IMPES SIMULATOR

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Abstract

Numerical method using Matlab is employed to solve multiphase 2D flow and transport equation in the absence of gravitational force and capillary pressure under incompressible condition. Which transport is solved explicitly and pressure is solved implicitly. The simulation result is presented in water saturation and pressure velocity solution.

Introduction

IMPES is a method to find solution of saturation and pressure which the solution is calculated sequentially. Under incompressible condition, pressure and velocity solution can be calculated as following.

$$-\nabla.(\lambda_T \nabla P) = q \quad (1)$$

$$u_T = -\lambda_T \nabla P \quad (2)$$

Velocity solution is then employed to solve saturation solution in certain time step as following.

$$\frac{\partial(\phi S_\alpha)}{\partial t} - \nabla.(f_\alpha u_T) = q_\alpha \quad (3)$$

The last saturation is obtained by.

$$S_N = 1 - \sum_{1}^{N-1} S_\alpha \quad (4)$$

And fractional flow and total mobility is defined by.

$$f_\alpha = \frac{\lambda_\alpha}{\lambda_T}\ , \quad \lambda_T = K \sum_{1}^{N} \frac{k_{r\alpha}}{\mu_\alpha} \quad (5)$$

Methodology

IMPES is used for solving saturation and pressure sequentially. Saturation is solved explicitly, while pressure is solved implicitly. .

1. **Explicit Saturation Method**

   Explicit method employs Euler forward method in time grids which enables saturation prediction in next time step based on known current saturation. In explicit method, equation 3 is discretized as following.

$$\phi \frac{S_{ij}{}^{n+1} - S_{ij}{}^{n}}{\Delta t} + \left(\frac{f_{i,j}{}^{n}\, U_{X\, i+1,j} - f_{i-1,j}{}^{n}\, U_{X\, i,j}}{\Delta x} \right) + \left(\frac{f_{i,j}{}^{n}\, U_{Y\, i,j+1} - f_{i,j-1}{}^{n}\, U_{Y\, i,j}}{\Delta y} \right) = q_{i,j} \quad (6)$$

Equation 6 can be rearranged as following.

$$S_{ij}{}^{n+1} = S_{ij}{}^{n} + \frac{\Delta t}{\phi} \left[q_{ij} - \left(\frac{f_{i,j}{}^{n}\, U_{X\, i+1,j} - f_{i-1,j}{}^{n}\, U_{X\, i,j}}{\Delta x} \right) - \left(\frac{f_{i,j}{}^{n}\, U_{Y\, i,j+1} - f_{i,j-1}{}^{n}\, U_{Y\, i,j}}{\Delta y} \right) \right] \quad (7)$$

2. Implicit Pressure Method

In this study, incompressible fluid is used which no density is changing along the process. Thus, no iteration is required in order to find pressure solution. Pressure profile is only changing due to change in total mobility since multiphase flow is going through the domain.

$$-\nabla . (\lambda_T\, \nabla P) = q$$

Result and Discussion

Result of numerical simulation is presented in terms of saturation and pressure profile along the reservoir. In order to identify the effect of heterogeneity, and space and time grid resolution, sensitivity study is undertaken. Some default input parameter are presented in table 1 below.

Table 1 : Default Input Parameter

Parameter	*Value*	*Unit*
LX	*100*	*m*
LY	*100*	*m*
krwe	*0.7*	-
kroe	*0.8*	-
S_{wc}	*0.2*	-
S_{or}	*0.1*	-
ϕ	*0.3*	-
μ_w	*0.001*	*Pa.s*
μ_0	*0.01*	*Pa.s*

1. Homogenous Reservoir

Consider 2D reservoir with properties as mentioned in table 1 above. Space and time grid sensitivity is undertaken to identify the effect of space and time grid resolution towards the saturation and pressure profile.

a. Space grid sensitivity

Three cases are constructed to see what changes caused by space resolution in homogenous reservoir. The domain is divided into 20, 30, and 40 number of grids for both x and y direction while maintain simulation time to be 4×10^8 seconds. Result of space grid sensitivity is presented in figure 1 below.

