CMTC-485491-MS

The Mechanism and Simulation Research of “Foamy Oil ” during CO_2 Flooding

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This paper was prepared for presentation at the Carbon Management Technology Conference held in Houston, Texas, USA, 17-20 July 2017.

Abstract

Noticeable progress in understanding the high efficiency of “foamy oil ” in solution gas drive in heavy oil reservoirs has been made in recent years. However, “foamy oil ” during CO_2 flooding was still a special and novel phenomenon when CO_2 flood asphatic oil. The basic mechanism and corresponding numerical equation of seepage flow of ‘foamy oil’, in connection with CO_2 flooding, have not been reported. This paper presented the mechanism analysis and simulation study that addressed this issue.

A new viewpoint of foamy oil during CO_2 flooding was proposed with contrasting the similarity of ‘’foamy oil”during CO_2 flooding front withthat in dissolved gas flooding. During CO_2 floodingthe‘’foamy oil” could form when CO_2 contacted with oil because precipitated asphaltene could facilitate bubble nucleation, decrease the critical super-saturation and help in maintaining the dispersed gas flow by suppressing bubble coalescence, whichsimilar to ‘foamy oil ’ in depletion drive.Two main mechanisms were proposed. The first was enhancing oil recovery obviously by decreasing viscosity of crude oil, reducing interfacial tension, and swelling oil. The second mechanism wassteady gas/oil mobility helping in maintaining high pressure in the reservoirs.

Then, the compositional model considering bubble nucleation, growth and coalescenceand CO_2 flowing characteristic was established, combining the advantages of “equilibrium model” with that of “dynamic model”. With the establishment of the model, the flowing characteristic of ‘’foamy oil”during CO_2 floodingwas regarded as the function of time and flow condition. The relative permeability curve and critical saturation of bubble were modified to determine the influence of “foamy oil” on oil recovery.

Taken one oil field in north China as example, the compositional model calculation results

indicated that bubble was mainly located at the front of carbon dioxide flooding. High efficient flooding potentialwas achievedwith “foamy oil” existed in carbon dioxide displacing front which were in accordance with the anomalously good performance in oil production.This method of calculating foamy oil properties would provide the basics for developing numerical simulation models of foamy oil flowduring CO_2 flooding.

0 Introduction

Foamy oil flow is the name commonly used to describe a form of two-phase oil-gas flow in porous media which the gas phase remains partially or completely dispersed in the oil[1-4]. there were better expected production behavoir of primary depletion wells in may Canadian and Venzuela heavy oil reservoirs. “foamy oil ” during CO_2 flooding was still a special and novel phenomenon when CO_2 flood asphatic oil.However, no literatures about the formation mechanism of the above phenomena, and corresponding numerical equations to describe the flow law and the effect on the oil development of CO_2 flooding, have been reported. This paper presents a theory and model study that address these issues.

Inspired from a kind of phenomena in dissolved gas flooding in cold production of heavy oil, the concept of "foamy oil flow" was introduced into the miscible displacement process, the formation mechanism of the "foamy oil" in the process of CO_2 injection was explained. Then, the mathematical model of the “foamy oil flow” in the CO_2 process was proposed; finally, the distribution and dynamic characteristics of the “foamy oil flow” in the process of gas injection were numerically simulated.

1 "foamy oil" in the process of CO_2 displacement

1.1 The similarity between the "foamy oil" and the "foamy oil" in the CO_2 flooding

In China, special phenomena like "foamy oil flow" during CO_2 displacing asphaltic oil were reported. In Zheng 408 block of China, there were small bubbles dispersed in the oil phase when CO_2 huff and puff were carried.They mentioned that due to high viscosity, the precipitation of CO_2 in crude oil was formed as the formation of "foamy oil", which improved the oil flow capacity, increased elastic energy of crude oil and maintained the formation pressure [5].In Lukeqin oil reservoir of west China, the appearance of unnatural "foamy oil” during gas floodingwere also reported [6]. Experiment proved that natural gas reinjection in a heavy oil field increases foamy oil recovery when the reservoir pressure is below the pseudo-bubble pressure[7,8]. Experiments showed that gas could dissolve in the oil, which would cause oil swelling, viscosity reduction and artificial foamy oil formation.

Above experiment observation and field reports showed that during CO_2 flooding the‘’foamy oil” could form when CO_2 contacted with oil which similar to ‘foamy oil’ in depletion drive.When CO_2 contacted with crude oil constantly, pseudo-bubble pressure increased. When the displacement front pressure was lower than the corresponding pseudo-bubble pressure, dissolved gas might flow; however, because of some surfactants existence, gas dispersed as bubbles was formed by the surfactant and could not immediately formed as continuous gas phase. The "foamy oil" in the CO_2 flooding is very similar to ‘foamy oil ’ in depletion drive.

