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Gas-liquid flows in porous media and coupling effects

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Gas flood (N_2/CO_2) are promising EOR methods, meanwhile CO_2 trapping and sequestration are important for environmental protection. How to inspect and control gas-liquid flows are the core technology. Based on fundamental principle, established the numerical model to simulate coupling effects of gas-liquid flows in reservoir. Result shows that CO_2 swept area would form a low electrical potential enclosure, and gas-liquid front is the place where potential begin to decrease while production, this area would enlarge till injected gas break thought at production well, then potential begin to recover to zero, spatial variance would disappear. The result is instructive to the monitor gas-liquid flow process.

Key words: Gas-liquid Flows; Coupling Effect; Dynamic Monitoring; Gas Flood

INTRODUCTION

Gas-liquid flows phenomena are of significance for enviorment protection and reservior stimulation. CO_2 trapping and sequestration techniques are important methods to deal with global climate change and slow down greenhouse gas emissions currently. The main buried sites include oil and gas reservoirs, deep salt water layers and non-exploitable coal beds [1]. Meanwhile, gas stimulation methods, including gas flood, huff-puff, foam flooding are promising EOR method not only for unconviential reservoir, also for the hight permeability reservor development. There are many challenges behind the considerable economic and social benefits.How to inspect and control gas-liquid flows are the core technology. Its process level directly related to the injection of gas into the target layers, play the desired role and not leak to the outside. Current engineering measures include [2-3]: gravity, sonic logging, time-lapse seismic, 3D/4D seismic, resistivity tomography, and micro seismic monitoring. However, these methods are restricted by factors such as resolution, efficiency, price and so on. Each has its limitations. Cheap, continuous and efficient monitoring methods are the direction of future. In this paper , we simulated coupling electrical potential field changes caused by artifical gas source.

EQUATIONS AND MODELS

Streaming potential is a coupling effect between fluid flow and electrical flow in porous media. The measurement target is the signal in formation environment produced naturally. The basic equations can be described by (1) and (2) formulas [2].

$$\mathbf{q} = -L_{11}\nabla p - L_{12}\nabla \varphi \qquad (1)$$

$$\mathbf{j} = -L_{21}\nabla p - L_{22}\nabla \varphi \qquad (2)$$

q is flow velocity, j is current density,p is fluid pressure, φ is electrical potential, σ_r electrical conductivity of saturated fluid. $L_{11} = k/\mu$ $L_{12} = L_{21} = C_v\sigma_r$, $L_{22} = \sigma_r$. C_v is called flow potential coupling coefficient,which is an important parameter describing flow potential effect, and its definition is as follows (3).

$$C_v = \frac{\Delta\varphi}{\Delta p} = -\frac{L_{12}}{L_{22}} \qquad (3)$$

The second item on the right of formula (1) can be regarded as the feedback effect of the electrokinetic effect on the liquid flow. Under deep reservoir condition, this feedback effect is very small and can be neglected. Thus, (1) can be simplified as Darcy's law, and the coupling process becomes a one-way process of producing current.

The simulation is based on the injection of carbon dioxide. The critical temperature and pressure of CO_2 are 31 ^oC and 7.38MPa When the temperature and pressure are greater than the condition, they would enter into critical supercritical state [4-5].

The relative permeability of supercritical CO_2 and formation water is calculated by Van Genuchten-Mualem (VGM) method. The formula is as follows.

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$$K_{rw}=\begin{cases}\sqrt{S^*}(1-(1-(S^*)^{1/\lambda})^{\lambda})^2 & S_w<1\\ 1 & S_w=1\end{cases} \quad (4)$$

$$K_{rg}=\begin{cases}1-K_{rw} & S_{gr}=0\\ (1-\hat{S})^2\quad(1-\hat{S}^2) & S_{gr}\neq 0\end{cases} \quad (5)$$

$$S_w^{\;*}=(S_w-S_{wc})/(1-S_{wc}) \quad (6)$$

$$\hat{S}=(S_w-S_{wc})/(1-S_{wc}-S_{gr}) \quad (7)$$

K_{rw} is the relative permeability of water phase, K_{rg} is the relative permeability of gas phase, S_w is water saturation, S_{wc} is irreducible water saturation, S_{gr} is residual gas saturation. In this run, parameter value are $S_{wc}=0.25, S_{gr}=0.05, \lambda=0.75$.

