Development and Application of Lattice Gas Automata Model

by Dedy Kristanto

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[Papers]

"Mitigation of Nitrous Oxide in Indonesia; Technical Option and Policy Proposal "
Agung Sudrajad, Osami Nishida, Hirotsugu Fujita and Wataru Harano 1-14

"On Intraseasonal Kelvin Wave Resonance in the Sulawesi Sea Basin"
Fadli Syamsudin 15-21

"Area Width Expansion and Productivity of Palm Oil Plantation in Indonesia"
Dwi Aulia Puspitaningrum 22-34

"Growth of GaN thin film by pulsed laser deposition and its application on ultraviolet detectors"
D.Rusdiana, A.Suhandi, S. Karim, Sukirno, M. Budiman and M. Barmawi ....
....35-44

"Development and Application of Lattice Gas Automata Model for Simulation of Immiscible Displacement Process in Heterogeneous Porous Media"
Dedy Kristanto and Mariyamni Awang 45-61

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Development and Application of Lattice Gas Automata Model for Simulation of Immiscible Displacement Process in Heterogeneous Porous Media

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ABSTRACT

This paper present a pore-network model of two immiscible fluids in petroleum industry using lattice gas automata based on pores-and-throats representation of the heterogeneous porous media. The network has irregular geometry and pores or capillary segments of various different shapes and sizes distributed over the network in some irregular fashion, which is distinguishing two-dimensional networks. The main feature of this model is the mechanisms and mobilization in which immiscible carbon dioxide invaded the porous media occupied by oil could be simulated in dynamic condition process.

The FHP-II (Frisch, Hasslacher and Pomeau, FHP) of lattice gas automata model is applied for simulation of immiscible displacement process of carbon dioxide to displace oil reservoir on the two-dimensional pore network model. The shape of the regions of displacing and displaced fluids mechanisms was simulated. The effects of grain sizes and shapes, and its distribution that represented by effective porosity and permeability in porous media on the displacement mechanisms and displacement efficiency are studied. This simulation also could predict the residual oil saturation and displacement efficiency of the processes. Comparison with laboratory experiment was also presented. Reasonable good agreement between the lattice gas automata simulation and laboratory experiment results were achieved.

Keywords: Lattice Gas Automata, heterogeneous porous media, oil saturation, displacement efficiency

1. INTRODUCTION

An important aspect of any enhanced oil recovery (EOR) process in Petroleum Industry is the effectiveness of the process of injected fluids in removing oil from the reservoir rock pores at the microscopic scale. Microscopic displacement efficiency, E_D, largely determines the success or failure of a process. For crude oil, displacement efficiency is reflected in the magnitude of the residual oil saturation (S_{or}) remaining in the reservoir rock pores at the end of the process in places contacted by the displacing fluids. Because enhanced oil recovery processes typically involve the injection of multiple fluids, the displacement mechanisms and efficiency of displacement of these fluids through the porous media are of interest.

The FHP-II (Frisch, Hasslacher and Pomeau, FHP [1]) model of lattice gas automata is used for the simulation of immiscible fluids displacement in the two-dimension of heterogeneous porous media. The simulation conducted on the 800x600 lattice sizes, and the construction of heterogeneous porous media was varied based on the porosity values, which has ranges of 10% - 50%. While, the changes of grain shapes and porosities are to study of these effects on the displacement mechanisms bahaviour and displacement efficiency of the immiscible displacement processes. Furthermore, the simulation is divided into two steps of simulation run. The first run is for injection of oil (represenred by blue colour) into interconnected pore space network of porous media until the saturated conditions is reached. The second run is injection of carbon dioxide (represented by red colour) as a displacing fluid into porous media to displace oil that occupied entire interconnected pore space network of porous media until residual oil saturation (S_{or}) is reached.