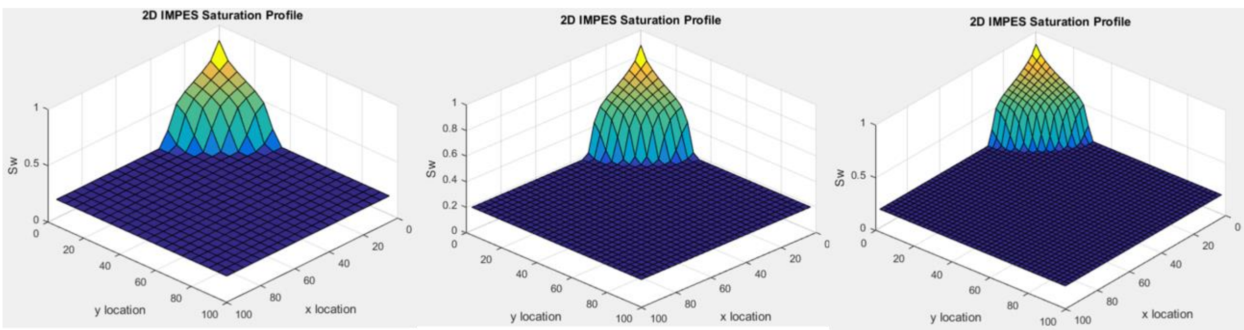

Figure 1 : Saturation profile in 2D homogenous reservoir with 20, 30, and 40 number of space grids from left to right

As presented in figure 1 above, in homogenous reservoir, space grid resolution does not affect areal sweep efficiency. The area covered or swept by water is the same for those three cases. However, in vertical sweep efficiency, smaller grid size shows more accuracy than larger one. It can be seen in figure 1, simulation with 50 space grid shows shock saturation more clearly. Although analytically shock is interpreted as a discontinuity in saturation, it physically appears to be a continuous but very rapid change in very tiny space. Numerical simulation really depends on grid resolution. In large grid size, shock is hard to observe. Thus, in order to model shock profile, smaller grid size is preferable in order to minimize error.

Pressure profile is not really affected by space grid resolution. In incompressible flow and homogenous reservoir, uniform pressure drop is happening if only one phase is flowing, or in the area in front of shock. Meanwhile in area behind the shock, multiphase flow applied. Therefore, a hump in pressure profile happens when there is a sudden change between single phase into multiphase flow. Pressure profile under space grid sensitivity can be seen in figure 2 below.

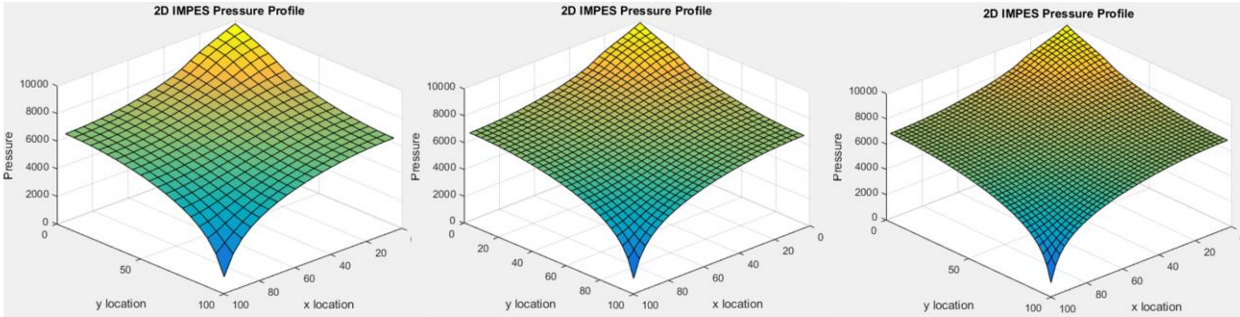

Figure 2 : Pressure profile in 2D homogenous reservoir with 20, 30, and 40 number of space grids from left to right

b. Time grid sensitivity

Three cases are constructed to see what changes caused by time resolution in homogenous reservoir. The domain is fixed in 40 number of grids, but simulation runs in 2 *x* 10^8, *3 x* 10^8, and *4 x* 10^8 seconds, or around 3 years difference between simulation time. Saturation profile in three different simulation time is presented in figure 3 below.

