INTERNATIONAL JOURNAL OF
NUMERICAL ANALYSIS AND MODELING
Volume 2, Supp , Pages 138–142

FULL IMPLICIT NUMERICAL SIMULATOR FOR POLYMER FLOODING AND PROFILE CONTROL

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Abstract. In this paper, taking account of the major physical and chemical mechanisms, such as: for polymer, shearing propertypermeability reduction, adsorption, inaccessible porous volumes, for gel, gelation speed, water viscosity changing with gel, permeability reduction, adsorption and retention in reservoir rocks, a three-dimensional, three-phase (oleic, vapor, aqueous) and six-component mathematical model has been established for polymer flooding and profile control. By use of full implicit finite difference method and calling PETSc linear solving system, the full implicit polymer flooding and profile control simulation software has been developed on PC-Linux environment based on black oil simulator, water flooding, polymer flooding and profile control simulation methods are integrated and applied into practice.

Key Words. numerical simulator, polymer flooding, profile control, full implicit, mathematical model.

1. Preface

With polymer flooding in Daqing, we have to face the problems, such as: a lot of polymer sewage was injected to stratum, polymer depth profile control and project setting, etc. In order to resolve actual problems and take full advantage of reservoir numerical simulation, it is urgent to require the technical support of polymer flooding and profile control simulation software.

Currently, there are some problems for POLYMER software used in Daqing, such as pinch and fault disposal and rock compressibility, etc. VIP-POLYMER upgrade software is applicable, whereas it is impossible of large scale application because of licence limit, profile control simulation software needs to be improved and refined.

In order to develop independent and practical simulation software for polymer flooding and profile control, a three-dimensional, three-phase (oleic, vapor, aqueous) and six-component (water, oil, gas, polymer, gel, cross-linker) mathematical model has been established for polymer flooding and profile control. Based on isothermal black oil model, the major physical and chemical mechanisms and other important factors are considered in the model, By use of full implicit finite difference method, the full implicit polymer flooding and profile control simulation software has been implemented on PC-Linux environment, water flooding, polymer flooding and profile control are integrated and applied into practice.

2. Mathematical model

According to mass balance equation, the basic differential equations of oil, water, gas, polymer, cross-linker and gel are derived and established as followed [1, 2]:

$$\text{(1)} \qquad \text{Oil:} \quad \nabla\left[\frac{K_{ro}K}{\mu_o B_o}\nabla(p_o-\gamma_o\nabla D)\right]+\frac{q_o}{B_o}=\frac{\partial}{\partial t}\left(\frac{\phi S_o}{B_o}\right)$$

$$\text{(2)} \qquad \text{Water:} \quad \nabla\left[\frac{K_{rw}K}{\mu_w B_w}\nabla(p_w - \gamma_w \nabla D)\right] + \frac{q_w}{B_w} = \frac{\partial}{\partial t}(\frac{\phi S_w}{B_w})$$

$$\text{(3)} \qquad \text{Gas:} \quad \nabla\left[\frac{K_{rg}K}{\mu_g B_g}\nabla(p_g - \gamma_g \nabla D)\right] + \nabla\left[\frac{K_{ro}K}{\mu_o B_o}R_s\nabla(p_g - \gamma_g \nabla D)\right] + \frac{q_g}{B_g} + \frac{R_{so}q_o}{B_o} = \frac{\partial}{\partial t}[\phi(\frac{S_g}{B_g} + \frac{R_{so}S_o}{B_o})]$$

$$\text{(4)} \qquad \text{Polymer:} \quad \frac{\phi}{\phi_p}\nabla\frac{K_{rw}K}{R_{kfp}\nu_w\mu_p}C_p\nabla(p_w - \gamma_w\nabla D) - \phi\frac{S_w}{\nu_w}D_p - \phi\frac{S_w}{\nu_w}R_p - C_p q_w = \frac{\partial}{\partial_t}(\phi\frac{S_w}{\nu_w}C_p + (1-\phi)\frac{\rho_r}{\rho_w\nu_w}\hat{C_p})$$