2. SIMULATION MODEL

In order to make progress in the study of immiscible fluid displacement in heterogeneous porous media, it is therefore necessary to simplify either the rock geometry or the fluid flow. In two dimensions, it could construct a simplified model of a single pore, and porous media modeled as a network of such interconnected pores. The fluid flow of two-phase fluid through such a network is modeled based on the assumption about the flow in these interconnected pores. The simplified of granular pore space as an array of wide pore interconnected by narrower regions, which call throats is illustrated in Figure 1.

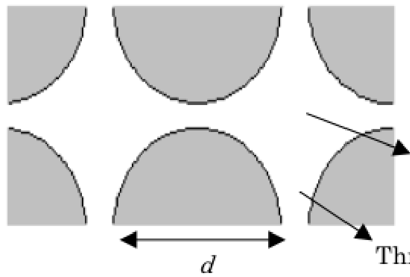


Figure 1. Schematic of porous media studied.

In the FHP-II model of lattice gas automata, at each site of two-dimensional hexagonal lattice particle can move into any of six directions. The cells are associated with the unit velocity vectors connecting the node to six nearest neighbors [1, 2],

$$c_i = \left(\frac{\cos \pi i}{3}, \frac{\sin \pi i}{3} \right), \quad i = 0, 1, ..., 6. \tag{1}$$

The unit velocity vectors, c_i, is unity and all particles have the same mass, momentum magnitude and kinetic energy, except for rest particles which are often included in order to increase the Reynolds number range. An exclusion principle is imposed which requires that no more than one particle at a given site can have the same momentum. This exclusion rule is included in order to minimize memory requirements, allowing bit operators.

Let $N_i(x,t)$ $(i = 0, 1,\ldots, 6)$ be the particle occupation in state i at site x and time t, then $N_i = 1$ or 0 represents a particle existence in the i state. There are two microscopic updating processes at each discrete time steps; streaming (particles moving) and particle collision. In the streaming process, particles move to the nearest neighbor sites along their momentum directions. In the collision process, particles at each site are scattered in such a way that the total particle number ($= \sum_{i=0}^{6} N_i$) and the total momentum ($= \sum_{i=0}^{6} c_i N_i$) are conserved at each site, where c_i $(i = 0, 1,\ldots, 6)$ is the unit vector pointing to the nearest neighbors and $c_0 = 0$. Kinetic equation for the particle state occupation can be written in a simple form,

$$N_i(x + c_i, t + 1) = N_i(x,t) + \Omega_i \tag{2}$$

where Ω_i is the collision operator, which includes the creation or annihilation of a particle in momentum state c_i and only depends on the information at the site x at t.

Denote $f_i(\mathrm{x},t)$, $f_i^{(r)}(\mathrm{x},t)$ and $f_i^{(b)}(\mathrm{x},t)$ as the particle distribution functions at space x and time t for total red and blue fluids, respectively. Here $i = 0, 1, \ldots, 6$, is the number of moving particle directions on a hexagonal lattice, and $f_i = f_i^{(r)} + f_i^{(b)}$. The equation (2) can be extended to simulate red (carbon dioxide) and blue (oil) fluids:

$$f_i^m(\mathrm{x}+c_i, t+1) = f_i^m(\mathrm{x},t) + \Omega_i^m(\mathrm{x},t) \tag{3}$$

where m denotes either the red or blue fluid, and $\Omega_i^m = (\Omega_i^m)^1 + (\Omega_i^m)^2$ is the collision operator. The first term of collision operator, $(\Omega_i^m)^1$, represents the process of relaxation to local equilibrium. The distribution function must satisfy conservation of mass and momentum:

$$\rho_r = \sum_i f_i^r = \sum_i f_i^{r(\mathrm{eq})} \tag{4}$$

$$\rho_b = \sum_i f_i^b = \sum_i f_i^{b(\mathrm{eq})} \tag{5}$$

$$\rho\,\mathrm{u} = \sum_{i,m} f_i^m = \sum_{i,m} f_i^{m(\mathrm{eq})} c_i \tag{6}$$