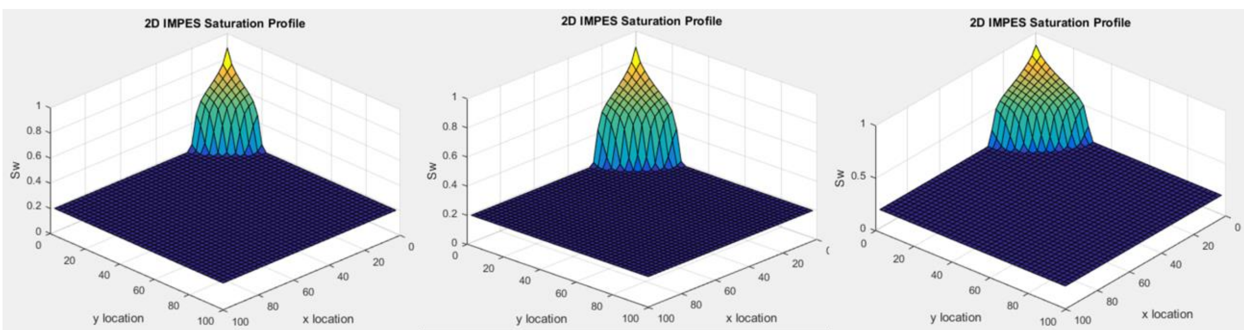

Figure 3 : Saturation profile in 2D homogenous reservoir with 2, 3, and 4 x 10^8 *secs simulation time from left to right*

As the simulation time increasing, saturation profile grows larger with same speed in both x and y direction. Therefore, uniform sweep area is obtained. All area of the reservoir domain will be covered by the injected water. No conservative issue encountered under homogenous reservoir condition.

Time step will always be changing throughout the simulation due to change in saturation which influence total velocity. Effect of time stop towards simulation stability will be discussed later in heterogeneous reservoir section.

Similar to pressure profile in space grid resolution, a hump also happens indicating change from multiphase flow region to single phase flow region. It can be seen in figure 4 below, hump in pressure profile follows the propagation of shock front.

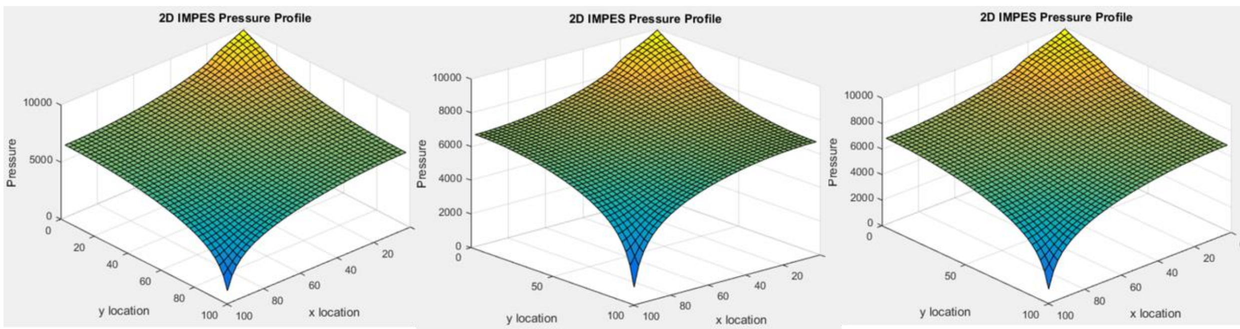

Figure 4 : Pressure profile in 2D homogenous reservoir with 2, 3, and 4 x 10^8 secs simulation time from left to right

2. Heterogeneous Reservoir

Now the 2D reservoir with properties as mentioned in table 1 have different value of permeability in each grid controlled by random function. Again, space and time grid sensitivity is undertaken to identify the effect of space and time grid resolution towards the saturation and pressure profile.

a. Space grid sensitivity

Similar to homogenous reservoir, 2D heterogeneous reservoir, domain is divided into 20, 30, and 40 number of grids for both x and y direction and fix simulation time to be *4 x 10^8* seconds. Space grid sensitivity in heterogeneous reservoir can be seen in figure 5 below.

