fluid parameters [13]. Isobo et al. [14] investigated the effect of random thermal conductivity on the temperature profile of a copper material with Monte Carlo method with different heat transfer time periods.

1.1 The Buckley Leverett equation

The Buckley Leverett equation [15] describes the flow of two immiscible and incompressible fluids in a horizontal and homogeneous porous medium. The equation stated as

$$\frac{\partial \mathbf{S}}{\partial t} + \nabla \cdot \left(\frac{q}{A\phi} f(s) \right) = 0 \quad (1)$$

is a nonlinear first order partial differential equation and solutions are mostly obtained through numerical methods though analytical solutions do exist with strong simplifying assumptions [16]. The buckley Leverett equation represents the simplest form of material balance in reservoir engineering using water flooding for secondary oil recovery. Flow in porous media occur under uncertain conditions and prediction results exhibit uncertainties due to the fact that data for both reservoir and fluid properties are difficult to obtain at reservoir conditions [16]. Thus, there is the presence of parameter uncertainty from predictions made out of the use of such data for model predictions.

Many researchers have studied the Buckley Leverett equation since its introduction in 1954 by Buckley and Leverett. Langtangen et al. [17] studied the simultaneous one-dimensional flow of water and oil in a heterogeneous medium modeled by the Buckley-Leverett equation. A variety of heterogeneity profiles were studied with Buckley-Leverett method by Chang and Yortsos [18] where it was shown that Capillary heterogeneity significantly affects the saturation distributions, which closely follow the heterogeneity variation. Frid [19] solved the initial boundary-value problem for the regularized Buckley-Leverett system, which described the flow of two immiscible incompressible fluids through a porous medium Siddiqui et al. [20] investigated the validity of the three-phase extension of the Buckley-Leverett theory experimentally using three immiscible liquids. Method of

characteristics (MOC) solutions to the threephase BuckleyLeverett problem was presented with and without gravity by Guzman and Fayers [21]. Terez and Firoozabadi [22] examined water injection in water-wet fractured porous media and its modeling using the Buckley–Leverett theory. A stochastic analysis of immiscible two-phase flow with Buckley–Leverett displacement was presented in heterogeneous reservoirs by Dongxiao and Tchelepi [23]. Kaasschieter [24] derived an entropy inequality from a regularization procedure, where the physical capillary pressure term is added to the Buckley-Leverett equation. An extension of the Buckley–Leverett (BL) equation describing two-phase flow in porous media was discussed by Van et al. [25]. Mustafiz et al. [26] used a semi-analytical technique and the Adomian decomposition method (ADM) to unravel the true nature of the one-dimensional, two-phase flow. Sumnu-Dindoruk and Dindoruk [27] solved the resulting nonisothermal two-phase convective flow equation in porous media analytically, including a tracer component. Chemetov and Neves [28] proposed a new approach to the mathematical modeling of the Buckley–Leverett system, for describing twophase flows in porous media. Wang and Kao [29] extended the second and third order classical central schemes for the hyperbolic conservation laws to solve the modified BuckleyLeverett (MBL) equation which is of pseudo-parabolic type. Wang and Kao [30] numerically verified that the convergence rate is consistent with the theoretical derivation by BuckleyLeverett (BL) equation. Larsen et al. [31] examined the relationship between backflow of water from the invaded zone and changed in skin owing to reduced water saturation and the associated change in mobility for homogeneous reservoirs with Buckley-Leverett methods.

For more rigorous investigations, stochastic variables were introduced into the Buckley Leverett equation leading to the stochastic Buckley Leverett equation. Cedric and Hamdi [32] used the parameterized physics informed neural network approach to quantify uncertainties in reservoir engineering problems with random porosity and permeability. A machine learning based hybrid multifidelity multilevel Monte Carlo method was applied by Nagoor and Ahmed [33] to quantify uncertainty in a stochastic BLE with random permeability. Valdez et al. [34] used polynomial chaos method to study the effect of input uncertainties for different random permeability models. Fagerlund et al. [35] investigated failure probabilities with random permeability using Monte Carlo method. A bayesian framework for UQ was introduced by James et al. to handle uncertainties from random viscosity ratio and permeability field. A random time dependent flux function was proposed by Wang et al. [36] which the approached with their proposed cumulative distribution function method. Fayadhoi et al. [37] considered random porosity and permeability and proposed the frozen streamline distribution method for uncertainty quantification.

To the best of our knowledge, no one has considered investigating uncertainty introduced into the Buckley Leverett equation due to randomness of a particular type of oil viscosity, most especially, the bonny light crude produced from the southern part of Nigeria.