To maintain interfaces between fluids, the Rothman's scheme [2] is used to force the red color momentum, $j^r = \sum_i f_i^r c_i$, to align with the direction of the local color gradient. The blue particle distribution can then be obtained using mass conservation along each direction,

$$f_i^b = f_i - f_i^r, \ (i = 0, 1, \ldots, 6) \tag{7}$$

Going through a Chapman-Enskog expansion procedure, one can rigorously prove that the Navier-Stokes equation will be valid for each phase with the additional property that the pressure difference in the interface will obey the Laplace's formula [2]:

$$\Delta p = p_r - p_b = \frac{2\sigma}{R} \tag{8}$$

where R is the radius of surface at the contact point and σ is the surface tension. The pressure is given by,

$$p = \frac{3}{7}\rho \tag{9}$$

The viscosity of fluid is given by [3],

$$\nu = \frac{1}{28}\frac{1}{d(1-d)^3}\frac{1}{1-4d/7} - \frac{1}{8} \tag{10}$$

where d is the mean density per link (= $\rho/7$).

In order to determine the macroscopic properties of a heterogeneous porous media, the absolute porosity of the porous media is determined by [4, 5],

$$\phi = \left(1 - \frac{V_s}{V_b}\right) \tag{11}$$

where V_s is the volume of the obstacles, and V_b is volume in two-dimensional space. However, the value of effective porosity is given by equation,

$$\phi_{eff} = ax^3 - (2a + \phi_C)x^2 + (a + 1 - \phi_C)x \tag{12}$$

where

$$x = \frac{(\phi - \phi_C)}{(1 - \phi_C)} \tag{13}$$

and a is constant (a = 0.3), and ϕ_C is a critical porosity or percolation threshold, respectively. The permeability coefficient (k) of a porous media is given by

Carman-Kozeny equation,

$$k = \frac{\phi_{eff}^{\ 3}}{c\tau^2 S^2} \tag{14}$$

where c is the Kozeny coefficient, τ is the tortuosity, S is the surface area and ϕ_{eff} is the effective porosity, respectively.

Furthermore, consider a porous media with $V_p = \phi > \phi_c$. Suppose the entire pore space is filled with fluids (oil phase). Then, now displace the oil phase from some of the pore and replace it with a second fluid, carbon dioxide (CO_2), in such a way that the oil phase is randomly distributed within the pore space. Let V_o be the volume of oil phase divided by the bulk sample volume. Since the oil phase is randomly distributed, the fraction of accessible porosity occupied by oil phase, S_{or}, is the same as the fraction of isolated porosity occupied by oil phase. Thus $V_o = \phi_{eff}\ S_{or}$. Then, residual oil saturation (S_{or}) at which the oil phase loses continuity, is given by [6],

$$1 - S_{or} = \frac{(1-\phi_c)}{\phi} \tag{15}$$

where ϕ_c is the critical porosity (porosity threshold) of a porous media. While, displacement efficiency (E_D) of the immiscible displacement process is given by,

$$E_D = \frac{N_p}{V_p} \text{ x } 100\% \tag{16}$$

where N_p is the oil recovery obtained and the pore volume (V_p) of a porous media is calculated by,

$$V_p = V_b\ \phi_{eff} \tag{17}$$

where ϕ_{eff} is an effective porosity given by Equation (12).

3. RESULTS AND DISCUSSION

Simulation results and discussion consist of the constructing of two-phase immiscible fluids displacement in heterogeneous porous media, estimations of residual oil saturation and displacement efficiency of the immiscible displacement process.

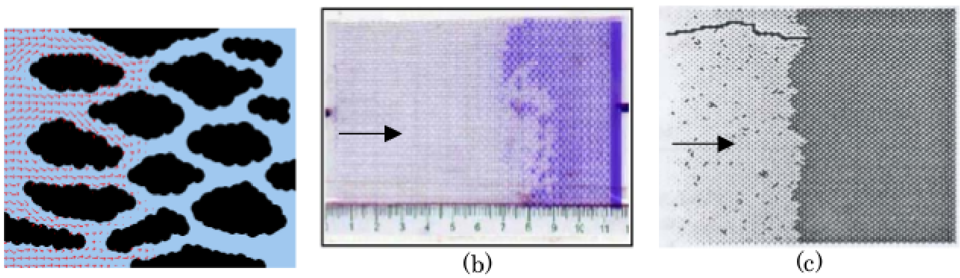
3.1. Constructing of Two-Phase Immiscible Fluids Displacement