1.2 Research status of“foamy oil”flow in dissolved gas drive

Foamy oil flow is the form of two-phase oil-gas flow which the gas phase remains partially or completely dispersed in the oil in dissolved gas flooding in cold production of heavy oil. Many scholars researched on “foamy oil” flow mechanism. Smith[9] was the first scholar who gave detailed accountsabout the rare phenomena. He described the "foamy oil flow" as a fluid characteristic of micro bubbles in the heavy oil. He believed that the mobility of heavy oil containing micro bubbles was several times higher than that of the ordinary single-phase oil. Maini[1] et al. observed this dispersed gas phase and call it “foamy oil” with experiment.He believed that "bubble oil" can exist with conditions as follows, ①viscous force that determine bubble growth should exceed the capillary force;②gravity cannot cause rapid separation in two-phase flow phase;③ interfacial chemistry effect is essential to prevent bubble coalescence. Kraus et al. [10] found that the effect of "foamy oil flow" on dissolve drive includes: ①increasing the compressibility of the fluid;② maintaining the reservoir pressure; ③ and delaying the gas production time.Thesescholarsreached a consensus that the "foamy oil" in dissolved gas flooding has an unusual effect to improve oil recovery.

1.3 Analysis of the stability of asphaltene to "foamy oil"

Other authors also proofed that precipitated asphaltene could facilitate bubble nucleation. Smith[9] believed a large number of asphaltene were located at the nucleation site of micro bubble in the bubble formation. However, he had no further research into the physical state of asphaltene and bubble after bubble was nucleated. He also had no further research into the effect of the asphaltene condensed around bubbles on the viscosity of crude oil.The research of Ward and Levart[11] indicated that small bubbles might appear on the asphaltic surface in a certain size under thermodynamic equilibrium, and the crude oil viscosity was reduced due to asphaltene precipitate from crude oil, which increased crude oil production. However, they did not provide a better explanation that the association between asphaltene and bubble was stronger than the asphaltene self-association.Claridge and Prats [12] suggested that asphaltenewas usually micelle like, which affected the viscosity of crude oil. When the pressure declined slowly to the bubble point pressure, the asphaltene and resin migrated to the bubble surface and formed a semi-solid film after the film formation hindered the further growth and merge of the bubble. At any time, the sum of the gas in the bubble and gas dissolved in the crude oil were equal to that of the original gas. Similarly, the quality of asphaltene adsorbed on the bubble and the asphalt with colloidal distribution were equal to the initial asphalt quality. It is also believed that the migration of asphaltene to the surface of the bubble decreased the viscosity of the crude oil. A large number of studies have shown that the bubble formation and the stability of the interfacial film increased with the increase of asphaltene concentration.F.Bauget et al. [13] presented results showing significant shift in the crude properties at asphaltenes concentrations of around 10%. His experimental suggested a significant increase in foamability, bubble stability and viscosity of crude at asphaltenes concentration of 10% and over. I.Adil and B.B.Maini [14] believed that althoughthe viscosity reduction effect was not obvious, asphaltene contributed bubble nucleation and decreased the critical saturation because of asphaltene foaming, which helped keep the dispersion of gas flow.

However, some researchers believed that it was not correct that the adsorption of asphaltene on the bubble surface reduced the viscosity of crude oil. In 1996, Huerta [15] et al. did not observe viscosity decrease when the pressure dropped to the bubble point pressure when they tested the critical gas saturation during heavy oil flowed in porous media. In a word, a large number of studies confirmed that the presence of asphaltenes has promoted the formation of bubbles in crude oil. However, there is no consensus on the effect of asphatene on the viscosity decrease of crude oil.

1.4 Numerical simulation of "foamy oil flow"

Numerical simulation of primary depletion in foamy oil reservoirs was still based on the empirical adjustments of conventional solution-gas-drivewith black oil model. Models can be classified into two categories: Equilibrium model and kinetic model [16-19].

① Equilibrium model

These models assume complete local equilibrium between different phases.One model is Pseudo-bubblepoint Model proposed by Kraus et al., another is Modified Fractional-Flow Models proposed by Lebel.Krausdescribed a “pseudo-bubblepoint” model, where the pseudo-bubblepoint pressure is an adjustable parameter in the fluid property description. Modified Fractional-Flow Models attempted to match production behavior by modifying the fractional-flow curve or the gas/oil relativepermeability curves.

②Kinetic Model

Kineticmodel believe that dispersed gas in oil phase is not a thermodynamically stable. Given sufficient timeand environment, the dispersed gas would separateinto free gas and oil phases. In the same time, bubble nucleation would also happen.

Coombe and Maini described a kinetic model that accounted for the physical change of the bubble in oil. They defined three nonvolatile components in the oil phase: dead oil, dissolved gas, and gas dispersed in the form of microbubbles. Sheng simulates the rate of bubble transformation to free gas by using the exponent decay method of super-saturation. The kinetic model was better than the equilibrium model method. However, the rate process of dissolved gas flooding was controlled by the rock / fluid characteristics and capillary number.

2 The establishment of mathematical model of "foamy oil flow" in CO_2 process

2.1 The influence of asphalt on the formation of foamy oil and its conditions

In this paper, precipitated asphaltene can facilitate bubble nucleation, decrease the critical super-saturation and help in maintaining the dispersed gas flow by suppressing bubble coalescence. Both asphaltenes and resins are surfactants in crude oil, and their appearance can form the physical barriers between bubbles and bubbles. In the process of CO_2 flooding, CO_2 and crude oil contacted which induced bubble pressure rise. At the front of CO_2 flooding, when the pressure is lower than the bubble point pressure, bubbles appear in crude oil. At this time, resin and asphaltenedistributed as colloidal state, migrate to the surface of the bubble and form a semi-solid membrane, which prevent the bubble further growing into a continuous gas phase and facilitate the bubble nucleation.

