碳酸盐岩油藏三重介质油藏数值模拟研究

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［摘要］以渗流力学理论为基础，在调研国内外资料的基础上，建立了碳酸盐岩三重介质油藏的渗流模型，模型中产量项考虑了只有裂缝向井底供液和溶洞、裂缝同时向井底供液两种情况，同时给出了溶洞、裂缝和基岩间窜流量的计算方法。利用 C++ 编写了三重介质数值模拟软件，通过模拟双孔双渗理论五点法模型，对比本文与成熟的商用油藏模拟器 ECLIPSE 的计算结果，验证了模型及软件的正确性。同时，给出了三重介质五点法模型的两种计算结果。

［关键词］碳酸盐岩油气藏；三重介质；油藏数值模拟；窜流
［中图分类号］TE319；TE344 ［文献标识码］A ［文章编号］1000-9752（2008）02-0119-05

对于碳酸盐岩油藏的渗流研究已近半个世纪，第一个双重介质的渗流模型由 Brentblatt 等人于1960年提出。在1963年 Warrant 和 Root[1]提出了另外一个重要的模型即 Warrant-Root 模型，得到了广泛的应用，是目前发展得最为完善的模型。目前大部分软件都一直采用 Warrant-Root 模型。之后对模型的改进主要集中在基质和裂缝的窜流计算方面。这包括 Kazami（1976）[2]、Saidi（1983）[3]、Thomas（1983）[4]、Coats（1989）[5]、Ueda（1989）[6]等人的研究成果。然而，在一些碳酸盐岩油田开发过程中遇到了一些问题，这些问题利用现有的双重介质理论是无法解释的。例如塔河油田的滚动勘探开发实践表明，塔河油田碳酸盐岩缝洞型油藏还存在第三种不可忽视的高孔高渗介质——溶洞系统。Closmaan（1975）[7]建立了第一个溶洞-裂缝-孔隙型三重介质达西渗流模型，随后刘慈群（1981）[8]也建立了三重连续介质渗流模型。但直到目前，国内外在三重介质的油藏数值模拟方面的研究工作相对较少。笔者在前人渗流机理研究工作的基础上，建立了三重介质的渗流数学模型，并采用全隐式求解方法进行求解，编制了相应的数值模拟软件。

1 三重介质三维三相黑油渗流模型

模型的基本假设如下：三重介质中的溶洞、裂缝和基岩为相互独立而又互相联系的水动力学渗流系统，3种介质在空间上是重叠的，溶洞和基岩为主要储油空间，裂缝为主要油流通道。

图1为三重介质的理想模型。假设溶洞、裂缝和基岩这3种介质中的流体之间存在窜流，主要通过裂缝进行渗流，同时溶洞间也存在流体渗流，基岩间不存在流体渗流。溶洞、裂缝均可向井底供液，在 Gilman & Kazemi（1983）[9]建立的双重介质模型的基础上，推导建立了碳酸盐岩油藏三重介质渗流方程。

溶洞内渗流方程：

$$\begin{cases}\nabla\left[\dfrac{KK_{ro}\rho_o}{\mu_o}\nabla(P_o-\rho_o gD)\right]_v+q_{vo}+\tau_{mvo}+\tau_{fvo}=\dfrac{\partial}{\partial t}(\phi S_o\rho_o)_v \\ \nabla\left[\dfrac{KK_{rg}\rho_g}{\mu_g}\nabla(P_g-\rho_g gD)\right]_v+\nabla\left[R_{so}\dfrac{KK_{ro}\rho_g}{\mu_o}\nabla(P_o-\rho_o gD)\right]_v \\ \quad +q_{vg}+\tau_{mvg}+\tau_{fvg}+R_{so}\tau_{mvo}+R_{so}\tau_{fvo}=\dfrac{\partial}{\partial t}(\phi S_g\rho_g+R_{so}\phi S_o\rho_o)_v \\ \nabla\left[\dfrac{KK_{rw}\rho_w}{\mu_w}\nabla(P_w-\rho_w gD)\right]_v+q_{vw}+\tau_{mvw}+\tau_{fvw}=\dfrac{\partial}{\partial t}(\phi S_w\rho_w)_v\end{cases} \tag{1}$$