The simulation of immiscible displacement process by lattice gas automata model consist of two different particle species to represent two-phase fluids, each being red colour for displacing fluid (carbon dioxide) and blue colour for displaced fluid (oil). The constructed of heterogeneous porous media varied based on the porosity value ranges of 10% to 50%. The direction of the fluids movement started from the left side at the injection rate of displacing fluid was 0.02 lattice unit^3 per time steps to the right side of the porous media and following the collision rules, where the type of injection was continuous CO_2 flooding.

The simulation is divided into two steps of displacement. First displacement is for oil phase (blue colour), and second displacement for carbon dioxide (red colour). The network model of heterogeneous porous media initially saturated with oil as a wetting fluid and occupied the entire of the connected pore spaces. The second displacement, carbon dioxide gas as a non-wetting fluid was injected into the porous media, displacing oil until the residual oil saturation is reached. This displacement process, where the wetting fluid is displaced by non-wetting fluid represents a drainage process.

Furthermore, the type of advance assumed as piston-like displacement, where the carbon dioxide advances in a connected front occupying the centers of the pore space to displace the oil phase. The piston-like displacement of the front assumed was done by maintaining the injection flow rate of displacing fluid below the critical flow rate of the system. In drainage process, the advance of the carbon dioxide is impended on the throats, and the filling of pores depends on the number of connected nearest neighbors that are already filled with the oil as displaced fluid at the first flow and carbon dioxide as displacing fluid at the second flow. The flow regime is controlled by the flow rate (which influences the extent of flow in pore spaces) and the geometry of the pore space. From this displacement process described, it is able to study the effects of different porosity and permeability of porous media on the displacement mechanisms and displacement efficiency during the immiscible carbon dioxide displacement process.

Comparison of the displacement mechanisms between simulation result with the laboratory experiments, and result obtained by Kharabaf and Yortsos [7] is shown in Figure 2. The simulation of immiscible displacement process in heterogeneous porous media by lattice gas automata is shown in Figure 2a. Red colour represents carbon dioxide and blue colour stands for oil. Figure 2b shows the result conducted from the laboratory micromodel experiments of immiscible displacement process, where carbon dioxide displacing oil. White colour represents carbon dioxide, blue colour for oil and oil trapped. While Figure 2c shows the immiscible gas displacement from the work of Kharabaf and Yortsos [7]. Grey colour represents the invading phase (CO_2), dark colour shows the non-invaded phase (oil). Trapped sites are also denoted by dark colour.



(b) (c)

(a)

Figure 2. Comparison of immiscible displacement mechanisms in porous media: (a) Simulation result; (b) Laboratory micromodel experiment result; and (c) Kharabaf and Yortsos result

From Figure 2, it is obvious that simulation result of the developed simulator qualitatively has a good approach with that obtained from the laboratory micromodel experiment, and Kharabaf and Yortsos [7] result. In the simulation result (Figure 2a), the relatively stable displacement front when carbon dioxide displaces oil from the porous media could be maintenance and the piston-like displacement assumed was achieved. However, in near the lower part of the porous media the displacement front relatively left behind than the other parts, indicated with the red dot arrows. In the laboratory micromodel experiment result (Figure 2b), the instability of displacement front occurs in the middle and lower parts of the porous media, and the upper part the displacement front relatively left behind. While, in the Kharabaf and Yortsos [7] result (Figure 2c), the displacement front at the region in between upper and middle part of the porous media relatively left behind, but overall the displacement front is stable. Furthermore, based on the result shown in Figure 2, it is concluded that the developed simulator is applicable to simulate the immiscible displacement mechanisms of carbon dioxide displaces oil in the heterogeneous porous media. Qualitatively, the displacement front movement of the simulation result was in good agreement with the Kharabaf and Yortsos [7], and laboratory micromodel experiment result.