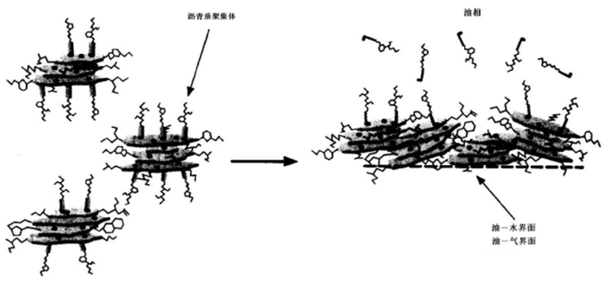


Figure1 depiction of stabilization mechanism of asphaltene

2.2 Establishment of numerical model of "foamy oil flow"at the CO_2 flooding front

Based on the above analysis, this paper believed that the key to simulate the process of gas injection during "foamy oil flow" is to establish dynamic model to describe the flow characteristics of "bubble oil" with time, at the same time, the bubble flow in"foamy oil flow"is different from continuous gas phase flow, whichis not consistent with the flow rate of crude oil and need to be calculated by interpolation. It is believed that appropriate critical gas saturation value is the key to simulate the bubble nucleation in the simulation of the bubble flow.

In this paper, the multicomponent model considering bubble nucleation and CO_2 flowing characteristic was established, combining the advantages of "equilibrium model" with that of "kinetic model".

2.2.1 assumptions

Besides basic hypotheses of conventional compositional model, many other assumptions are considered. During CO_2 injection, "foamy oil flow" exist in oil and gas system; there are n_c fixed hydrocarbon components in the oil and gas system, the n_c component presented as bubble which dispersed in the oil phase with the thermodynamic properties of gas phase; the thermodynamic parameters of bubble were calculated bymultiphase equilibrium model of asphatic oil system during CO_2 injection near pseudo-bubble pressure, where the properties of the micro bubble is the same as the gas flashed by equations; the flow of bubbles is different from that of the continuous gas phase, which is not consistent with the flow rate of crude oil.

2.2.2 Compositional Model of "foamy oil" at the CO_2 front

The compositional model of multiphase multicomponent flow considering "foamy oil" under CO_2 injection is as follows:

$$\nabla\cdot\left[\frac{kk_{ro}}{\mu_o}\rho_o y_{io}\nabla\Phi_o\right]+\nabla\cdot\left[\frac{kk_{rg}}{\mu_g}\rho_g y_{ig}\nabla\Phi_g\right]+\sum_{k=1}^{n_f}\sum_j q_{ik}y_{ij}-\frac{\partial\left[\phi\sum_j\rho_j y_{ij}S_j\right]}{\partial t}=0 \quad (1)$$

$$\nabla\cdot\left[\frac{kk_{rw}}{\mu_w}\rho_w\nabla\Phi_w\right]+\sum_{k=1}^{n_f}q_{wk}-\frac{\partial\left(\phi\rho_w S_w\right)}{\partial t}=0 \quad (2)$$

$$\nabla\cdot\left[\frac{kk_{ro}}{\mu_o}\rho_o\nabla\Phi_o\right]+\nabla\cdot\left[\frac{kk_{rg}}{\mu_g}\rho_g\nabla\Phi_g\right]+q_t-\frac{\partial\left(N_o+N_g\right)}{\partial t}=0 \quad (3)$$

2.2.3 Phase Equilibrium Equations

The phase equilibrium equations[20,21] for the components are

$$\ln f_{ig}=\ln f_{io};\quad i=1,\dots,n_c-1 \quad (4)$$

2.2.4 kinetic equation

This paper argues that the nucleation of bubbles is a non-equilibrium process.Precipitated asphaltene could facilitate bubble nucleation, decrease the critical super-saturation and help in maintaining the dispersed gas flow by suppressing bubble coalescence,The unbalanced process among CO_2, dissolved gas and free gas can cause oil dissolved in gas phase, thereby delay the emission and the formation of transparent bubble than real thermal bubble. This process is affected by the nucleation kinetics. The nucleation of bubbles is a stochastic process controlled by supersaturation, so the supersaturation required for nucleation depends on the length of nucleation time. Therefore, it is not enough to solve the thermodynamic properties of bubbles only with the state of equation. The formation of bubbles is also affected by the adhesion of asphaltene, which is similar to the process of chemical reaction:

In this paper, gas is mainly composed of three parts: light hydrocarbon components, bubbles and CO_2. The reactions among them can be described by two reaction equations:

Reaction 1:

CO_2+ light hydrocarbon components → bubble (5)

Reaction speed: $x_1=F_1\times[CO_2]+F_2\times$ [light hydrocarbon components]

Reaction 2 :

bubble → CO_2+ light hydrocarbon components (6)

Reaction speed: $x_1=F_1\times[CO_2]+F_2\times$ [light hydrocarbon components]

Where: X1 is the reaction rate, Fi frequency coefficient, [] is the mole fraction.