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［作者简介］李勇（1982-），男，2005年大学毕业，博士生，现主要从事碳酸盐岩油藏数值模拟研究工作。

裂缝内渗流方程:

$$\begin{cases} \nabla\left[\frac{KK_{ro}\rho_o}{\mu_o}\nabla(P_o-\rho_o gD)\right]_f + q_{fo} + \tau_{mfo} - \tau_{mvo} = \frac{\partial}{\partial t}(\phi S_o\rho_o)_f \\ \nabla\left[\frac{KK_{rg}\rho_g}{\mu_g}\nabla(P_g-\rho_g gD)\right]_f + \nabla\left[R_{so}\frac{KK_{ro}\rho_g}{\mu_o}\nabla(P_o-\rho_o gD)\right]_f \\ \quad + q_{fg} + \tau_{mfg} - \tau_{fvg} + R_{so}\tau_{mfo} - R_{so}\tau_{fvo} = \frac{\partial}{\partial t}(\phi S_g\rho_g + R_{so}\phi S_o\rho_o)_f \\ \nabla\left[\frac{KK_{rw}\rho_w}{\mu_w}\nabla(P_w-\rho_w gD)\right]_f + q_{fw} + \tau_{mfw} - \tau_{fvw} = \frac{\partial}{\partial t}(\phi S_w\rho_w)_f \end{cases} \tag{2}$$

基岩内渗流方程:

$$\begin{cases} -\tau_{mfo} - \tau_{mvo} = \frac{\partial}{\partial t}(\phi S_w\rho_w)_m \\ -\tau_{mfg} - R_{so}\tau_{mfo} - \tau_{mvg} - R_{so}\tau_{mvo} = \frac{\partial}{\partial t}(\phi S_g\rho_g + R_{so}\phi S_o\rho_o)_m \\ -\tau_{mfw} - \tau_{mvw} = \frac{\partial}{\partial t}(\phi S_w\rho_w)_m \end{cases} \tag{3}$$

式中,下标 o、g、w 分别表示油、气及水的参数;下标 m、f、v 分别表示基岩系统、裂缝系统和溶洞系统的参数; K 为渗透率,μm^2,其中下标 r 表示相对渗透率; τ 为双重介质间窜流量, τ_{mvo} 表示基岩系统与溶洞系统间油相的窜流量(其他参数相似表示方法); D 为由某一基准面算起的深度,m,向下为正; q 为井的产量,m^3/d; ρ 表示密度,kg/m^3; P 为压力,atm(1atm = 1.0325 ×10^5 Pa); μ 为粘度,mPa·s; t 为时间,d; S 为饱和度,%; g 为重力加速度,m/s^2; R_{so} 为溶解气油比; ϕ 为孔隙度。

辅助方程、边界条件、初始条件在此省略。

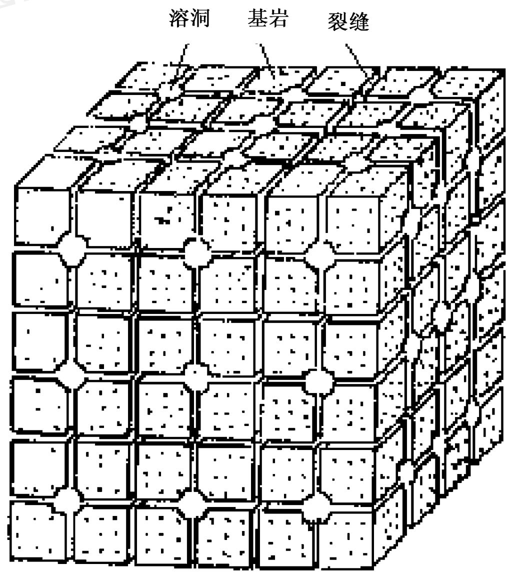

图 1 三重介质理想模型图

2 介质间窜流量的计算

以裂缝与基岩的窜流量计算为例,对于溶洞与裂缝、溶洞与基岩间窜流量的计算方法与此类似。采用 Gilman & Kazemi 计算窜流量的方法[9]计算基岩与裂缝间的窜流量,具体如下:

油组分间的窜流量 $-\tau_{mfo} = -\lambda_o(P_{om} - P_{of})$ (4)

水组分间的窜流量 $-\tau_{mfw} = -\lambda_w(P_{wm} - P_{wf})$ (5)

气组分间的窜流量 $-\tau_{mfg} - R_{so}\tau_{mfo} = -\lambda_g(P_{gm} - P_{gf}) - \lambda_o R_s(P_{om} - P_{of})$ (6)

式中, τ_{mfo}、τ_{mfw}、τ_{mfg} 分别为基岩与裂缝间油、水、气的窜流量;其中:

$$\lambda_o = 0.001127\sigma K_m V_b\left[w\left(\frac{K_{rw}\rho_w}{\mu_w}\right)_m + (1-w)\left(\frac{K_{rw}\rho_w}{\mu_w}\right)_f\right] \tag{7}$$

$$\sigma = 4\left(\frac{1}{L_x^2}+\frac{1}{L_y^2}+\frac{1}{L_z^2}\right) \qquad V_b = \Delta x\cdot\Delta y\cdot\Delta z$$

式中, L_x、L_y、L_z 是岩块在 3 个方向的尺寸; Δx、Δy、Δz 分别为网格在 X、Y、Z 方向的网格大小,m。w 的取值取决于上游是裂缝还是基岩, $w = 0$ 或 1。当 $w = 1$ 时,表示窜流是从基岩向裂缝;如果 $w = 0$,则表示窜流是从裂缝到基岩。对于 λ_w 和 λ_g 的计算方法与 λ_o 相似。

3 井的处理

由于模型假设裂缝和溶洞均可向井底供液,所以井的处理涉及到裂缝和溶洞的渗流方程中产量项的

处理，采用全隐式方法对井产量进行处理。假设所有井为定液量生产，则当井穿过多个网格时，当给定产液量 Q_l 时，第 k 层各相产量的计算公式为：

$$Q^{n+1}_{uxk}=\left(\begin{array}{l}M^{n}_{uxk}+\dfrac{\partial M^{n}_{uxk}}{\partial P_{\mathrm{of}}}\delta P_{\mathrm{of}}+\dfrac{\partial M^{n}_{uxk}}{\partial S_{\mathrm{wf}}}\delta S_{\mathrm{wf}}+\dfrac{\partial M^{n}_{uxk}}{\partial X_{\mathrm{gf}}}\delta X_{\mathrm{gf}}\\ +\dfrac{\partial M^{n}_{uxk}}{\partial P_{\mathrm{ov}}}\delta P_{\mathrm{ov}}+\dfrac{\partial M^{n}_{uxk}}{\partial S_{\mathrm{wv}}}\delta S_{\mathrm{wv}}+\dfrac{\partial M^{n}_{uxk}}{\partial X_{\mathrm{gv}}}\delta X_{\mathrm{gv}}\end{array}\right)Q_l \tag{8}$$

$$M_{uxk}=\frac{[WI\lambda_u]_{xk}}{\sum_{j=1}^{m}[WI(\lambda_{\mathrm{o}}+\lambda_{\mathrm{w}})]_{\mathrm{v}j}+\sum_{j=1}^{m}[WI(\lambda_{\mathrm{o}}+\lambda_{\mathrm{w}})]_{\mathrm{f}j}}$$

$$WI=\frac{2\pi\Delta z}{\ln\dfrac{r_{\mathrm{e}}}{r_{\mathrm{w}}}+s}\qquad \lambda_u=\frac{KK_{\mathrm{r}u}\rho_u}{u_u}\qquad r_{\mathrm{e}}=0.208\Delta x$$

式中，下标 u 分别代表 o、w 和 g，x 分别代表 v 和 f；r_{e}、r_{w} 分别为井泄油半径和井筒半径，mm；s 为表皮因子；δ 代表本迭代步内变量的变化；X 当为三相时代表含气饱和度 S_{g}，当为两相时为饱和压力 P_{b}。