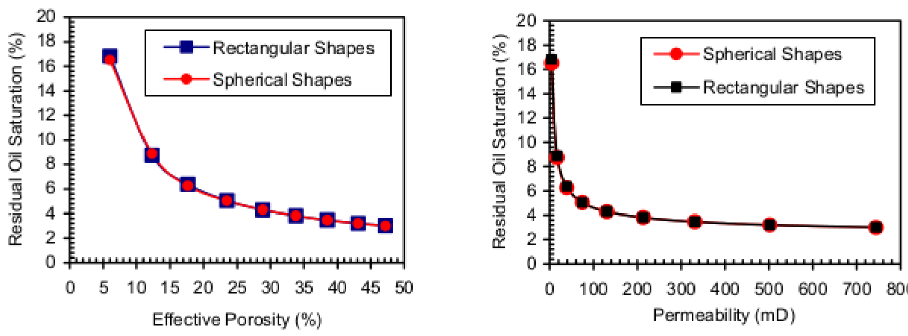
3.2. Estimation of Residual Oil Saturation

In prediction of the sensitivity of oil recovery that represented by the residual oil saturation value to the injection of displacing carbon dioxide gas, are crucially dependent on the permeability and effective porosity of porous media [8, 9, 10]. The comparison of residual oil saturation results from the displacement process is shown in Table 1, and Figure 3.

Table 1. Residual oil saturation (S_{or}) results from the displacement process.

Eff. Porosity, (%)	Permeability, (mD)	S_{or}, (%)
6.126	4.44143	16.50767
12.278	16.86075	8.737417
18.034	38.83125	6.267827
23.511	74.78043	5.040662
28.861	130.3054	4.291639
33.784	213.4396	3.811982
38.497	331.0193	3.467725
43.102	502.1887	3.204074
47.56	744.2541	2.997477

Based on the residual oil saturation results listed in Table 1 and Figure 3, it is shown that increasing in porosity and permeability of porous media would decrease the residual oil saturation. This is because the oil (wetting fluid) is trapped principally in the pores, and the carbon dioxide gas (non-wetting fluid) is more mobile and could not displace all the portion of oil in the entire pores. The simulation results was similar with the results by Dullien *et al.* [11], which has been shown that for very slow rate experiments in packs of roughened beads, the residual oil saturations as low as 1% is possible.



(a) (b)

Figure 3. Simulated residual oil saturation as a function of: (a) effective porosity; and (b) permeability of porous media.

Table 2. Comparison of simulated residual oil saturation results with the other researchers [12].

Researchers	**S_{or}**
Dumore and Schols (1974)	2.9% - 3.2 %
Kantzas *et al*. (1988)	1% - 9.1%
Vizika (1993)	11% - 23%
Kalaydjian *et al*. (1993) (Clashach sandstone)	10% - 30%
Kalaydjian *et al.* (1993) (Fountainbleu sandstone)	16% - 20%
Skurdal *et al*. (1995)	4.7% - 6.7%
Zhou and Blunt (1995)	1.49% - 5.25%
Simulation results	2.997% - 16.507%

Table 2 shows a comparison of residual oil saturation results from this simulation with the experimental results from other researchers [12]. This table gives several references reporting residual oil saturation after gas injection in porous media. Even though the experiments given in the Table 2 were not conducted under identical conditions with the difference is sometimes relatively slight, but it shown that the simulation results are also relevance and reasonable comparing with results obtained by other previous researchers. The lower values of residual oil saturation of the simulation results are closely match the experimental results by Dumore and Schols [12]. While the higher values of simulation results are closely match the experimental results by Kalaydjian's [12] for Fountainbleu sandstone, and in the ranges of Clashach sandstone.