In the calculation, The thermodynamic parameters of gas,bubble and crude oil, molecular weight, compression coefficient, critical pressure and critical temperature, are calculated at the pressurewhenbubble existed in the expansion experiment with EOS.

3 Model solution

3.1 Interpolation treatment of phase permeability curve

As mentioned above, one imbalance process of "foamy oil flow" during CO_2 flooding existsbetween dispersedbubble and free gas. Another imbalance process is related with fluid distribution in reservoir. The capillary force controls the distribution of fluid.Therefore, it is assumed that the fluid is self - distribution, that is, there is lowest free energy distribution at the surface of the fluid / fluid and solid / fluid interface. As a result, according to this assumption, gas begins to flow must be continuous, and isolated bubbles are capillary force trap. This imbalance process is affected by the surface tension, absolute permeability and the maximum flow gradient near the bubble. Therefore, adjusting the relative permeability curve of the bubble is the key to the simulation.

At the same time, the critical gas saturation is an important parameter in the "foamy oil flow". In the critical gas saturation, the continuous gas phase forms and begins to flow. However, the calculation of the critical gas saturation depends on different experimental techniques and data processing methods. Different critical gas saturation was defined. One method of obtaining the critical gas saturation is extrapolating gas phase relative permeability. Another method is to measure the degree of saturation of the gas flow at the beginning of the gas expansion. These two methods are not the same as the measured critical gas saturation. Because of the differences in the value of the critical gas saturation, the determination of the critical gas saturation is another key to the simulation of the gas flow.

（1）The calculation of relative permeability curve of pseudo"bubble"component

In this paper, firstly the bubble is treated as a pseudo component, the critical saturation of the relative permeability curve of bubble and gas are defined separately, and then the relative permeability curve of the gas phase is normalized by the original measurement. Next, the definition of relative permeability components are carried out:the critical saturation critical saturation of bubbles is defined lower than other gas components due to the bubble flow before the formation of free gas.

First of all, for gas-fluid systems, the conventional liquid and gas phase permeability curves are shown in figure 2.

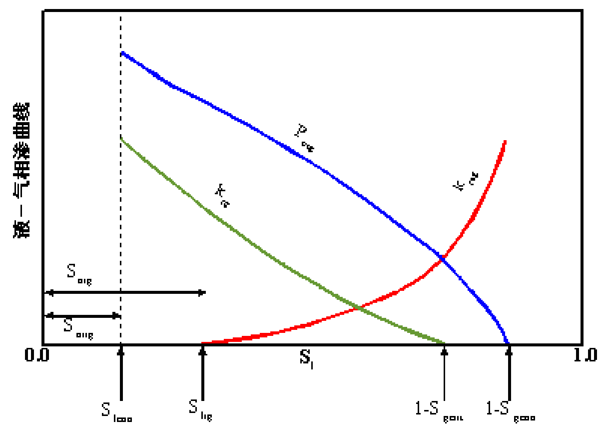


Figure 2 schematic for gas-liquid relative permeability

Then, the critical saturation and permeability of the bubble are user defined with experiment data. Because the rate of bubble is slower than that of the free gas, the relative permeability is smaller when the water saturation is relatively small. Therefore, through defining connate water saturation, the relative permeability curve of the bubble is determined in the range of $\left[S_{lcon}, 1-S_{gcrit}\right]$ and $\left[S_{lrg}, 1-S_{gcon}\right]$.For example: the gas phase relative permeability curve data are shown in table 1. The critical saturation of the bubble is 0.25, the relative permeability of the bubble is about 0.05, and the relative permeability of oil and water are 1.0. According to the above method, the relative permeability data are obtained in table 2. Mapping two sets of curves, the bubble flow at small rate is earlier than gas in graph 3.

Table 1 the relative permeability curve of gas phase

S_l	k_{rg}	k_{rog}
0.25	0.5	0
0.3634	0.456	0.016
0.4432	0.351	0.05
0.5163	0.2543	0.1
0.5923	0.1843	0.15
0.6697	0.1227	0.22
0.7457	0.0817	0.3
0.8216	0.0467	0.44
0.8975	0.029	0.6
0.9428	0.0113	0.84
0.9589	0.0043	0.93
0.965	0.001	0.97
0.97	0.0001	0.99
0.975	0	1

Table 2 the relative permeability curve of bubble

S_l	k_{rg}	k_{rog}
0.25	0.05	0
0.328207	0.0456	0.011035
0.3634	0.038886	0.016
0.383241	0.0351	0.024454
0.433655	0.02543	0.045933
0.4432	0.024155	0.05
0.486069	0.01843	0.079322
0.5163	0.014941	0.1
0.539448	0.01227	0.115229
0.591862	0.00817	0.149712
0.5923	0.008141	0.15
0.644207	0.00467	0.196944
0.6697	0.003808	0.22
0.696552	0.0029	0.248265
0.727793	0.00113	0.281151

