Study of relative permeability variation during unsteady flow in saturated reservoir rock using Lattice Boltzmann method

Étude de la variation de la perméabilité relative au cours d'écoulement transitoire dans une roche réservoir saturée en utilisant la méthode des réseaux de Boltzmann

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ABSTRACT: The importance of relative permeability coefficient on the productivity of oil reservoirs is well-known in Petroleum Geomechanics. Relative permeability is one of the main macroscopic parameters that heavily influence the two-phase flow regime in saturated porous rock which governs the rate of oil extraction from the well. In this study the dominant mechanisms of the flow of two immiscible fluids (water and oil) in porous media have been studied at the pore scale by using a developed simulator based on Lattice-Boltzmann Method. The validity of the numerically-derived relative permeability values demonstrate the capability of Lattice Boltzmann Method in modeling the complicated pore scale phenomena encountered in petroleum geomechanics.

RÉSUMÉ: L'importance du coefficient de perméabilité relative pour la productivité des réservoirs est bien connu en géomécanique pétrolière. La perméabilité relative est l'un des principaux paramètres macroscopiques fortement influençant le régime d'écoulement bi-phasique dans des roches poreuses saturées qui régit le l'extraction du pétrole. Dans cette étude, les mécanismes dominants de l'écoulement de deux fluides non miscibles (eau et huile) dans les milieux poreux ont été étudiés à l'échelle des pores en utilisant un simulateur développé sur la base des réseaux de Boltzmann. La validité des valeurs numériquement obtenues pour la perméabilité relative démontre la capacité de la méthode des réseaux de Boltzmann pour la modélisation des phénomènes complexes rencontrés à l'échelle des pores en géomécanique pétrolière.

KEYWORDS:Relative Permeability, Lattice Boltzmann Method, Steady/Unsteady Flow, Petroleum Geomecahnics

1 INTRODUCTION

Relative permeability is an essential petro-physical property required for description of multi-phase flow in petroleum reservoirs. It is a direct measure of the ability of the porous medium to produce one fluid when two or more fluids are present. This flow property is the result of the composite effects of porosity, pore geometry, wettability, saturation history, reservoir temperature, reservoir pressure, overburden pressure, and rock type. The relative permeability curves are very important in the study of reservoir productivity. They are used in predicting production rate and recovery from the reservoirs during all recovery stages (primary, secondary, and tertiary).
Briefly, there are two basic approaches for determination of relative permeability curves from laboratory core flow tests: steady and unsteady state methods. In the steady-state method, the fluids are injected simultaneously into core plugs. In the unsteady-state method, a fluid is injected to displace another fluid present in the core. Steady-state test data processing is relatively simple, but the experiments are tedious and lengthy, because attaining steady state fluid saturations within the core requires long times, in the order of hours, following the initiation of tests under certain fluid injection rates. In contrast, unsteady-state laboratory tests can be performed rapidly and the tests better represent the real physics of the phenomenon. However, recording of a number of parameters are not possible during the experiment and also data interpretation is a much more difficult task. In both methods, data processing is further complicated unless fluid displacement rates are sufficiently high to minimize the core inlet and outlet capillary end-effects. Details on each technique are covered in Keehm et al. (2004), and Ramstad et al. (2011).

Recently, pore-scale numerical modeling has emerged for simulation of fluid flow through porous media. The main advantage of such models is incorporating the micro-scale processes that control the large-scale phenomena. Fluid/fluid and fluid/solid interactions are examples of such processes that have significant effects on the flow regimes.

A recently developed computational fluid dynamic method which is ideal for simulating fluid flows in complicated geometries such as porous media at the pore scale is Lattice Boltzmann Method (LBM) (Chen & Doolen, 1998). LBM is suitable for modeling intricate fluid flow problems such as multiphase flow in complex structures. LBM was applied to flow through porous media soon after its emergence in 1989 (Succi, 1989). Considerable growth of its application in modeling multiphase flow through porous media mainly origins from its algorithm simplicity and accuracy in handling irregular flow paths, modeling the behavior of fluid/fluid interfaces and simulation of fluid/solid interactions (e.g. Chen & Doolen 1998; Pan et al. 2004; Schaap et al. 2007).