The trend of increasing residual oil saturation (S_{or}) with decreasing porosity, and the trend of increasing pore to throat diameters with decreasing porosity are essentially a topological phenomena. At reduced porosity there are many non-connected pores. So that, the effective porosity of pore space is low, giving rise to high residual oil saturation. In reality, neighboring pore has varying degrees of connectedness, depending on the size of throat connecting them. Thus, when a throat is reduced in size by the solid to the point of critical porosity, the throat is effectively nonexistent, insofar as it affects on the permeability and residual oil saturations [8, 9]. A trend of increasing residual oil saturation with decreasing porosity quite similar to that found by the other researchers as shown in Figure 4. The difference between the lattice gas automata result and other researcher measurements is that for porosity values below 20% the curve for the residual oil saturation is below compared with the other researcher curves.

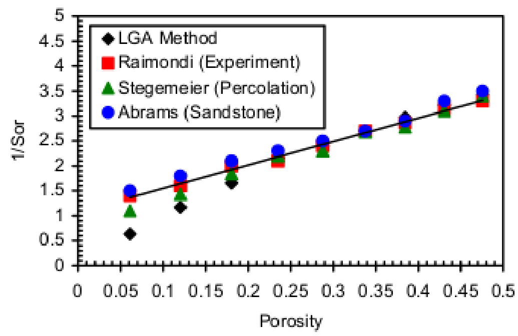
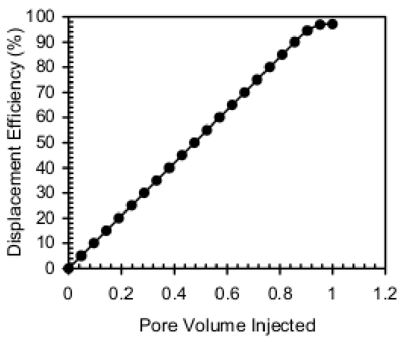


Figure 4. Comparison of the dependence of $1/S_{or}$ on porosity of the simulation result with other researchers

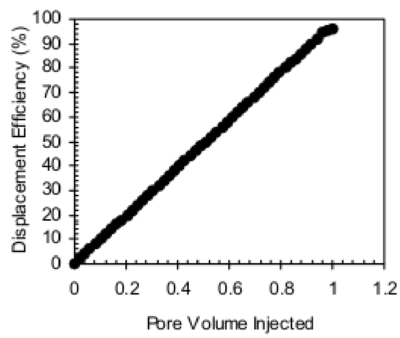
Based on the simulation results of residual oil saturation, it is concluded that the simulation model was able to estimate the residual oil saturation that actually represents the real porous media. The porosity and permeability of heterogeneous porous media have a significant effect on the residual oil saturation obtained from the displacement processes. Where, increasing of porosity and permeability of porous media would decrease the residual oil saturation. The simulation results of residual oil saturation were in good agreement comparing with the laboratory experiment.

3.3. Estimation of Displacement Efficiency

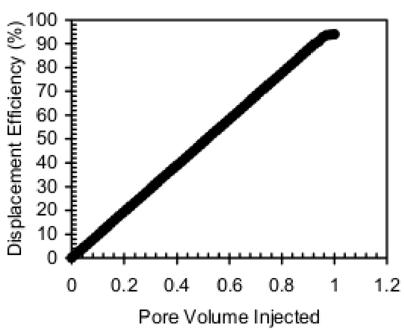
In a displacement process, oil recovery depends on the volume of porous media or reservoir contacted by the injected fluid. A quantitative measure of this contact is the displacement efficiency (E_D). The displacement efficiency in this research then could be defined as the fraction of pore volume oil displaced by the carbon dioxide as the injected fluid, or the fraction of pore volume oil that has been contacted by the carbon dioxide. From this sequence of displacement efficiency, the simulation was conducted to study the effects of properties of porous media on the displacement efficiency of displacement process with particular emphasis on the effect of porosity and permeability [8, 9]. The simulation results of displacement efficiency are shown in Figure 5.



