MICRO-SCALE TWO-PHASE FLOW SIMULATION OF LATTICE BOLTZMAN METHOD FOR CAPILLARY HYSTERESIS

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OBJECTIVES

Application of X rays CT scanner to the core flooding analysis is enabling the simultaneous saturation measurement, more accurate relative permeability and the capillary pressure in cooperation with the simulation. However, unless either of the relative permeability or the capillary pressure is known, the other side cannot be uniquely determined. To develop a simulation technology, which can explain theoretically such experimental phenomenon, is an important subject, and this research focused on a promising technique: Lattice Boltzmann Method (LBM) as micro-scale flow simulation method.

INTRODUCTION

The theoretical method to predict core flow characteristics such as permeability from a basic theory has not been established yet, though the simulation of the flow phenomenon in the reservoir and the research of a basic theory concerning the fluid behavior have been conducted for many years. Many reservoir flow simulations are based on the continuum approximation model theory, experiment based Darcy's law for absolute permeability and Buckley Leverett theory. Although no one has yet been able to prove it inapplicable, it might be a time to think another approach for a pore scale microscopic phenomenon.

Recent major approaches are the network model and percolation model. The network model is a method of modeling the core flow by a network of connected pores. The network model uses the experimental equation, which will limit its universality to handle a micro-scale structure of the core or to correspond to non-homogeneous flow.

On the other hand, the Lattice Boltzmann method simulates a complex fluid movement through the virtual particle distribution function along with a cycle of translation and collision, which is applicable to micro flow simulation. LBM is applicable to pore scale simulation and can reproduce the effect of pore shape or pore size distribution, and the effect of wettability on microscopic two-phase flow phenomenon in porous media such as snap off behavior and film flow. This method will provide results consistent with the Navier-Stokes fluid mechanics equation. The physical properties such as density, flow velocity, temperature, and pressure are calculated from the distribution function, through Chapman Enskog multi-scale development, which solves for changes with time of a virtual particle distribution function.

LBM is considered to have the following advantages:

1) It can handle very complex shapes and the boundary conditions, because the model can handle as reflection of the distribution function "bounce back".
2) It can calculate interfacial movements of two phase, oil–water, system independently, which were evaluated as an average in the past.

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3) It can describe wettability (contact angle) change of the boundary, which has a big influence on the flow characteristic.
4) It may have application to a large-scale simulation in a parallel computer.

METHODS

The following approaches were executed.

1) Preliminary 2D simulations were made to calculate the capillary pressure curve of Berea sandstone and two-phase flow behavior. The pore throat distribution of the rock sample is examined and that characteristic was used to construct a simple pore model.
2) Simulation of two-phase flow was conducted in a virtual core. The pore shapes and the wettability are varied and their effect on snap off behavior and film flow has been studied.
3) The wettability dependency of capillary pressure and hysteresis has been calculated in a virtual core. The influence of water-wet, oil-wet, and neutral conditions on the capillary pressure was simulated and a qualitative dependency was found.
4) Micro-scale two-phase flow simulation of LBM technology can describe any condition or scenario. That is impractical to do experimentally. It could be used as a tool to develop and evaluate ideas and the theory.

RESULTS

Two-phase flow in the porous media is analyzed using the model (Figure 1). Then, the following points are found in this study for the application of the Lattice Boltzmann method to the pore scale phenomenon analysis in the reservoir.

Reproduction of two-phase flow in porous media, such as snap off (Figure 2) and film flow behavior is confirmed. As an example the film of thin oil is formed on an oil-wet wall, and oil is dragged by viscous resistance with water and effuses outside (Figure 3). However, a high-resolution simulation is necessary to describe the difference between the pressure boundary conditions.