In this study a 2D LBM-based numerical code is developed which is capable of modeling steady-state and unsteady-state flow of two immiscible fluids through porous media. After validation of the code by some benchmark problems, a well-documented experimental work was simulated by the developed model.

2 LATTICE BOLTZMANN METHOD

The most popular LB model is the Bhatnagar–Gross–Krook (BGK) model (Chen et al. 1992) with a standard bounce-back (SBB) scheme for fluid–solid boundaries. However, some problems have encountered difficulties with this popular method. In BGK method the collision operator is approximated by a single-relaxation-time (SRT) approximation, which has some defects such as numerical instability and viscosity dependence of boundary locations, especially in under-relaxed situations (Qian et al. 1992). The viscosity dependent boundary

conditions pose a severe problem for simulating flow through porous media because the intrinsic permeability becomes viscosity dependent, while it should be a characteristic of the physical properties of porous medium alone. The deficiencies inherent in the BGK model can be significantly reduced by using a multiple-relaxation-time (MRT) approach (He et al. 1997), which separates the relaxation times for different kinetic modes and allows tuning to improved numerical stability and accuracy. In this study we used D2Q9 MRT as they were introduced by Lallemand and Lue (2000), Extensive details can be found in Lallemand and Lue (2000), and Li et al. (2005).

The Lattice-Boltzmann method for single-phase flow describes fluid flow as collisions of mass particles in a lattice (Chen et al., 1992). In two-phase flow, we follow almost the same procedures as in the single-phase case, except that we have two different types of particles representing two immiscible fluids, and we need to calculate surface tension and wettability. There are several popular Lattice Boltzmann (LB) techniques for the analysis of multiphase flows, three of which are the methods of Gunstensen et al. (1991), Shan & Chen (1993), and free energy approach by Swift et al. (1996). All three methods have been employed in numerical researches and each one has its distinct advantages. A review of these methods can be found in Nourgaliev et al. (2003). Among all of these LBM models, Shan & Chen's model (SC model) is widely used due to its simplicity and remarkable versatility. It can handle fluid phases with different densities, viscosities and wettabilities, and handle different equations of state as well. In this study, the multi-component (2 fluids) single phase version of SC model has been applied (Sukop &Thorne, 2006).

3 VERIFICATION

In multi-component LB models, the bubble test is often conducted to check the ability of the model in relating the pressure difference (Δp), radius of curvature (R) and interfacial tension (γ) together in the situation that a bubble of one fluid is immersed in another fluid, which should indicate that Δp varies linearly with respect to curvature $1/R$ based on the well-known Laplace law:

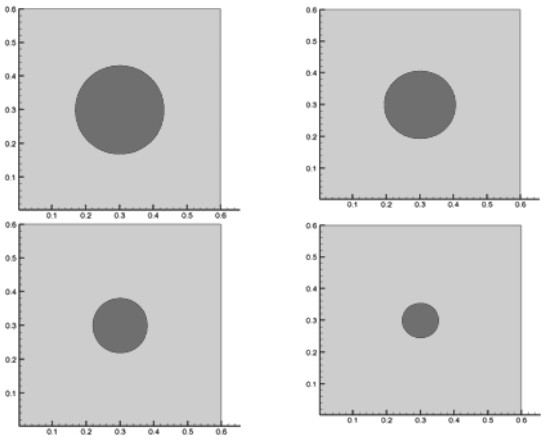
$$p_{in} - p_{out} = \gamma / R \quad (1)$$

Four different sizes of bubbles (Figure 1) are used for the numerical experiments. Figure 1b shows the capillary pressures for four different bubbles. The theoretical prediction is shown as a solid line. The simulated values (symbols) are obtained by simply calculating pressures inside and outside the bubbles at the end of the numerical simulations. The numerical results show very good agreement with the theoretical values.