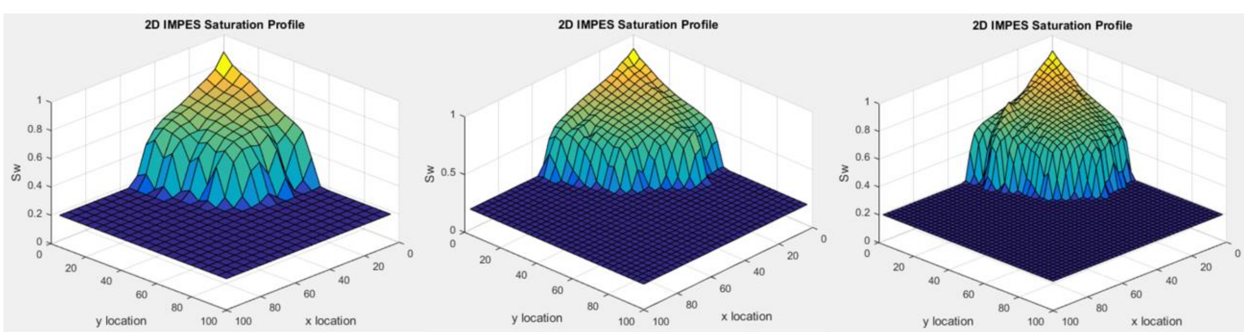

Figure 5 : Saturation profile in 2D heterogeneous reservoir with 20, 30, and 40 number of space grids from left to right

Permeability is generated randomly throughout the reservoir using random function which must be different for every simulation run. Water flows through its preferred path according to permeability value. Thus shock front will be different in each grid location, and reduce areal sweep efficiency. Due to its randomness, there is probability that a grid cell with high permeability is bounded with other grids with tiny permeability or even no flow boundary if it is attached to reservoir boundary. Unlike in homogenous reservoir, if such this case happens, in high simulation time conservative principle can no longer hold. Saturation explodes to be more than one. Water will find its own way to flow.

Another problem encountered is stability limitation. In heterogeneous reservoir, sometimes stability cannot always be ensured. Stability condition is derived by CFL assuming linear relation although actually the saturation problem is not linear. CFL condition requires average velocity. Since velocity varies due to variation of permeability, sometimes when velocity in a grid point is too far different from average velocity, stability cannot hold.

Pressure profile in heterogeneous reservoir is highly dependent on heterogeneity. The quantity of pressure drop between grids may be different. Pressure drop is inversely proportional to permeability. The higher permeability, the lower pressure drop required to flow the water. Pressure profile in 2D heterogeneous reservoir in different grid resolution is shown in figure 6 below.

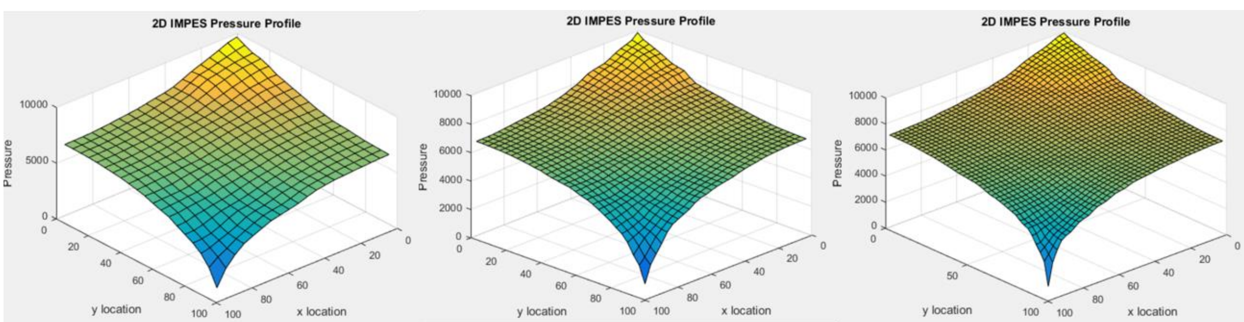

Figure 6 : Pressure profile in 2D heterogeneous reservoir with 20, 30, and 40 number of space grids from left to right

b. Time grid sensitivity

Simulation runs in 3 different time to see effect of time sensitivity in heterogeneous reservoir. The domain is fixed in 40 number of grids, but simulation runs in 2×10^8, 3×10^8, and 4×10^8 seconds, or around 3 years difference between simulation time. Saturation profile in three different simulation time is presented in figure 7 below