1) The sensitivity of parameters that influence two-phase flow in porous media has been investigated. When the aspect ratio is small or the interfacial tension is low, the snap-off did not occur. (Aspect ratio is the ratio of pore body to throat pore size) Moreover, as the shapes of an oil drop changes on the upstream side and on the downstream side due to flow, contact angle was predicted qualitatively.
2) The Micro-scale two-phase flow distribution may be predicted. A two-throat system is used by LBM to simulate the velocity and pressure distribution in the pore throat. At the pore scale a) flow velocity distribution, b) pressure distribution (Figure 4) and also c) capillary hysteresis are simulated (Figure 5). The effects of surface tension, aspect ratio, pressure differential and capillary number were examined.
3) Reproducibility of capillary pressure and hysteresis have been examined. The capillary pressure is changed by using simple pore shapes to model a part of Berea sandstone, and determine if the model can predict the capillary pressure of two-phase fluid flow during the drainage process. The capillary pressure calculated by the simulation is almost equal to the capillary pressure estimated from the width of throat diameter and the surface tension. This model is able to predict the pressure at which oil begins to be displaced in the drainage process. In the imbibition process (reproduction of snap off

behavior), water starts infiltration, when the capillary pressure is below the critical pressure calculated from the surface tension and the width of throat. For the imbibition process, it is also confirmed that capillary hysteresis is caused by a two-dimensional shape.

4) Wettability dependency of flow behavior has been predicted. The characteristic oil shape is shown for each wettability, when oil remained as the difference of the hysteresis curve (Figures 6, 7, 8). Also flow behavior and the oil collection rate are different depending on the wettability.
5) As a summary, the Lattice Boltzmann method may simulate a complex fluid movement in micro-scale flow simulation. LBM can also describe the effect of pore shape or pore size distribution, and the wettability of microscopic two-phase flow.

APPENDIX

Characteristic and background of Lattice Boltzmann method

The LBM for multiphase fluid flows start from the following kinetic equation for the discrete velocity distribution function, f_i^k for red and blue fluids on a discrete lattice:

$$f_i^k\,(x + ei\,,t{+}1) = f_i^k\,(x,t) + \Omega_i^k\,(x,t),$$

where k denotes colors of particles, red or blue, i are the moving particle direction.

The Ω_i^k is a collision operator that is comprised of two parts, $\Omega_i^k = (\Omega_i^k)^A + (\Omega_i^k)^B$

The first term, represents a process of relaxation to local equilibrium.

ACKNOWLEDGEMENTS

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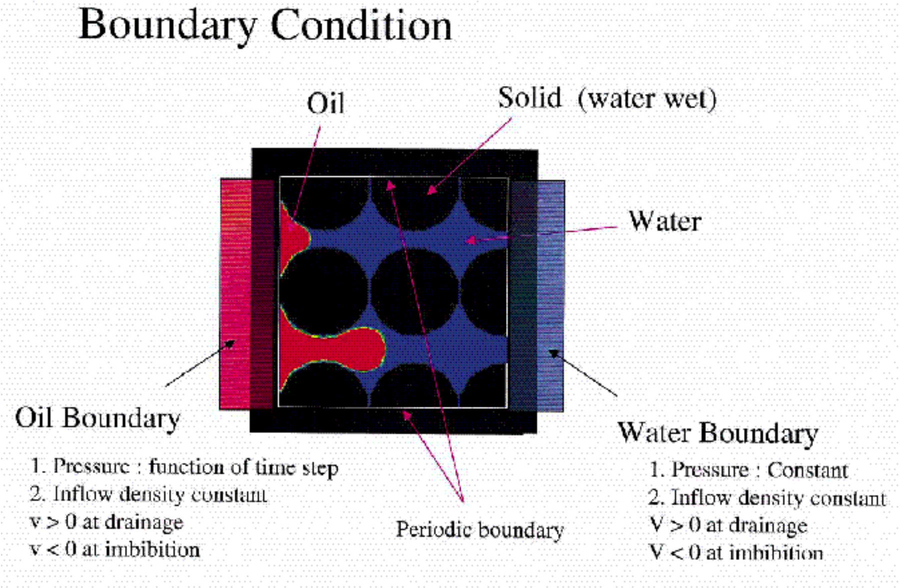