The potential coupling coefficient and conductivity are important parameters affecting amplitude and distribution of potential data. Measurement target of multiphase flow conditions is mainly affected by water saturation, although at present about the multiphase flow coupling coefficient changes have no unified quantitative model, but the main trend is that coupling coefficient has positive correlation growth with water saturation. According to core test results [6], relationship between relative coupling coefficient and water saturation can be deseribed by the linear formula (8).

$$C_r=\hat{S} \quad (8)$$

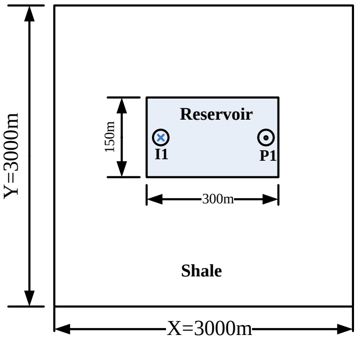
The calculation of electrical conductivity adopts Archie’s law, such as (9), neglecting the conduction of rock surface

$$\sigma_r=\phi^{1.8}S_w^{\;2}\sigma_w \quad (9)$$

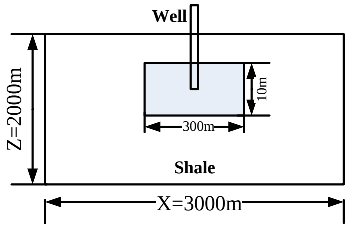
σ_r is the conductivity of rock saturated by fluid, ϕ is the porosity of rock, S_w is saturation of formation water, σ_w is the conductivity of formation water .

RESULTS AND DISSCUSSIONS

As shown in Figure 1, reservoir size is 300×150 ×10m, the complete study area size is 3000×3000× 2000m, reservoir depth is 1500m, initial pressure is 15MPa, CO_2 density is 780kg/m^3, viscosity of supercritical CO_2 is 0.05 $mPa\cdot s$, the density of water is 1000kg/m^3, water viscosity is 0.65. Homogeneous reservoir with porosity 25% and permeability 0.65D, one injection well (I1) with steady pressure 17MPa, one production well (P1) with steady flow rate 20m^3/d, run for 6 years.



(a) X-Y Plane



(b) X-Z Plane

Fig. 1. Schematic diagram of model

According to Berea sandstone core test [6], under saturated water conditions, core conductivity is 0.003S/m, coupling coefficent is about -30mV/0.1MPa; under steady-state conditions, CO_2 flow through the core is about -3mV/0.1MPa, conductivity is 0.0026 S/m. This result shows that the difference between the two conditions is of one order magnitude, but conductivity variations are quite limited.

If liquid CO_2 passes through air dried core, it will change to -0.02mV/0.1MPa. The whole area is wrapped by shale, shale’s conductivity is 0.01S/m. The calculation process is, firstly the flow of CO_2 and formation water is solved, and then finite difference method is used to solve the electrical problem.

As shown in Figure 2, electrical potential (U) and gas saturation (Sc) saturation distribution in X-Y plane. The left column is the potential distribution of middle depth at different time, the right column is correspond CO_2 saturation distribution. The saturation map shows that, along with CO_2 injected into the formation, it would promote stable gas-liquid front. After 900 days of production, the front has swept half areas of reservoir .After 1350 days, injected CO_2 breakthrough at production well.