0.738897	0.00043	0.292838
0.743103	0.0001	0.297267
0.7457	3.22E-05	0.3
0.746552	1.00E-05	0.301571
0.75	0	0.307931
0.8216	0	0.44
0.8975	0	0.6
0.9428	0	0.84
0.9589	0	0.93
0.965	0	0.97
0.97	0	0.99
0.975	0	1

(2)Determination of relative permeability of oil phase

In the three-phase system, the relative permeability of water phase is determined by the two-phase oil water system. The relative permeability of oil phase in three-phase system is calculated by Stone formula II. Stoneformula II was:

$$k_{ro} = k_{rocw}\left[\left(\frac{k_{row}}{k_{rocw}} + k_{rw}\right)\left(\frac{k_{rog}}{k_{rocw}} + k_{rg}\right) - k_{rw} - k_{rg}\right] \qquad (7)$$

In the three-phase system, the relative permeability of water phase is determined by the two-phase oil water system. In this paper, the gas phase is composed of two parts. In order to solve the relative permeability of oil phase, it is the key to determine the average permeability of gas phase. We assume that the average relative permeability of gas bubbles as the weighted average in the gas phase mole fraction of bubble's relative permeability and the relative permeability of gas flow.As shown in Figure 4, the average relative permeability of gas is obtained, and then the relative permeability of oil phaseis determined by formula (7) .

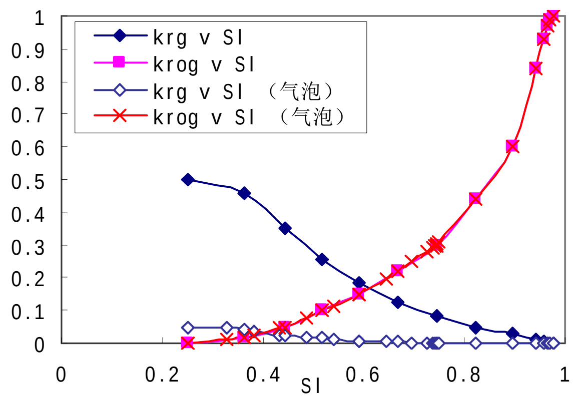


Figure 3comparsion of the relative permeability between gas and bubble

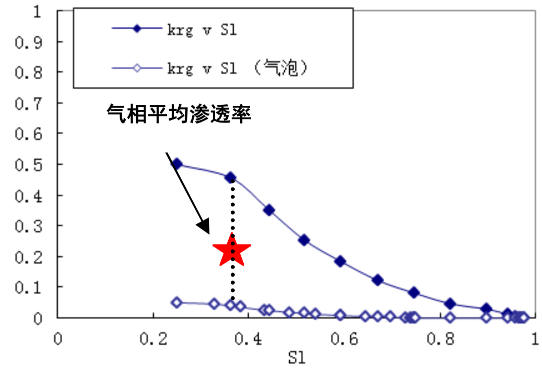


Figure 4 the determination of average relative permeability of gas phase

In the whole system, the relative permeability of oil phase and gas phase are not only a function of saturation, but also the percentage of bubble function.Therefore, the calculation is not easy to converge, which required to adjust the numerical algorithm making the calculation convergence.

3.2 Adaptive implicit method for solving component model

The 2n + 3 equations in above are discretized with finite-difference techniques. The resulting discretized equations for the flow of components in the oil and gas phases are:

$$\Delta T_o^m y_{oi}^m \Delta \Phi_o^{n+1} + \Delta T_g^m y_{gi}^m \Delta \Phi_g^{n+1} + V q_i^m = \frac{V}{\Delta t}\left[N_i^{n+1} - N_i^n\right] \quad (8)$$

Similarly the discretized equation for the flow of water is:

$$\Delta T_w^m \Delta \Phi_w^{n+1} + V q_w^m = \frac{V}{\Delta t}\left[N_w^{n+1} - N_w^n\right] \quad (9)$$

The discretized equation forthe flow of the total hydrocarbon equation is

$$\Delta T_o^m \Delta \Phi_o^{n+1} + \Delta T_g^m \Delta \Phi_g^{n+1} + V q_t^m = \frac{V}{\Delta t}\left[N_o^{n+1} + N_g^{n+1} - N_o^n - N_g^n\right] \quad (10)$$

The phase equilibrium equations for the components are:

$$\ln f_{ig} = \ln f_{io}\ ;\quad i = 1,\dots,n_c \quad (11)$$

Volume constraint equations are:

$$\sum_j \frac{N_j^{n+1}}{\rho_j} = \phi^{n+1};\ j = 0, g, w \quad (12)$$

The superscript n and n+1 represent previous time step and new time step, respectively. The superscript m is equal to n (IMPES method) or n+1 (full implicit method).