In this study, we apply the Monte Carlo simulation method for uncertainty quantification to a subsurface reservoir model, the Buckley Leverett equation, which describes the flow of two immiscible fluids in a horizontal channel. Our aim is to investigate the effect of the randomness of viscosity of oil on the saturation profile of water during secondary recovery process of crude oil in a reservoir system. Our objectives include the formulation of a stochastic Buckley Leverett equation with water saturation as quantity of interest, characterization of the random parameter to obtain its probability distribution for the propagation of uncertainty into the system and quantification of the uncertainty of the results through Monte Carlo method [38]. The rest of the paper has problem formulation followed by the method of solution, results presentation and discussion and ends with conclusion.

2 Problem formulation

Given the model in equation (1), for horizontal flow with negligible capillary pressure (Wang et al, 2013) fractional flow of water is given as

$$f_w(S) = \frac{1}{1 + \frac{K_{ro}\mu_w}{K_{rw}\mu_o}} \quad (2)$$

where, $f_w(S)$ is fractional flow of water phase which is a function of saturation, K_{ro} is the relative permeability of oil, K_{rw} is relative permeability of water, μ_w is viscosity of water and μ_o is viscosity of oil.

The basic assumptions [36] are

1. the two fluids are immiscible and incompressible
2. Fluid flow is in one dimension (horizontal)
3. Negligible capillarity and gravitational effect
4. Homogeneous rock formation
5. Constant viscosity of water
6. uniformly distributed random viscosity of oil
7. Water is injected from left at $x = 0$ at constant rate

Based on assumption number 6, equation (1) becomes a stochastic equation with final form in one dimension given as

$$\frac{\partial S_w}{\partial t} + \frac{q_T}{A\phi} \frac{\partial f_w(S)}{\partial x} = 0 \quad (3)$$

with initial and boundary conditions given as

$$\begin{aligned} S_w(x, 0) &= 0 \\ S_w(0, t) &= 1 \\ \mu_o &\sim U[1, 2.94] \end{aligned}$$

where q_T is the total flow rate, A is the cross sectional area of core sample and ϕ is the porosity of the medium.

We applied the Monte Carlo method for uncertainty quantification Fagerlund et al. [35]. We used the finite volume method to obtain a numerical scheme for the deterministic solution for each random variable.

First, we adopt the Power law representation of the relative permeabilities, see Nwaigwe and Sudi [39] and Holden and Risebro [40] for more details.

$$k_{rw}(S) = S_w^2 \quad (4)$$

giving us the flux function as

$$f_w(S) = \frac{S^2}{S^2 + \left(\frac{\mu_w}{\mu_o}\right)(1 - S)^2} \quad (5)$$

The finite volume numerical scheme.

Given the differential form of the model

$$\frac{\partial S_w}{\partial t} + \frac{v}{\phi} \frac{\partial f_w(S)}{\partial x} = 0 \quad (6)$$

We convert to the integral form

$$\frac{\partial}{\partial t} \int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} S dx + \frac{v}{\phi} \int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \frac{\partial f_w(S)}{\partial x} dx = 0 \quad (7)$$

We discretize the time and space variables as

$$\frac{\Delta x}{\Delta t} (S_i^{n+1} - S_i^n) + \frac{v}{\phi} [f^n(S_{i+\frac{1}{2}}) - f^n(S_{i-\frac{1}{2}})] = 0 \quad (8)$$

which gives us

$$S_i^{n+1} = S_i^n - \frac{v}{\phi} \frac{\Delta t}{\Delta x} [f^n(S_i^n, S_{i+1}^n) - f^n(S_{i-1}^n, S_i^n)] \quad (9)$$

Which was implemented with the FV solver (Nwaigwe, 2016) [41]. For every viscosity value generated from the uniform distribution, to account for the randomness of viscosity of Bonny light crude oil, we compute a deterministic solution for the quantity of interest. This process propagates uncertainty into the model. Thus, for all the random values of the viscosity of oil generated, we get a collection of solutions and by the Monte Carlo method, we take the ensemble average.

$$\bar{S} = \frac{1}{N} \sum_{j=1}^N S_j(x, t) \quad (10)$$

where N is the total number of random values generated for a solution at each point. Our final solution is the distribution of the mean saturation of water over the spatial domain $x \in (0, 1)$ for particular time steps. the variance is given as

$$\sigma_S^2 = E[(S - \bar{S})^2] = \frac{1}{N} \sum_{j=1}^N (S_j - \bar{S})^2 \tag{11}$$

The input parameter dataset is as given in the table below

Table 1. Reservoir data from Nembe well 01

parameter	value
porosity	0.3
velocity($\frac{qw}{A}$)	0.5
μ_w	1
μ_o	U[1, 2.94]

3 Results

Given the dataset and the finite volume scheme, we carry out our numerical experiment for 150 random variables at every point on the spatial domain. Our results for the uncertainty quantification problem are the mean and variance of the stochastic solutions. We compute means and corresponding variances and present our results graphically below.