Another well-studied model of immiscible displacement, the so-called pore doublet model, is a little more complicated. A typical pore doublet consists of two tubes with different diameters, joined at both ends (Figure 2). Since the capillary pressure is inversely proportional to the radius of the tube, the capillary pressure of the smaller tube is greater than that of the bigger tube. Drainage-type snap-off occurs when the external pressure gradient is big enough to overwhelm the capillary pressure of the bigger tube, but is not big enough for the smaller tube. Theory and laboratory experiments show that under this condition the wetting phase in the smaller tube is trapped, while that in the bigger tube it is replaced by the non-wetting phase (Lenormand et al., 1983). Figure 2show that the two-phase Lattice-Boltzmann method successfully replicates the drainage-type snap-off, which tells us that the method accurately describes capillary pressure phenomena of porous media. If the displacing fluid is wetting, then both tubes will be swept out by the wetting fluid (figure 2.b)

4 RELATIVE PERMEABILITIES

One of the most comprehensive sets of experimental works regarding relative permeability was pursued by Payatakes and his co-workers (Valavanides et al. 1998, Tsakiroglou et al. 2007) who performed experiments on the steady and unsteady flow regimes in porous core consisting of a chamber-and-throat network. Here, both steady and unsteady states experiments of Payatakes were selected for evaluation of the results of the developed LBM model. The dimensions of their specimen is 0.16 ×0.11 m, and its absolute permeability is k = 8.9 μm^2. The distance between the centers of the adjacent chambers is 1221 μm, the mean throat depth is 116.6 μm, and the mean throat width is 167.5 μm.



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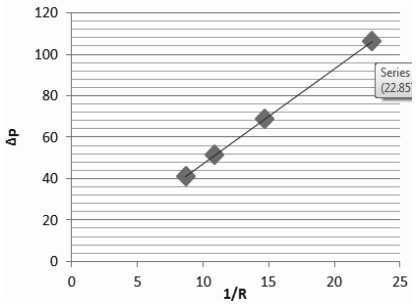

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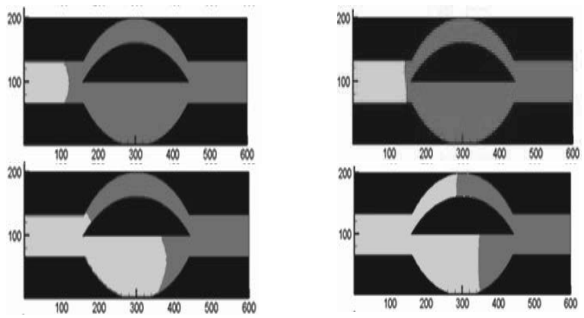
Figure 1. (a) Four different sizes of bubbles in steady-state condition (b) capillary pressure vs. reciprocal of bubble radius. Simulated values (symbols) agree well with the theoretical prediction (solid line).



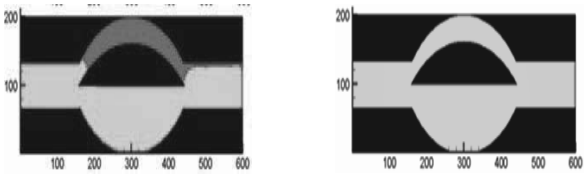


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Figure 2. Drainage-type snap-off in a doublet. (a) Displacing fluid (green) is non-wetting and displaced fluid (red) is wetting. (b) Displacing fluid is wetting and displaced fluid is non-wetting.

The properties of the pair of the tested fluids are presented in Table 1. The simulations were carried out in a two-dimensional medium similar to the chamber-and-throat type networks used in the experiments (see Figure 3). It should be mentioned that the dimensions of the model could not be considered as large as that of the experiment due to high computational costs.