The above differential equationsare expanded, and the iterationsare written in the form of iteration allowance

(1)fugacity equation（$i = 1,\dots,n_c - 1$， n_c -1equations）

$$R_{n_c - 1} = \ln f_{ig} - \ln f_{io} = 0 \quad (13)$$

(2) kinetic equation（one equation）

$$\mathbf{R_{nc} = Rea(CO_2 + light\ hydrocarbon\ components \leftrightarrow bubble)} \quad (14)$$

(3) Component mobility equation （$i = 1,...,n_c$， n_c -1equations）

$$R_{2n_c-1} = \Delta T_o^m y_{oi}^m \Delta\Phi_o^{n+1} + \Delta T_g^m y_{gi}^m \Delta\Phi_g^{n+1} + Vq_i^m - \frac{V}{\Delta t}\left[N_i^{n+1} - N_i^n\right] \tag{15}$$

(4) Total hydrocarbon equation

$$R_{2n_c} = \Delta T_o^m \Delta\Phi_o^{n+1} + \Delta T_g^m \Delta\Phi_g^{n+1} + Vq_t^m - \frac{V}{\Delta t}\left[N_o^{n+1} + N_g^{n+1} - N_o^n - N_g^n\right] \tag{16}$$

(5) Water flow equation

$$R_{2n_c+1} = \Delta T_w^m y_{wi}^m \Delta\Phi_o^{n+1} + \Delta T_g^m y_{gi}^m \Delta\Phi_g^{n+1} + Vq_i^m - \frac{V}{\Delta t}\left[N_i^{n+1} - N_i^n\right] \tag{17}$$

(6) Volume constraint equation

$$R_{2n_c+2} = \sum_j \frac{N_j}{\rho_j} - \phi = 0; j = 0, g, w \tag{18}$$

The $2n_c+2$ primary unknowns per grid block are: $p, N_1, N_2, ...N_{n_c}, N_w, N_{1g}, N_{2g}, ..., N_{n_c g}$ .This can be obtained by solving simultaneoulsy the system of Equations (18) with Newton's method. As the adaptive method is used. Some gridblocks will be Implicit Pressure.

Therefore, the presented model is based on the compositional model, combining the advantages of "balance model" and "dynamic model", the flow characteristics of “foamy oil flow” as the function of time and the flow conditions, and adjusting the permeability and the critical saturation of bubble to determine the" bubble flow "effect on production performance.

4 Case study

4.1 Reservoir

XL reservoir oil field locates in the Northeast of China. The field is sandstone reservoir with no gas cap and no active water.The structure is dome anticline close to East-west trending cut by north-south fault.

The reservoir is characterized by low porosities and low permeability.The original formation pressure of reservoir is 15MPa. The field oil-bearing area is 2.66km^2, which has an OGIP of 118.2 * 10^{4}t.

There are 25 wells with 4 injectorsand 21 producers (Figure 5), which are divided into four oil production platforms. The well spacing is 300m. Original well pattern is nine point area water injection with N 67.5° E well array direction. October 1994 water was begun to be injected. Up to the present, the oil recovery is 11.7%.

CO_2 injection area of the XL oilfield was located in the northern part of the XL oilfield, which is characterized by 2.5 degrees dip angle, 1350-1600m burial depth, no fault and no active aquifer. The characteristics of this area are beneficial for CO_2 flooding.

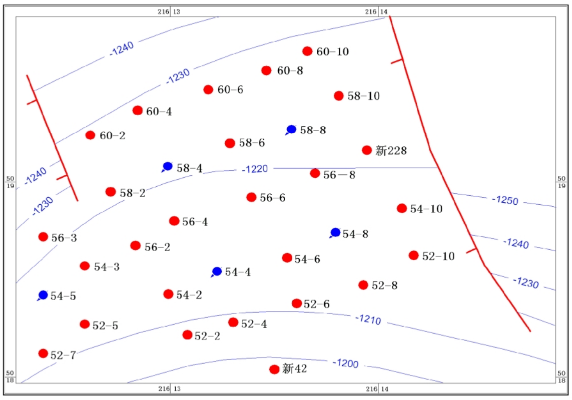


Figure 5 the well location map of JL reservoir

Therefore, for a clear understanding of effect of "foamy oil flow" on oil production and asphaltene deposition, we have done field-scale history matching and prediction.

Field Grid. Fig. 6 shows an area view of the field model grid.Locations of wells are displayed on the grid. The model consists of 11 layers. The total simulation grid number is 33440(80 *38* 11).