Figure 1 Schematic of 2D LBM Model

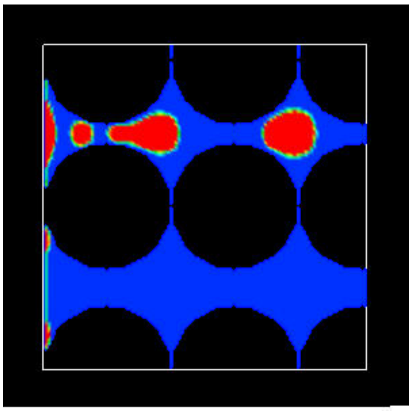

Figure 2 Snap-off behavior in water-wet model

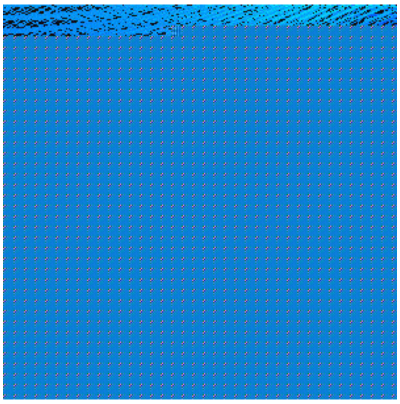

Figure 3 Film-flow behavior in oil-wet model

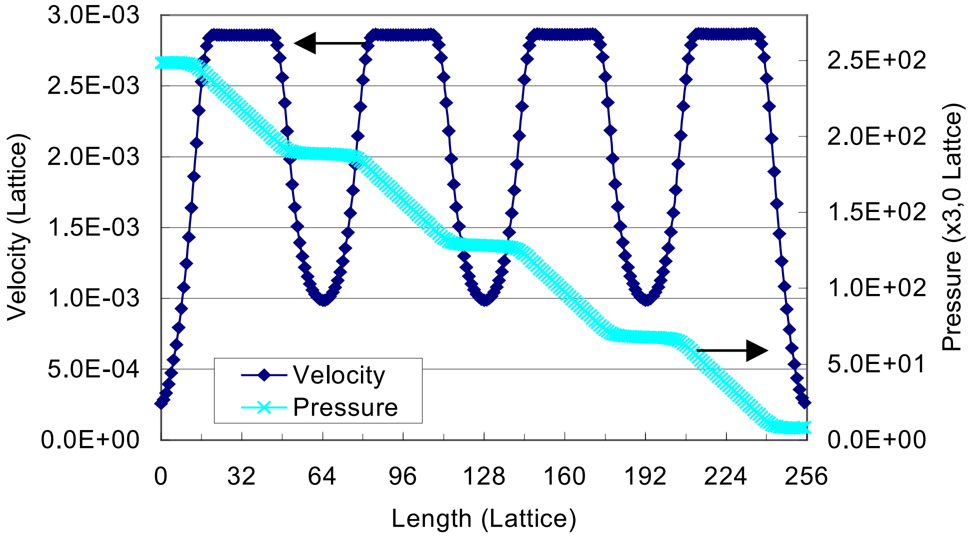

Figure 4 Velocity and Pressure Profile

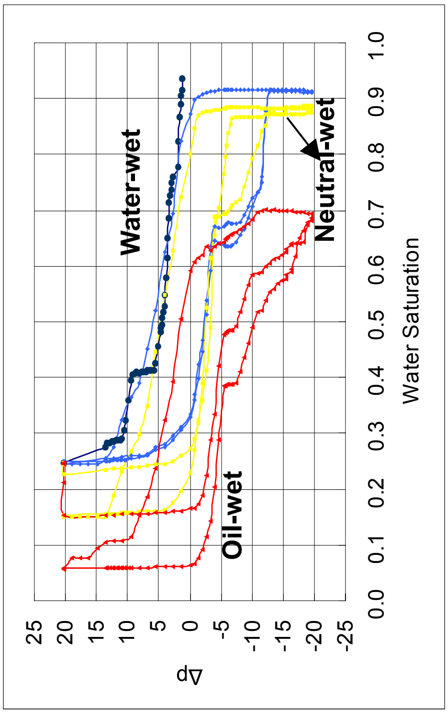