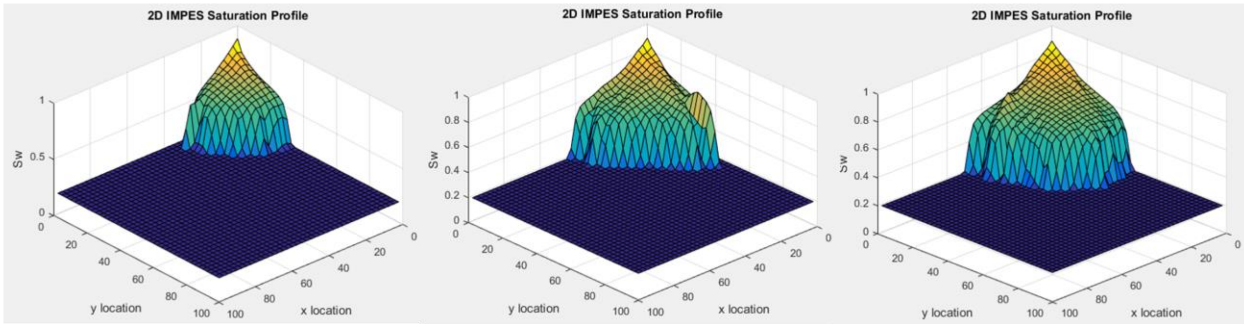

Figure 7 : Saturation profile in 2D heterogeneous reservoir with 2, 3, and 4 x 10^8 secs simulation time from left to right

Water will flow further as the simulation time increasing. Here, conservative principle can be a big issue. In larger time, water explosion can occur in certain grid which is bounded by low permeable grid.

Also in larger time, this simulation sometimes cannot perfectly model the flow in real reservoir due stability issue. As discussed in space grid sensitivity in heterogeneous reservoir, unstable solution might happen if there is a big difference between velocities in particular grid with average velocity. One solution to tackle this problem is reducing CFL. However, reducing CFL means longer running time.

Like in homogenous reservoir, pressure profile in heterogeneous reservoir also possesses a hump indicating where the location of shock. In front of shock, only one phase fluid is flowing. But the pressure drop varies depending on heterogeneity. Pressure profile in 3 different time is shown in figure 8 below.

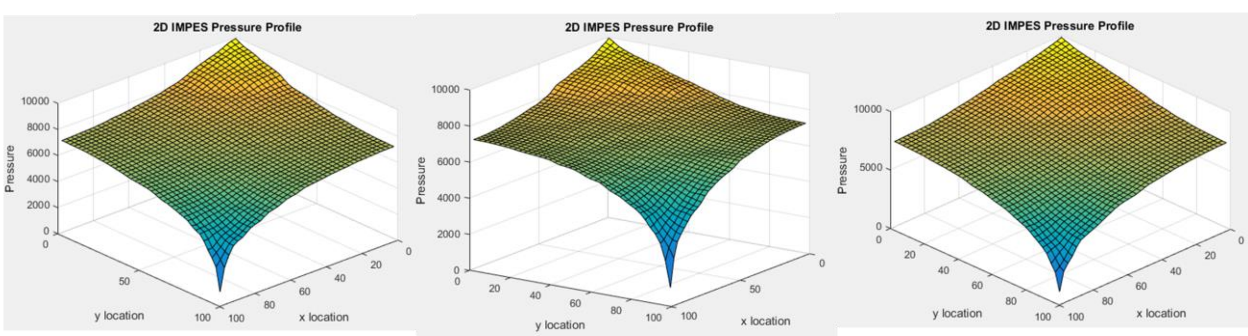

Figure 8 : Pressure profile in 2D heterogeneous reservoir with 2, 3, and 4 x 10^8 secs simulation time from left to right