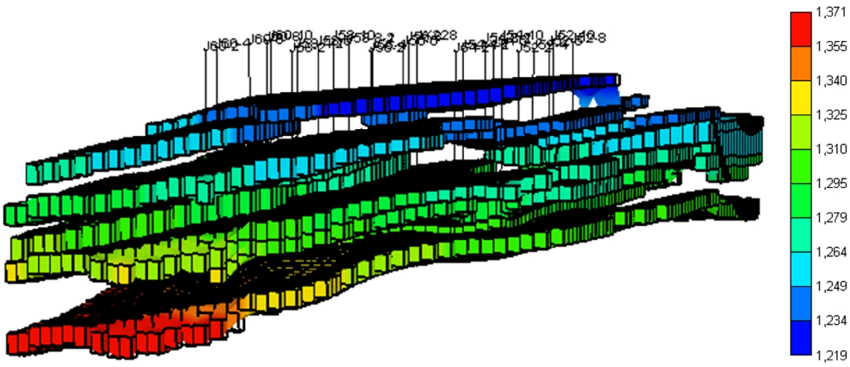
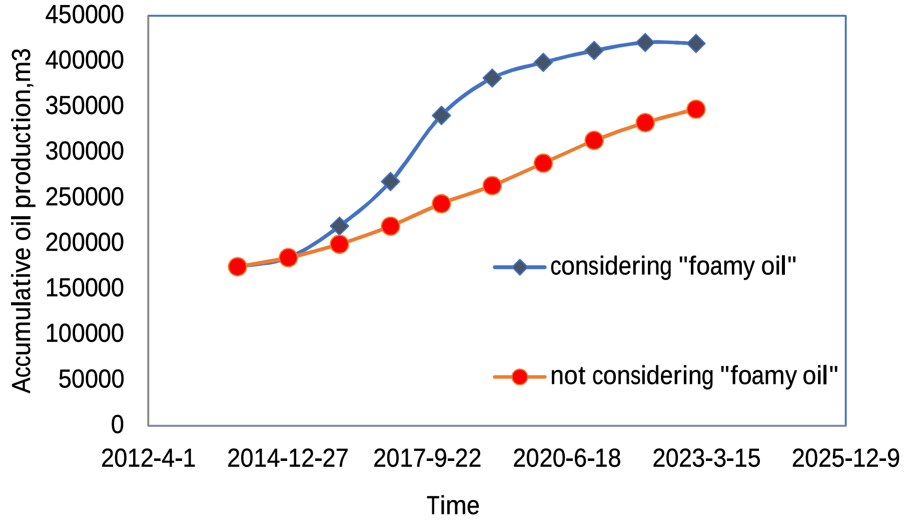


Figure 6 the structural diagram of numerical simulation of CO_2 flooding areaof Xinli oil field

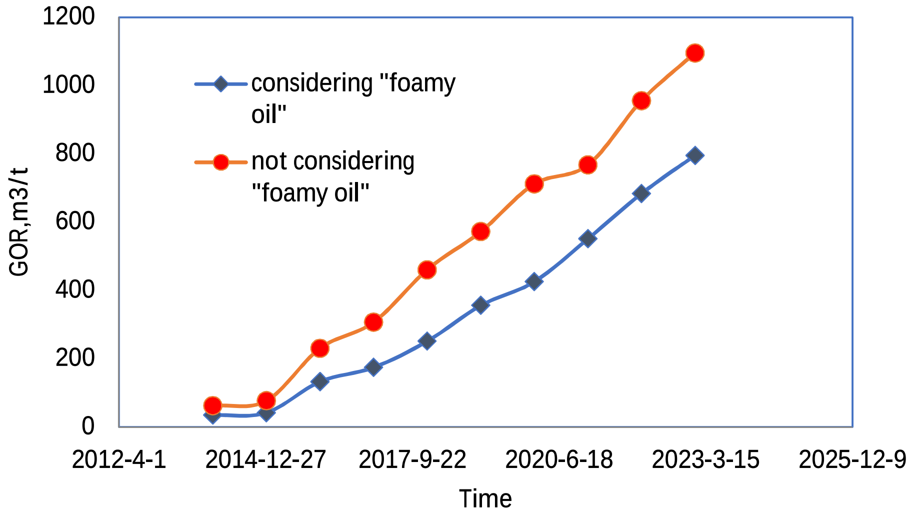
4.2CO_2 displacement dynamics considering "foamy oil flow"

4.2.1 Effect of "foamy oil flow" on oil production and asphaltene deposition

Simulation research showed that the displacement efficiency considering "foamy oil flow" improved significantly compared with normal numerical simulation without considering “foamy oil”(figure 7(a)) , and gas oil ratio was higher than that without considering the "foamy oil flow"(Figure 7 (b)), which showed"bubble" in the oil phase is beneficial in the production during CO_2 flooding, mainly because gas expands to occupy the space occupied by the original liquid, increase the compressibility of the fluid and delay the gas production time. The dispersed bubbles can reduce the relative permeability of the gas phase, thus increase the oil production rate, reduce the production gas oil ratio, and ultimately improve oil recovery.