Figure 5 Capillary hysteresis in water-, neutral- and oil-wet model

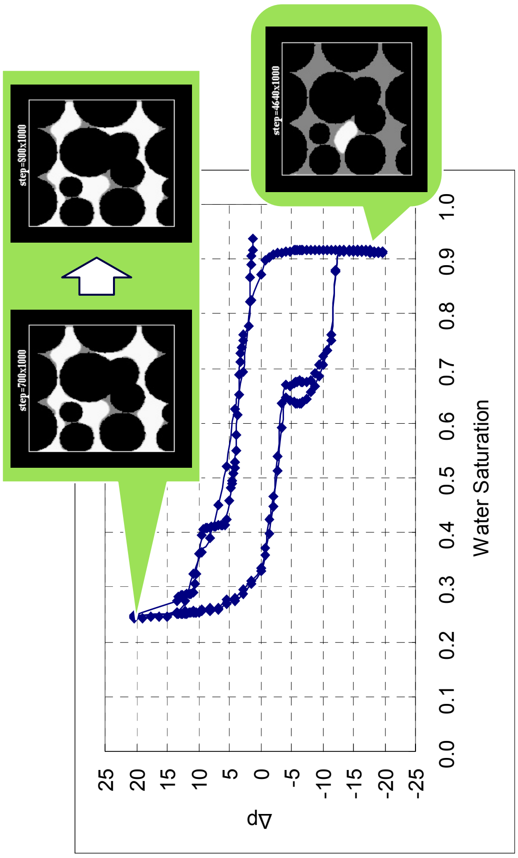

Figure 6 Capillary hysteresis in water-wet model

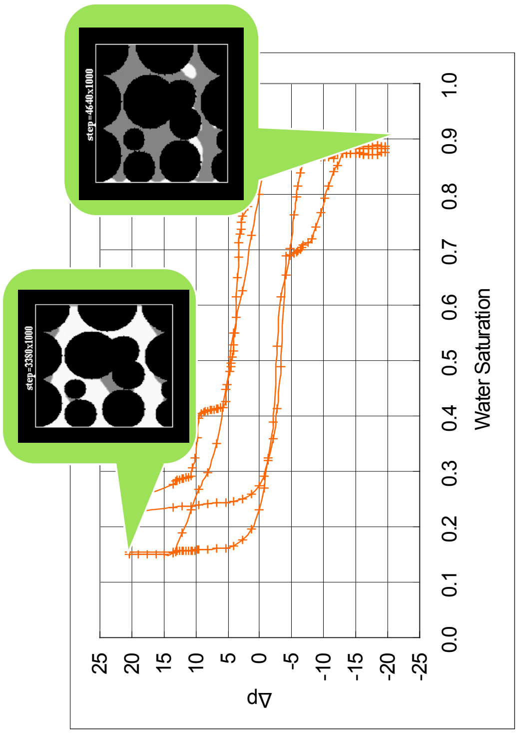

Figure 7 Capillary hysteresis in neutral-wet model

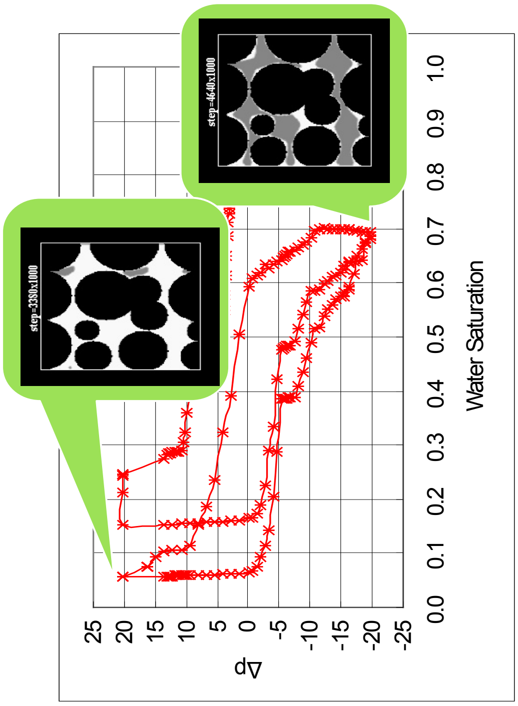

Figure 8 Capillary hysteresis in oil-wet model

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