Table 1.Physicochemical properties of fluids

	Non-wetting fluid (n-nonanol)	*Wetting fluid (formamide)*
Viscosity(Pa s)	0.00964	0.00335
Density(kg/m^3)	816	1116
Interfacial tension(mN/m)	4.3	
Contact angle	9	

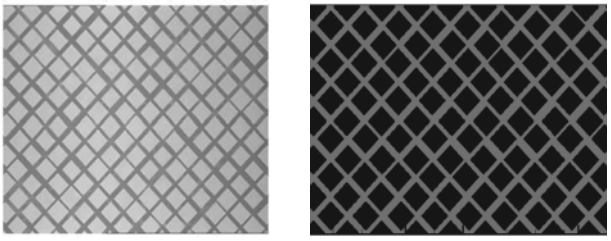

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Figure 3. (a) A segment of the glass-etched chamber-and-throat network used in experiments (b) domain used in LB simulation.

At first, the saturated permeability of the medium was determined by the numerical modeling for a steady-state Darcy's velocity after applying a constant body force for one phase and setting the density of the other fluid equal to zero at all locations. The result was k = 8.82μm^2 which is remarkably close to the experimental value of 8.9 μm^2 It is important to note that the employed MRT approach in the developed LBM code has yielded more accurate predictions of both saturated as well as relative permeabilities compare to the standard BGK model, which leads to a viscosity dependent permeability.

4.1 *Steady state*

To simulate the steady-state experiments, we distributed fluid phases in the model according to target saturation. Flow at a given *Ca is* then commenced.

$$Ca = \frac{\mu_w u_s}{\gamma} \quad (2)$$

Where u_s is the superficial flow velocity of the injected wetting phase at the entrance, μ_w is the viscosityof the wetting phase, γ is the interfacial tension.

We imposed periodic boundary conditions and allowed both fluids to enter and exit the model. Phase saturations were thus constant during the simulations. We applied the same body force to each phase, thus the global pressure drop was the same for both fluids. This eliminated the capillary end effects since there were no gradients in capillary pressures.

The two immiscible fluids flow until the relative permeabilities and the pressure drop have converged. When the system has converged and steady-state flow is established, the steady-state relative permeability of two fluids from average flow fluxes of the wetting and non-wetting fluids are calculated at several sections along the direction of the flow in the domain. Figure 4a shows an example of the initial distribution of the fluids in the domain and Figure5shows the experimental relative permeability curve as well as the results of LB simulation performed at a similar capillary number. According to Figure 5the numerical results are in relatively good agreement with experimental measurements.

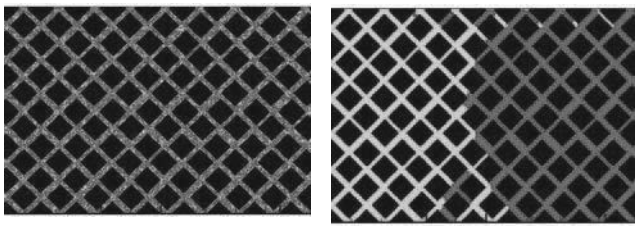

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Figure 4. (a) example of initial distribution of the fluids in steady-state simulation (b) example of invasion of wetting fluid(green) in unsteady state simulation.

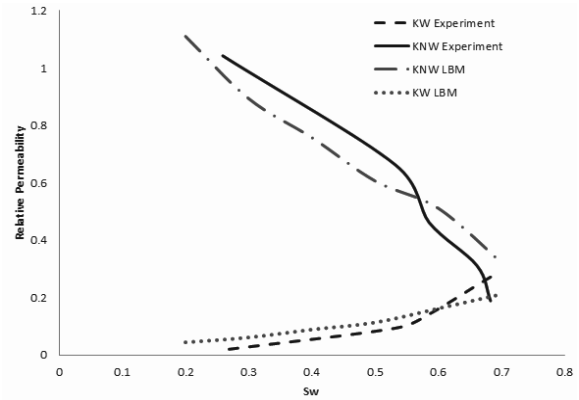

Figure 5.Comparison of LB modeling results and experimental relative permeability curves (steady state)(Ca=5E-6).