(a) cumulative oil rate

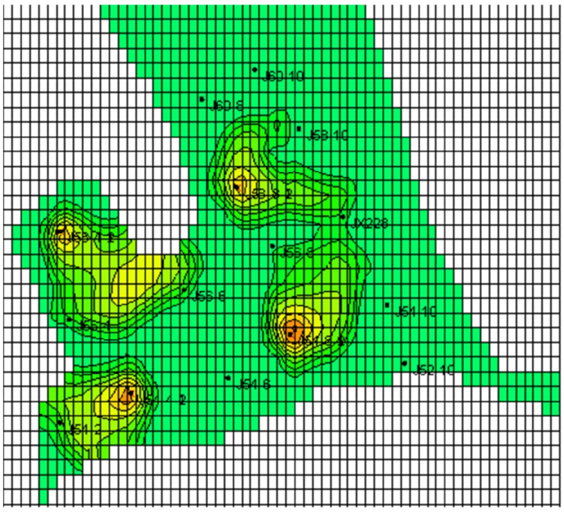


(b) gasoil ratio

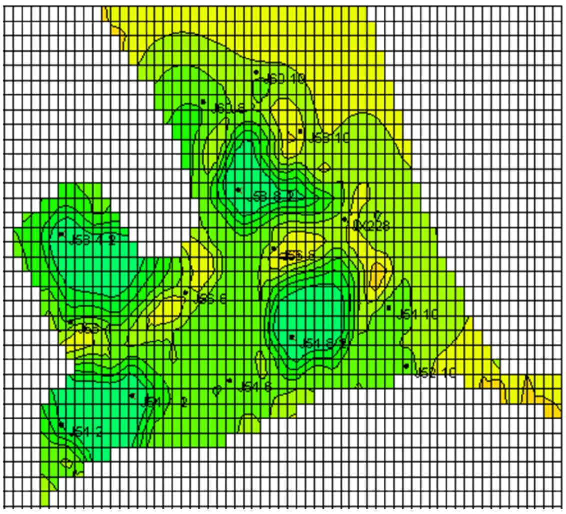
Figure 7 the effect of foamy oil on production

4.2.2 Distribution law of "foamy oil flow"

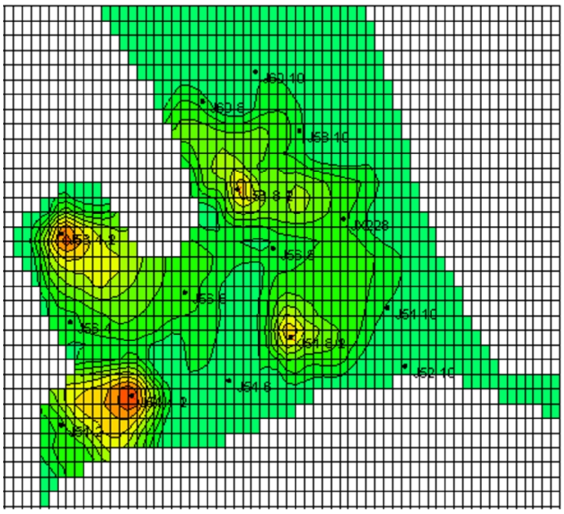
Simulation research showed the relationship between the percentage of CO_2 and the percentage of bubbles in different CO_2PV. Seen from figure 8 (a) (b),in the early injection stage, bubble is located at the frontier of CO_2 flooding, which showed similar flow mechanism of "foamy oil flow" in dissolved gas flooding; at CO_2 flooding period, the bubble was still mainly appeared in the flooding front and tend to flow to big porosity area. Therefore, it can be inferred that, when the gas breakthrough, the role of "foamy oil flow" will be reduced. However, before gas breakthrough, the characteristics of "foamy oil flow" can significantly improve the displacement efficiency.



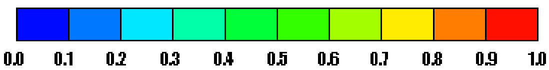
(a)CO_2 mole percentage of injection of 0.05 PV

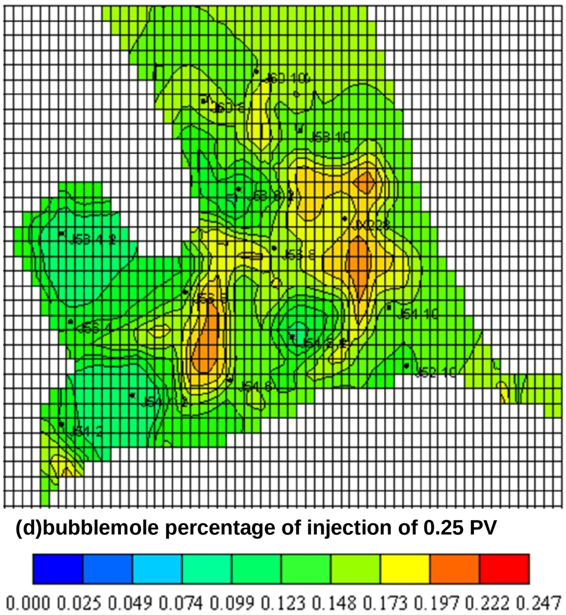


(b)bubble mole percentage of injection of 0.05 PV



(c)CO_2 mole percentage of injection of 0.15 PV





(d)bubblemole percentage of injection of 0.25 PV

Figure 8 the distribution graph of bubble content of layer I

5 Conclusions and recommendations

CO_2 flooding "foamy oil flow" is a kind of special phenomenon of CO_2 displacement of asphaltene crude oil. In this paper, by comparing the similarity between the "foamy oil" in CO_2 displacement and the "foamy oil" in the dissolved gas drive, the bubble nuleation mechanism is explained.

Through the research on the surface activity of asphaltene, the possibility of the "bubble" of asphaltene stabilization was confirmed. Considering the influence of asphalt on the formation of "foamy oil" and the dynamic change process of "foamy oil", a mathematical model considering the "foamy oil flow" during CO_2 flooding was established.

The calculation results showed that the bubble mainly located at CO_2 flooding front, which showed bubble material similar to "foamy oil flow" to stabilize gas injection frontier; when the gas breakthrough, mole percentage of bubble" significantly reduced. Compared with normal numerical simulation without considering “foamy oil”, high efficient flooding potential was achieved with “foamy oil” existed in CO_2 displacing front, which deserves further research.

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