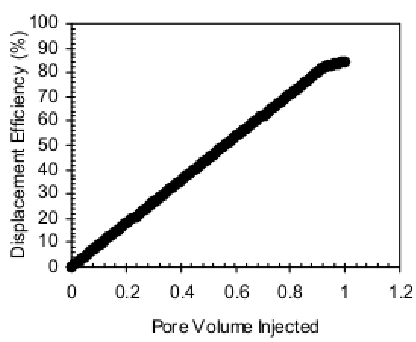
(a) Eff. Porosity = 47.56%



(b) Eff. Porosity = 28.861%



(c) Eff. Porosity = 18.034%



(d) Eff. Porosity = 6.126%

Figure 5. Simulated displacement efficiency for effective porosity of porous media ranges of 47.56% to 6.126%

Figure 5 shows the simulated displacement efficiency of porous media with effective porosity ranges of 47.56% to 6.126%. The graphs were plotted between displacement efficiency achieved as a function of pore volume injected of carbon dioxide into the porous media. It shown that all the graphs have similar trends, where as the pore volume injected of carbon dioxide increases the displacement efficiency also increases until certain value. Then, the curves start to level off (horizontal) and relatively come stable due to no more oil in the porous media could be displaced by carbon dioxide, and leave the residual oil behind as the residual oil saturation as determine the maximum oil recovery from the porous media or reservoir. Summary of the effective porosity effect on displacement efficiency results is presented in Table 3. It is shown that with decreasing in effective porosity value of porous media from 47.56% to 6.126% leads to decrease in the displacement efficiency that could be achieved. It means that the ability of carbon dioxide injected as a displacing fluid into porous media to displace the oil that occupy the pore and throats of porous media is higher in the large pore spaces than in low pore spaces. Furthermore, it was demonstrated that changing of porous media model from the high to low value of effective porosity could be affects on the displacement efficiency of the displacement process. The reason for this was that in the high porosity of porous media the oil as a wetting phase more easily to be displaced by carbon dioxide as a non-wetting phase rather than in the low porosity regions.

Table 3. Simulated of displacement efficiency (E_D) results from the displacement process.

Eff. Porosity, (%)	Permeability, (mD)	E_D, (%)
6.126	4.44143	83.49233
12.278	16.86075	91.26258
18.034	38.83125	93.73217
23.511	74.78043	94.95934
28.861	130.3054	95.70836
33.784	213.4396	96.18802
38.497	331.0193	96.53228
43.102	502.1887	96.79593
47.56	744.2541	97.00252

From Table 3 and Figure 6a it is shown that the porous media that have a high values of effective porosity, the displacement efficiency that could be obtained in the displacement process also higher. The trend of these curves show rapid increasing from the effective porosity of 6.126% to 18.034%, obtained of displacement efficiency each being values of 83.49233% to 93.73217%. While, for the values of effective porosity above 18.034%, the increasing in displacement efficiency was relatively slow and stable.

Based on the effective porosity values of porous media, the displacement efficiency had ranges of 83.49233% to 97.00252%. Thus, it demonstrates that the grain sizes geometry and their distributions in porous media could also effect on the displacement efficiency.

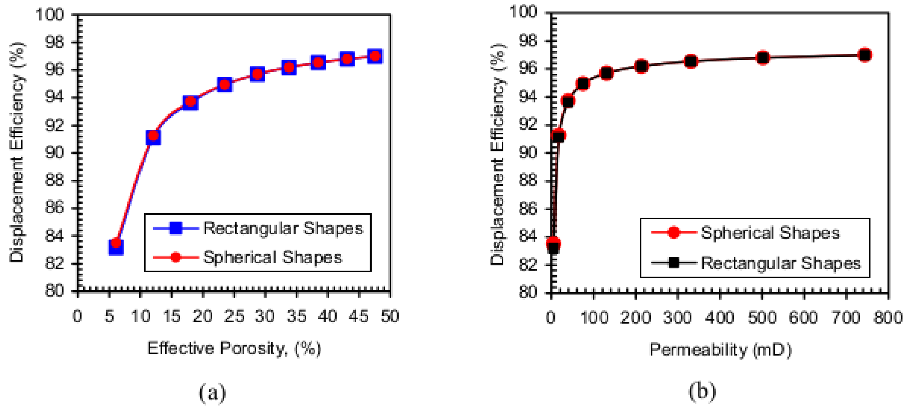


Figure 6. Simulated displacement efficiency as a function of: (a) effective porosity: and (b) permeability of porous media