$$\text{(5)} \qquad \text{Cross-linker:} \quad \frac{\phi}{\phi_p}\nabla\frac{K_{rw}K}{R_{kfp}\nu_w\mu_p}C_\chi\nabla(p_w - \gamma_w\nabla D) - \phi\frac{S_w}{\nu_w}R_\chi - C_\chi q_w = \frac{\partial}{\partial_t}(\phi\frac{S_w}{\nu_w}C_\chi + (1-\phi)\frac{\rho_r}{\rho_w\nu_w}\hat{C_\chi})$$

$$\text{(6)} \qquad \text{Gel:} \quad \frac{\phi}{\phi_p}\nabla\frac{K_{rw}K}{R_{kfg}\mu_g}C_g\nabla(p_w - \gamma_w\nabla D) + \phi S_w R_g - C_g q_w = \frac{\partial}{\partial_t}(\phi S_w C_g + (1-\phi)\frac{\rho_r}{\rho_w}\hat{C_g})$$

$$\text{(7)} \qquad \text{where} \quad R_i = k_i C_\chi^d C_p^f$$

$$\text{(8)} \qquad D_p = -\alpha C_p$$

The main influences are considered in the model, such as: for polymer solution, shearing propertypermeability reduction, adsorption, inaccessible porous volumes; For gel, gelation speed and water viscosity changing with gel, permeability decrease, adsorption and retention in reservoir rocks, etc..

3. Numerical model

We adopt fully implicit difference scheme to make the mathematical model dispersed, and then obtain nonlinear algebraic equations. These unknowns in equations are grid phase pressure, grid phase saturation, grid component concentration (polymer, gel and cross-linker) and well production/injection rate or well flowing pressure. By expanding equations with Taylor series, linear system is produced. We solve the equations using linear equation solver (SLES) in PETSc. The equations are:

$$\text{(9)} \qquad [J]^k \cdot \overrightarrow{u}^{k+1} = -\overrightarrow{r}^k$$

4. The development and application of simulator

On the basis of DQHY simulator, the implicit numerical simulator for polymer flooding and profile control has been implemented on PC-Linux environment. It keeps the detailed description of black oil model for reservoir geology, liquids property and production performance and has the main function of polymer flooding and profile control numerical simulation, water flooding, polymer flooding and profile control simulations are integrated. The software is convenient to use, the users only need to add the polymer flooding and profile control card in data file, then the simulation could be started on PC-cluster.

Main functions: (1) the development effect of water flooding, polymer flooding and profile for could be modelled for single well or field; (2) optimize parameter and project; (3) the study of mechanism and sensitivity for polymer flooding and profile control.

The concept model has been computed by use of the simulator, the speed and precision is similar to one of VIP-POLYMER. The first example is the contract of development in different polymer concentration. the development effects of water flooding and polymer flooding are computed and contrasted in different concentration. The model is homogeneous with monolayer, well space is $250m$, there are four injection wells and nine production wells, the permeability is $800md$, porosity is 0.25, the cell number is 1681, the injection concentration respectively is $300ppm$, $700ppm$ and $1000ppm$, the results are showed by Figure 1. The second example is the contract of development effect in different polymer quantity, namely, the development effects in different injection volume ($0.32PV$, $0.48PV$ and $0.64PV$) are predicted, the predicted curves of water cut and total oil production are showed by Figure 2. The third example is the contract of profile control effect for low permeability layer, the model is homogeneous and has two layers, the permeability is respectively $200mD$ and $800mD$, control profile 200 days after water flooding 3000 days, and then water flooding, the results are showed by Figure 3. The development effect of low permeability layer is obviously improved by control profile.

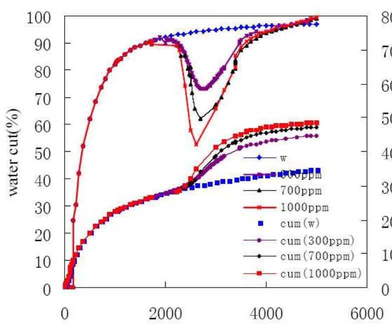

Figure 1. Contract of development effect in different polymer concentration.