4.2 *Unsteady state*

The unsteady-state method is widely used because it is fast and qualitatively resembles the flooding process in the oil reservoir. However, it is an indirect method. Relative permeabilities are calculated, not measured. Typically, the Johnson, Bossler and Naumann (JBN) method (Johnson et al. 1959) or its variants are used to calculate relative permeabilities from the measured production data and pressure drop. This method is based on the assumptions that the flow velocity is high enough thereby making capillary end effects negligible and that the flow velocity is constant. In addition, the flow components should behave as immiscible and incompressible fluids comprising a stable displacement.

Numerical simulation of the variation of relative permeabilities under unsteady- state situation is a difficult task that has not been performed before. Here, by using the developed LBM code and employing MRT technique an attempt has been made

to model this experiment at the pore scale. To set up our unsteady-state simulations, we use periodic external boundary conditions. Both fluids could exit the model, but only the displacing fluid can enter the model. This makes the velocity field continuous during the displacement and enhances the stability of the simulations. The pressure field was controlled by a body force that was applied equally to both fluids.

The body force is regulated to keep a constant total mean velocity and thus constant capillary number (Ramstad et al. 2010). The effluent composition and pressure drop across the model are continuously monitored. Figure 4bshow the evolution of the wetting phase into the medium and Figure6shows the experimental relative permeability curve as well as the results of LB simulation performed at similar capillary number. The LBM code predicts the trends of the variations of relative permeabilities correctly however, the discrepancies look more for unsteady-state relative permeability curves compare to those of the steady state. One of the sources of uncertainty in the current numerical results is the unfavorable effects of spurious velocities. In a SC type LBM simulation, largest spurious velocities occur near the interfacial region of the fluids (Jia et al., 2008). Therefore, high spurious velocities may affect the calculated fluxes especially for very slow or creep fluid flows. On the other hand, as mentioned before the experimental values are not measured directly from the tests. They are calculated using the JBN method. This may also contribute to the difference that is seen between the experimental and numerically-derived values.

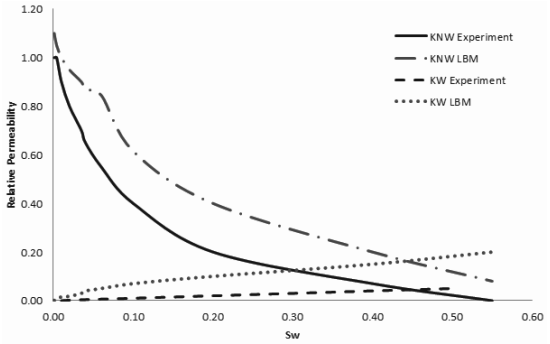

Figure 6.Comparison of LB modeling results and experimental relative permeability curves (unsteady state)(Ca=5E-6).

5 CONCLUSIONS

A newly developed Lattice Boltzmann-based numerical code has been described in this paper. This model is based on Shan & Chen (SC) formulation which is capable of simulating the simultaneous flow of two immiscible fluids at the pore scale considering all the important interacting effects such as interfacial tension and capillary. Using this code the variation of relative permeabilities of two-fluid flow under steady state and unsteady sate conditions has been simulated which is of utmost importance in petroleum reservoir engineering. MRT approach has been employed in the code to eliminate the problem of the dependency of the results to the viscosity. The obtained results indicate that LBM is a powerful method that can simulate complex problems pertaining flow in porous materials as well as solving difficult issues in petroleum geomechanics. Results obtained in this study about the variation of the relative permeabilities in the reservoir rock reveal that although the results for steady state two-fluid flow is quite promising, the modeling of unsteady flow warrants further investigation.

6 REFRENCES

Chen H., Chen S. and Matthaeus W. H.,(1992), Recovery of the Navier–Stokes equations using a lattice-gas Boltzmann methods. Phys. Rev. A, 45: 5339–5342.

Chen S. and Doolen G. (1998). Lattice Boltzmann method for fluid flows. Annual Review of Fluid Mechanics,30, 329–364.