In Figure 6b shown in above, the simulated displacement efficiency as a function permeability of porous media was presented. It is shown that the permeability of porous media could also affect on the displacement efficiency. A proportional relationship is found to correlate the permeability values and displacement efficiency also increases. The trend of curves was quite similar to that presented in Figure 6a. However, it is worth clarifying that at permeability ranges of 4.44143 mD to 38.83125 mD, the curves increase rapidly and after that the trend of curves came relatively linear. It demonstrates the fact that permeability of porous media is a function of pore size and shape distribution of solid grains in the porous media. It can be concluded that permeability can effect strongly the distribution of the fluids in the pores. Hence, it was also demonstrated that changing of porous media model from the low to high permeability would increase the displacement efficiency.

Furthermore, to validate the displacement efficiency resulted from simulation a comparison between simulation results and those obtained from laboratory micromodel experiment was conducted, as shown in Figure 7. The displacement process in the laboratory was conducted with micromodel having porosity of 54% and permeability of 1.28 Darcy, while for simulation the porosity was 47.56% and permeability of 744.2541 mD. From Figure 7, it can be seen that the trend of both curves is very similar with the difference only 0.88483%. The displacement efficiency estimated result from the simulation was 97.00252%, while the laboratory experiment was 97.88735%. The displacement efficiency result from the laboratory micromodel experiment is higher compared with the simulation result. Based on the Figure 7, it is obvious that the estimation of simulated displacement efficiency was in excellent agreement with the results of laboratory micromodel experiment. The estimations closely match with experimental data with difference less than 5%. Thus, conclusion can be withdrawn as that the estimation of displacement efficiency by this simulation model is an adequate representation of the macro-level of porous media as in laboratory experiment.

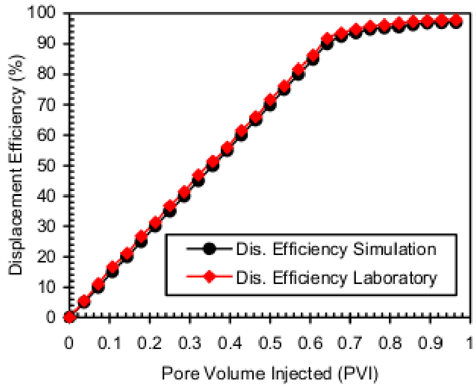


Figure 7. Comparison of displacement efficiency results from simulation and laboratory experiment

4. CONCLUDING REMARKS

The displacement mechanisms and estimations of displacement efficiency of the immiscible displacement process in heterogeneous porous media were simulated well by FHP-II model of lattice gas automata. The heterogeneity of porous media is very affected on the displacement mechanisms and displacement efficiency. The model of a random spherical and/or rectangular shapes and its network representation of the pore space were adequate to predict the properties and behavior of fluid flow in heterogeneous porous media. The simulation model was also able to estimate the residual oil saturation that actually represents the real porous media. The simulated residual oil saturation has ranges of 2.997477% to 16.83069%. The estimation of displacement efficiency by this simulation model was an adequate representation of the macro-level and real porous media as in laboratory experimental. The simulated displacement efficiency has ranges of 83.16931% to 97.00252%. Validation of displacement efficiency with laboratory experiment also was done and excellent agreement achieved with difference less than 5%. The simulation was applicable in the petroleum engineering to investigate the immiscible displacement process in heterogeneous porous media.

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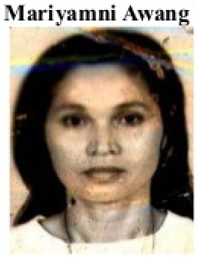

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