由式 (8) 可以看出，每层的溶洞或裂缝对井的产量贡献大小是井所在网格处的溶洞以及裂缝中的含油饱和度、含水饱和度以及含气饱和度或饱和压力的函数。

对于定井底流压条件，其求解方法相似。对于注入井的处理，原理与方法和生产井的处理基本相同，正负号相反。

4　模型应用

利用 C＋＋语言编写了三重介质油藏三维三相渗流方程的全隐式求解数值模拟软件，其主模块流程图见图 2。该软件既可以模拟三重介质复杂碳酸盐岩油藏，也可以进行传统的双孔双渗、双孔单渗油藏模型的数值模拟；该软件可模拟平面、剖面、三维问题，还可模拟处理单相、两相和三相渗流问题。该模拟器采用动态分布内存技术，为模拟计算节省了大量的内存空间。

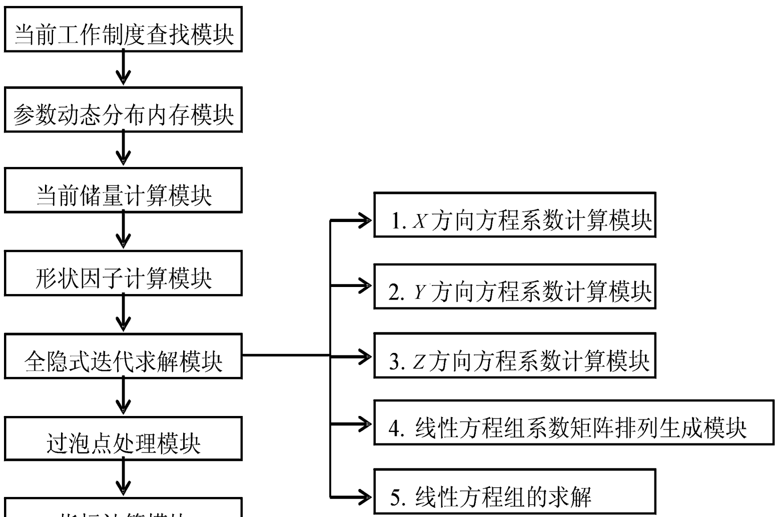

图 2　主模块流程图

由于目前商业化软件尚未有三重介质模拟模块，故为了检验本文数值模拟方法的正确性与可靠性，选取反映实际油田情况的参数，对五点法双孔双渗理论模型进行了模拟，对比了采用本软件的计算结果与国外成熟的油藏数值模拟软件 ECLIPSE 的计算结果。采用的模拟参数见表 1。

表 1　裂缝和基岩介质的基本参数列表

裂缝网格数	9 ×9 ×1	基岩网格数	9 ×9 ×1
裂缝网格大小/ m	30 ×30 ×10	基岩网格大小/ m	30 ×30 ×10
裂缝孔隙度	0.039585	基岩孔隙度	0.1392
裂缝渗透率/ $10^{-3}\mu m^2$	200	基岩渗透率/ $10^{-3}\mu m^2$	50
裂缝网格初始压力/ MPa	20.5	基岩网格初始压力/ MPa	20.5
裂缝网格初始含油饱和度	0.65	基岩网格初始含油饱和度	0.7
裂缝原油压缩系数/ MPa^{-1}	3.0×10^{-6}	基岩原油压缩系数/ MPa^{-1}	3.0×10^{-6}
注入井注入量/ $m^3\cdot d^{-1}$	-20	生产井产量/ $m^3\cdot d^{-1}$	80