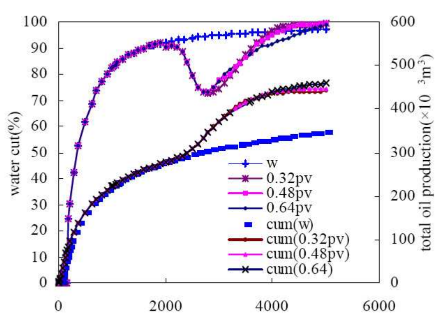

Figure 2. Contract of development effect in different polymer quantity.

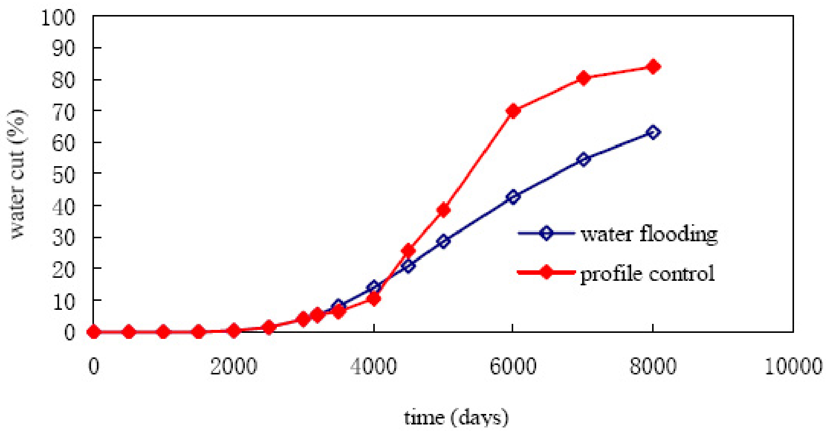

FIGURE 3. Water cut contract of low permeability layer.

5. Conclusions

(1) A three-dimensional, three-phase (oleic, vapor, aqueous) and six-component mathematical model was established for polymer flooding and profile control. The model could be representative of the main physical and chemical mechanisms of polymer flooding and profile control.

(2) By use of full implicit finite difference method and calling PETSc linear solving system, the full implicit simulation software for polymer flooding and profile control has been developed on PC-Linux environment based on DQHY simulator.

(3) The software has the functions of water flooding, polymer flooding, profile control and any combination of them. It has good practicability and can be applied into practice.

(4) The results have proved its practicability. It can be used in history match, project prediction, effect evaluations of many oil displacement manners and sensitivity analysis of parameters, etc. The software can provide strong technical supports for optimizing design of polymer flooding scheme and tracking adjustment, it will be applied widely in Daqing Oilfield.

Symbol definition:

K–absolute permeability, μm^2;
K_{ro}, K_{rw}, K_{rg} — relative permeability of oil, water, gas, μm^2;
μ_o, μ_w, μ_g — viscosity of oil, water, gas, $mPa \cdot s$;
μ_p, μ_g — viscosity of polymer solution, gel, $mPa \cdot s$;
$\rho_o, \rho_w, \rho_g, \rho_r$ — density of oil, water, gas and rock, g/cm^3;
p_o, p_w, p_g — pressure of oil, water, gas, KPa;
t — time, s; h — thickness of oil layer, m;
q_o, q_w, q_g — flow rate of oil, water, gas, m^3/s;
B_o, B_w, B_g — volume compressibility of oil, water, gas;
S_o, S_w, S_g — saturation of oil, water, gas;
ϕ — rock porosity in oil layer;
ϕ_p — the porosity accessible of polymer solution;
C_p, C_χ, C_g — concentration of polymer solution, cross-linker and gel, 10^{-6};

$\hat{C}_p, \hat{C}_\chi, \hat{C}_g$ — absorbent concentration of polymer solution, cross-linker and gel, 10^{-6};

R_{kfp}, R_{kfg} — permeability reduction factor of polymer solution and gel solution;

D_p — decomposition of polymer;

R_i — rate of consumed/fomed mass concentration of polymer/cross-linker/gel;

k_i — reacting coefficients;

d, f — exponents.

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