



## Lattice-Boltzmann Color Gradient Method for Fluid Flow Simulation in Porous Media with Viscosity as A Function of Temperature

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### Introduction

Study of fluid flow in porous media is required in many areas including porous rocks. Permeability of reservoir rock used to be measured through SCAL (Special Core Analysis Laboratory) procedure. Influence of temperature on fluid flow as viscosity change is of interest in EOR but it is not easy to observe. Digital Rock Physics (DRP) is a new developing method that may be applied to estimate permeability and open the possibility to investigate fluid flow. Some parameters of fluid flow can be changed easily by means of computer simulation, the analysis is easier to repeat, the result is virtually 'observable', and generally less time consuming. However, finding the perfect algorithm to do the simulation is a challenging task and is currently being the hot topics among scientist and computational fluid dynamics practitioners. Some computational methods had been used to estimate fluid flow permeability inside porous media. This paper presents LBM with color gradient scheme as a tool for simulating immiscible multiphase flow in porous rocks. This scheme is an alternative of the previously popular Shan-Chen's scheme. Although the development of color gradient scheme in 3D domain is still new, we implemented the scheme into 3D pore structure image and measure the relative permeability. Influence of temperature on fluid flow as viscosity changes, is also analyzed.

### Methods

The color gradient, or better known as Rothmann-Keller (RK), scheme is variation of LBM that models interaction force between fluid particle to be linearly proportional with density gradient, have been developed since 1998. We used the algorithm step as proposed by Latva-Kokko (2005) and further developed by Phillips-Reis (2007). The boundary condition used in this paper is constant flux at inlet and constant pressure at outlet. The capillary number that describe flow regime inside porous media is defined as,  $N_c = \rho v u_i / \sigma$ , where  $u_i$  is the constant uniform inlet velocity,  $\sigma$  is interfacial tension between fluids that is related empirically to  $A$  which correspond to surface tension, i.e.:  $\sigma/A=2.79$ . The relative permeability is computed using formula (Raeni, 2012),  $k_{r,k} = (Q_k / \Delta P_k) / (Q_{k,SP} / \Delta P_{k,SP})$  with  $k_{r,k}$  is relative permeability of phase- $k$  where  $k=[n;w]$  denotes non-wetting and wetting phase respectively,  $Q_k$  is flow rate and defined as  $Q = \int u \cdot n_\alpha \varphi_k dA$  with  $\varphi_k = \rho_k / (\rho_n + \rho_w)$ ,  $n_\alpha$  is vector normal to the flow direction being investigated. The subscript  $SP$  indicates that the variable corresponds to single phase system. The pressure drop  $\Delta P_k$  is defined as velocity weighted average of the pore scale pressure gradient and can be written as (Nordbotten, 2008),  $\Delta P_k = (1/Q_k) \int_V u \cdot (\nabla P_k) dV$  where in LBM,  $p_k = 3\rho_k(1 - \alpha_k)/5$ .

Velocity profile of the flow shows different path after inserting temperature in its viscosity. Dependence of viscosity on temperature is based on Arrhenius model,  $\nu = A \cdot 10^{B/(T-D)}$  and  $\ln \mu = \ln \mu_c + C/(T - T_c)$  for wetting and non-wetting phase respectively, where  $T_c = 460$  °R, and the parameters  $\mu_c$  and  $C$  are correlated with the API gravity as  $\ln \mu_c = -0.0739^\circ API + 1.1697$  and  $C = 0.2881^\circ API^2 - 26.314^\circ API + 925.74$  (Civan, 2006).

## Results and Discussion

We simulate non-wetting fluid invasion into pore space that initially filled with wetting fluid. Figure-1a shows fluid flow for different capillary numbers. The nature of capillary number is ratio between viscous force and capillary force.

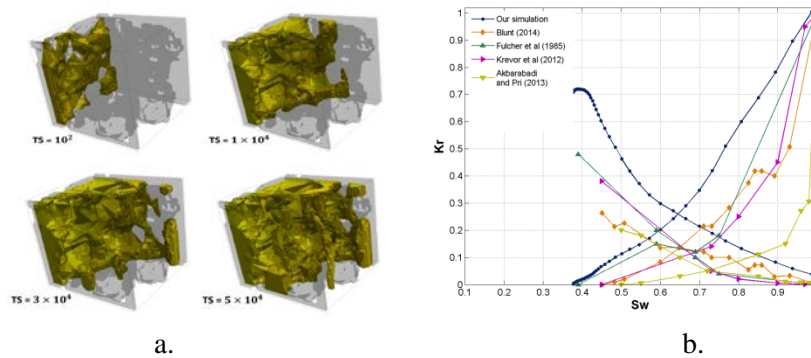


Figure-1. Fluid flow pattern and relative permeability.

Relative permeability curve is shown in Figure-1b. It shows that maximum penetration of the non-wetting fluid is until  $Sw = 0.3$ . We implemented the LBM-RK algorithm to simulate flow in Berea sandstone and calculate the relative permeability. The result is overestimated compared to the relative permeability experiment. This overestimate may be due to the difference in sample size, since the simulation is performed on cubical sub-sample which is much smaller than core sample. Simplifying the pore structure by taking a sub-sample of the original rock image may give inaccurate representation. Figure-2 shows flow pattern at different temperatures. It is shown that irreducible non-wetting phase is replaced by wetting phase differently as temperature changes.

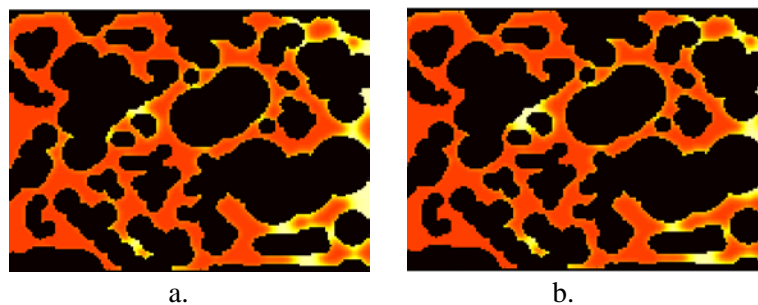


Figure-2. Flow pattern at different temperature (a. 360 K and b. 400 K).

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