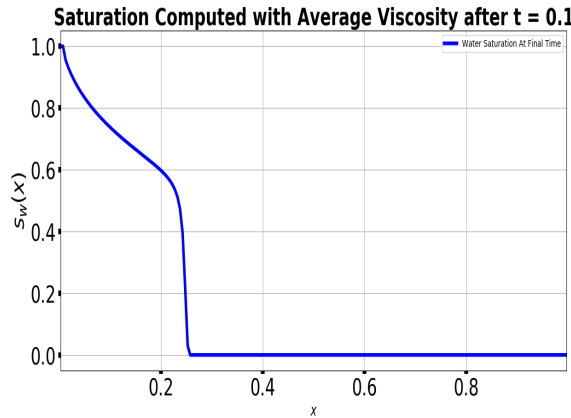


Fig. 1. Deterministic solution’s saturation distribution after 0.1 time units

At the left boundary, saturation of water is 100% that is at ($x = 0$) while saturation of oil in the reservoir is also 100%. As water is injected into the reservoir at a given constant velocity, it displaces the oil gradually which reduces the saturation of oil in the reservoir. As time increases, we experience an increase in water saturation in the reservoir as the saturation of oil continues to decrease. From our results, Fig. 1 to Fig. 3 show the solution of the deterministic model as time increases. The result showed that after 0.1 seconds water has flooded the reservoir up to a distance of 0.26 unit distance with a saturation of about 0.6%. We note here that the deterministic solution gives an exact value of the saturation at any given distance and time. Our deterministic solution also follows the physics of the water flooding process which explains the correctness of our method for the Buckley Leverett equation.