3. **Mobility Ratio Sensitivity**

Mobility ratio sensitivity is generated by changing the value of water viscosity to 10 times smaller, equal, and 10 times larger than oil viscosity. Simulation is run in 2D homogenous reservoir with 40 number of grid size in both x and y direction and simulates *4 x 10*^{8} seconds water flow. Result of mobility ratio sensitivity is shown in figure 9 below. Mobility ratio affect both areal and vertical efficiency. In higher water viscosity, shock saturation is higher than the one in low water viscosity. In multiphase flow region, pressure drop is also higher in higher water viscosity case. The reservoir needs higher pressure drop to push the same amount of water mass.

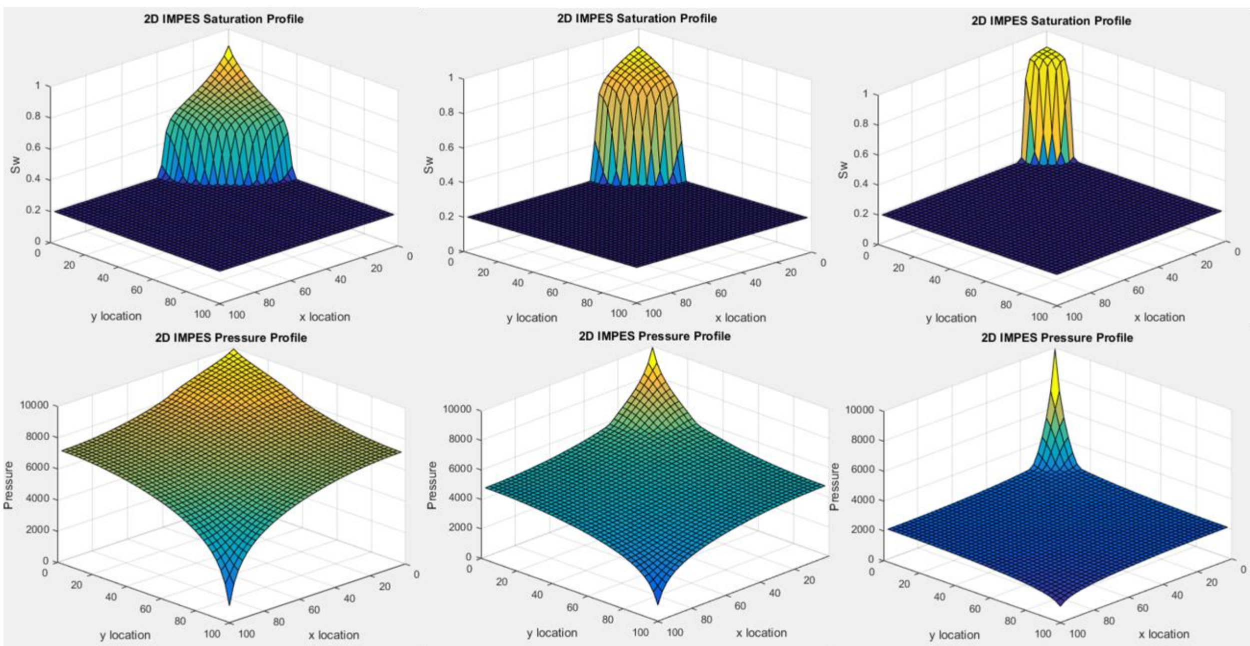

Figure 9 : Saturation and pressure profile in $\mu_w < \mu_o$ *,* $\mu_w = \mu_o$ *,* $\mu_w > \mu_o$ *from left to right*

Conclusions

Some conclusions can be withdrawn from this study as following.

1. IMPES solve saturation explicitly and pressure implicitly in sequence.
2. Stability and conservative issue sometimes happen in heterogeneous reservoir.
3. Permeability heterogeneity plays important role on determining areal sweep efficiency.
4. Mobility ratio influences vertical efficiency and pressure profile.

References

Hajibeygi, Hadi. Lecture Notes 2017 AES1350 Reservoir Simulation.

Cusini, Matteo. Assignment 3 2017 Notes.