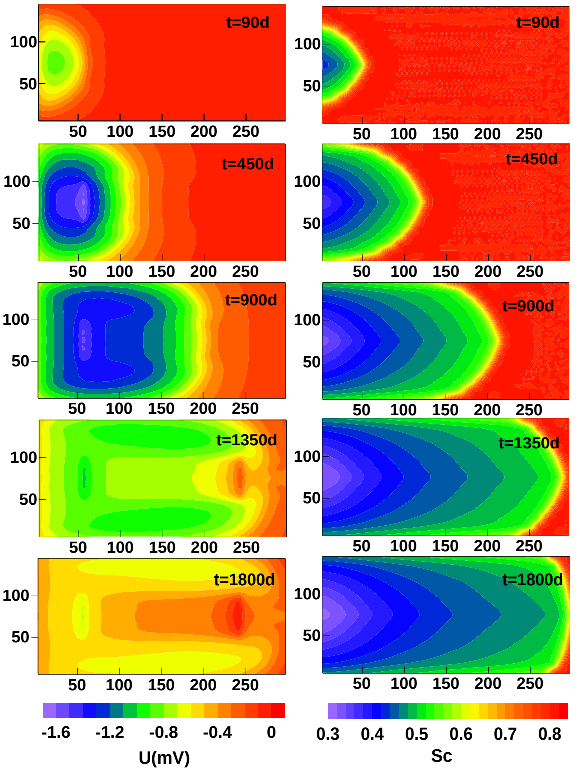


Fig. 2. Electrical potential (U) and gas saturation (Sc) in X-Y plane

Compare with potential map, after 90 days injection well bottom would form a low potential area, the low potential would expand and form an enclosed area. Potential at injection well began to increase at 450 days. Along with production, low potential region would move on to the production well continuously. So position of the potential drop is basically same as saturation front. When CO_2 arrived at production well, potential drop reached maximum, then gradually recovered from negative to zero, so the red part of 1350 ~1800 days would gradually increase to initial state. If multi-position electrical potential can be obtained at surface or underground condition, these data would be a visual representation of CO_2 migration process.

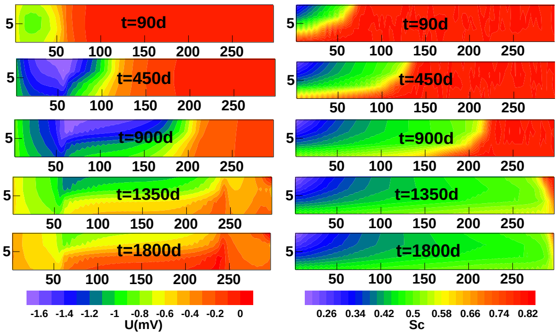


Fig. 3. Electrical potential (U) and gas saturation (Sc) in X-Z plane

As shown in Figure 3, electrical potential (U) and gas saturation (Sc) in X-Y plane, due to density difference, injected gas would form an arc front. At 450 days, injected CO_2 contact the bottom of the reservoir. Potential distribution shows a closed low potential area with narrow width, which is related to the geometry of the model.

When gas move along X-axis direction, after 450~900 days affected areas gradually increased, potential value began to decline .After 900 ~1350 days, zero potential areas began to recover ,after 1800 days, potential at bottom of the reservoir has restored to the initial state. If the geological structure is polygon, and CO_2 emitted at the top or bottom layers, abnormal potential changes would happen.

The above results show that injection of CO_2 may cause marked difference of electrical potential, and the main trend is the decrease of potential, especially at the leading edge position [7-8]. However, calculated magnitude of the potential difference is no more than 2mV, interpretation quality depend on the interference of environment conditions. Refer to electrical logging experience [9-10], it is difficult to obtain abundant and sufficient observation value; however, the vertical direction with fixed electrodes and continuous measuring, thus potential signals are quite useful, and is the development direction of future.

CONCLUSION

The CO_2 swept area would form a electrical potential drop zone, which will continue move to the production well. When CO_2 breaks through extraction well, electrical potential would gradually returns. The injected CO_2 moves along the top of the reservoir, whose changes are more obvious than other place in reservoir. The reasonable measuring position should be selected at the bottom of the injection well, or at bottom of producing well and observation well. By placing a plurality of measuring electrodes, electrical potential can be obtained continuously. The plane and vertical difference of potential can characterize the migration liquid-gas contact front. The coupling coefficient and low salinity of formation water in liquid CO_2 only differ by an order of magnitude, the conductivity properties similar to the calculated potential difference was smaller, whether has the potential interference intensity may depend on interpretation of the measured formation environment, according to the needs of strata and fluid terms and conditions.

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ТЕЧЕНИЕ ГАЗ-ТЕЧНОСТ В ПОРЬОЗНА СРЕДА И СВЪРЗАНИ ЕФЕКТИ

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(Резюме)

Продухването с газова смес (N_2/CO_2) е обещаваш метод за ускорен добив на нефт, като улавянето и отстраняването на CO_2 е много важно за опазването на околната среда. Наблюдението и контролът върху на течението газ-течност в този случай са ключови за тази технология. За тази цел е съставен математичен модел, чрез който се симулират свързаните ефекти в резервоара. Резултатите показват, че зоната на изчистване на CO_2 формира включение с нисък електричен потенциал. Фронтът на фазовата граница газ-течност е мястото, където потенциалът започва да намалява. Тази зона се увеличава до пробива на инжектирания газ в кладенеца, като потенциалът спада до нула. Резултатите са полезни за наблюдението на газо-течния процес.