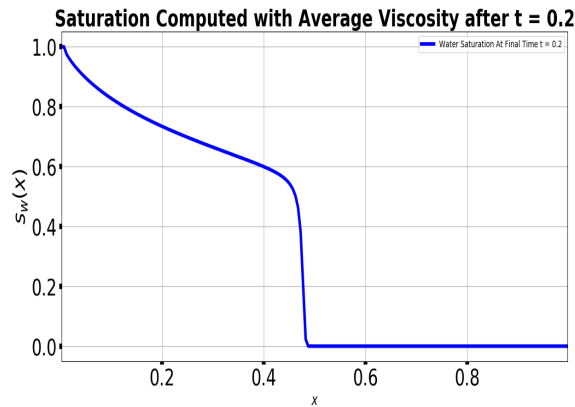


Fig. 2. Deterministic solution's saturation distribution after 0.2 time units

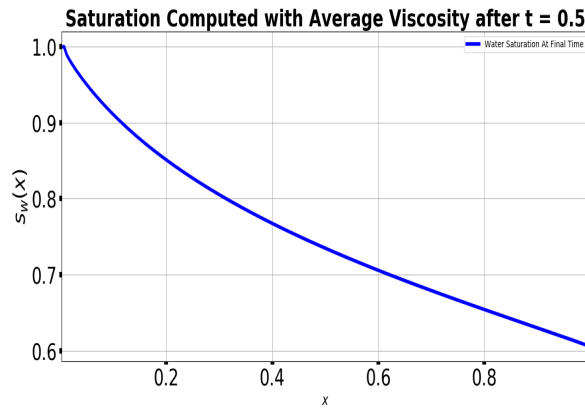


Fig. 3. Deterministic solution's saturation distribution after 0.5 time units

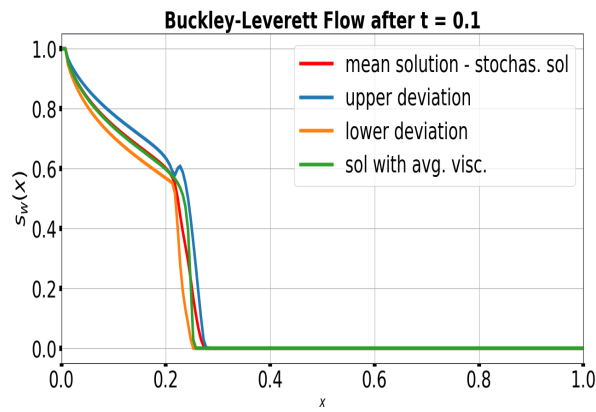


Fig. 4. Stochastic solution's saturation distribution after 0.1 time units

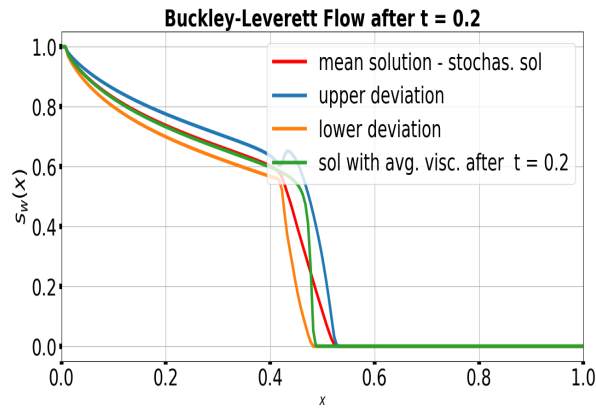


Fig. 5. Stochastic solution's saturation distribution after 0.2 time units

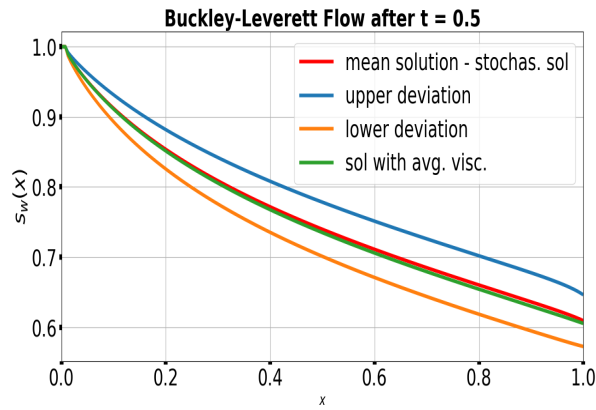


Fig. 6. Stochastic solution's saturation distribution after 0.5 time units

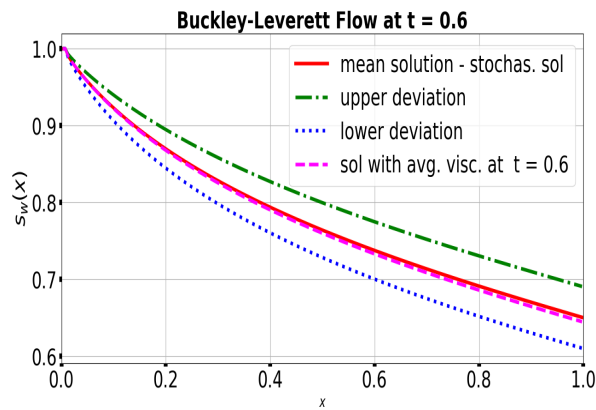


Fig. 7. Stochastic solution's saturation distribution after 0.6 time units

Fig. 4 to Fig. 6 show the results for the stochastic Buckley Leverett equation for the given data presented in table 1. We used random numbers generated from the uniform distribution to capture the uncertainties from the random viscose parameter giving rise to input uncertainty and a further random response. We take the mean and variance as statistics of the collection of random response following the Monte Carlo method. Our plots show the mean distribution at various times and the deviations from the mean to obtain the region of possible solutions due to uncertainty from the viscosity of oil. From our results, we can see after 0.1 seconds a mean water saturation of 0.6% with a deviation of $\pm 0.05\%$ thus, we can expect a saturation of 0.58% as well as saturation of 0.64% after 0.1 seconds. As time increases, we also see an increase in the range of water saturation between the upper and lower deviations from the mean distribution.

The exact solution from the deterministic model and the mean solution from the stochastic model when compared have only little difference over all the time considered. This may be as a result of the randomness of the oil viscosity used in the stochastic model. While the deterministic result gives an exact value for the problem, the stochastic result gives an average value and a range of expected values around the average. This is a major advantage of considering a stochastic model because in real life we can never be too certain with events. The stochastic model gives us probabilities of outcomes so that we can have a range of possibilities of results in our experiments, we can be properly guided by the statistics of our random responses.

4 Conclusion

In this research, uncertainty quantification of the Buckley Leverett model has been carried out using data from properties of the bonny light crude oil and its reservoir, specifically Nembe well 01 in the southern part of Nigeria. We have used the viscosity of the bonny light crude oil as the source of uncertainty in the Buckley Leverett equation to observe its effect on water saturation during secondary oil recovery process.

We were able to use the finite volume method which was implemented with the FV solver for a deterministic solution through which we propagated uncertainty into the model and used the Monte Carlo method to quantify the uncertainties. Our solutions, mean and variance of water saturation, were presented graphically and showed the effect of randomness of the oil viscosity on the saturation profile of water in the subsurface reservoir during water flooding process. This result can be used by petroleum engineers to observe fluctuations in production rates due to randomness of oil viscosity, since viscosity aids the speed of fluid flow.

We have been able to apply the theories of uncertainty quantification to real time data in this research. The research is the first to use the FV solver for the purpose of quantifying uncertainty with Monte Carlo method. Further studies can be done by increasing the number of random parameters in the governing equations as well as the increase in the dimension of the flux function for more rigorous mathematics. Data from other production wells can also be used for the purpose of results comparison.

Competing Interests

Authors have declared that no competing interests exist.

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