Ghassemi A., Pak A.,(2011), Numerical Study of Factors Influencing Relative Permeabilities of Two Immiscible Fluids Flowing through Porous media using Lattice Boltzmann Method, Journal of Petroleum Science and Engineering.,77, 135-145.

Gunstensen AK, Rothman DH, Zaleski S, Zanetti G., (1991), Lattice Boltzmann model of immiscible fluids. Physical Review A, 43, 4320-4327.

He X., Zou Q., Luo L. S., Dembo M.,(1997), Analytic solutions and analysis on non-slip boundary condition for the lattice boltzmann BGK model. Stat Phys., 87:115–136.

Jia X., McLaughlin J. B., Kontomaris K., (2008), Lattice Boltzmann simulations of flows with fluid–fluid interfaces, Asia-pacific journal of chemical engineering, 3: 124–143.

Johnson E.F., Bossler D.D., Naumann V.O,(1959), Calculation of relative permeability from displacement experiments, Trans. AIME **216**, 370.

Keehm Y., Mukerji T. and Nur A.,(2004), Relative Permeability Simulation using the Two-phase Lattice-Boltzmann Method., 5th Conference & Exposition on Petroleum Geophysics, Hyderabad-, India PP 696-703.

Lallemand P., Luo L.-S. (2000), Theory of the lattice Boltzmann method: Dispersion, dissipation, isotropy, Galilean invariance, and stability, Physical Review E 61:6546-6562.

Lenormand R., Zarcone C. and Sarr A., (1983), Mechanisms of the displacement of one fluid by another in a network of capillary ducts, J. Fluid Mech., 135, 337-353.

Li H., Pan C., Miller C.T., (2005), Pore-scale investigation of viscous coupling effects for two-phase flow in porous media, PHYSICAL REVIEW E 72, 026705.

Nourgaliev R.R., Theofanous T.G., Joseph D.D., (2003),The lattice Boltzmann equation method: the oretical interpretation, numerics and implications, International Journal of Multiphase Flow, 29: 117-169.

Pan C., Hilpert M. and Miller C. T., (2004), Lattice-Boltzmann simulation of two-phase flow in porous media, Water Res. Research 40, W01501.

Qian Y. H. d'Humie`res D., Lallemand P.,(1992),Lattice BGK models for Navier–Stokes equation. EurophysLett., 17:479–484.

Ramstad T., Idowu N. and Nardi C.,(2011),Relative Permeability Calculations from Two-Phase Flow Simulations Directly on Digital Images of Porous Rocks., Transp Porous Med,11-9877-8.

Ramstad T., Qren P.E., Bakke S.,(2010), Simulation of two phase flow in reservoir rocks using a lattice Boltzmann method. SPE J. **15**(4), 917–927.

Schaap M. G., Porter M. L. Christensen B. and Wildenschild D., (2007), Comparison of pressure-saturation characteristics derived from computed tomography and lattice Boltzmann simulations, Water Res. Research 43,W12S06.

Shan X, Chen H. (1993), Lattice Boltzmann model for simulating flow with multiple phases and components, Physical Review E, 47, 1815-1819.

Succi S.,Foti E. and HigueraF., (1989), Europhys.Lett., 1989, 10, 433.

Sukop, M.C. and D.T. Thorne, Jr., (2006), Lattice Boltzmann Modeling: An introduction for geoscientists and engineers, Springer, Heidelberg, Berlin, New York 172 p.

Swift M.R., Orlandi E, Osborn W.R., Yeomans J.M., (1996), Lattice Boltzmann simulations of liquid-gas and binary fluid systems, Physical Review E, 54, 5041-5052.

Tsakiroglou C. D., Avraam D. G., Payatakees A. C.,(2007),Transient and steady-state relative permeabilities from two-phase flow experiments in planar pore networks., Advances in Water Resources, 30 ,1981–1992.

Valavanides M.S., Constantinides, G.N. and Payatakes, A.C.,(1998), Mechanistic Model of Steady-State Two-Phase Flow in Porous Media Based on Ganglion Dynamics, Transport in Porous Media, 30, pp.267-299