下面是所计算的部分开发指标与 ECLIPSE 计算结果的对比，以此来定量地验证模型的正确性。其对比结果见图 3～6。

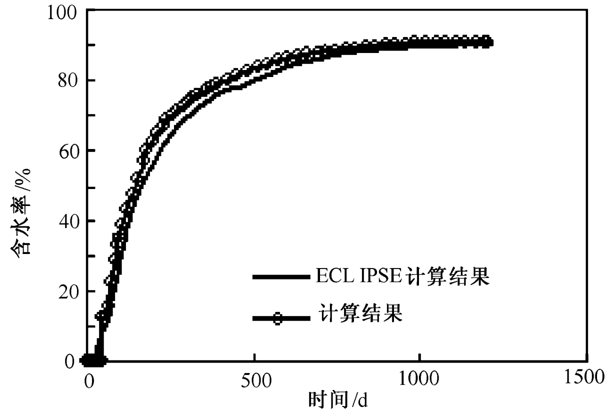

图 3 含水率曲线对比图

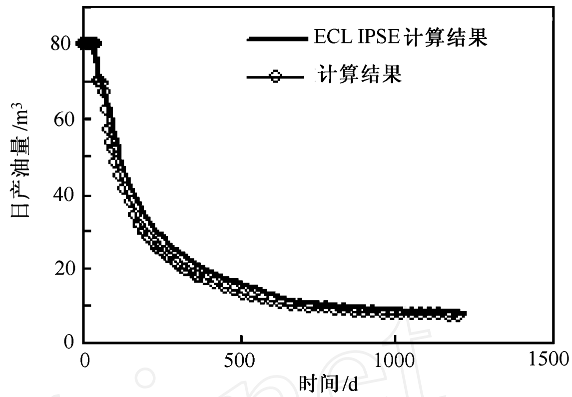

图 4 单井日产油对比图

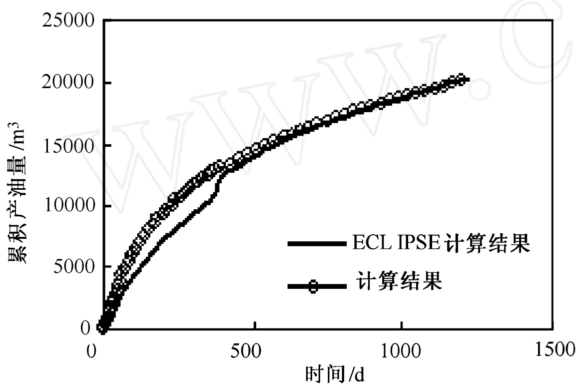

图 5 单井累积产油对比图

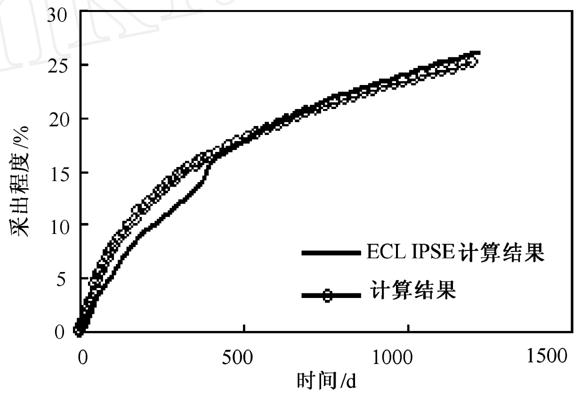

图 6 采出程度对比图

从图 3～6 中可以看出，对于五点法双重介质油藏来说，笔者计算的结果与商业软件 ECLIPSE 计算的结果差别不大。

当考虑油藏为三重介质时，表 2 给出溶洞介质的基本参数。对于裂缝和基岩来说，参数与上面介绍的模型相同，即采用表 1 中的数据。

表 2 溶洞介质的基本参数列表

溶洞网格数	9 ×9 ×1	溶洞网格大小/ m	30 ×30 ×10
溶洞间距/ m	30 ×30 ×10	溶洞孔隙度	0.019585
溶洞渗透率/ $10^{-3}\mu m^2$	2000	溶洞网格初始压力/ MPa	20
溶洞网格初始含油饱和度	0.65	溶洞原油压缩系数/ MPa	3.0E-6

由于无法与商业性软件进行对比，笔者考虑了当溶洞间和裂缝间均可渗流、基岩间不能渗流和只有裂缝间可以渗流、溶洞间和基岩间不能渗流两种情况，两种情况的结果对比见图 7～9。由结果可以看出，相比只有裂缝间可以渗流的情况，当溶洞间和裂缝间均可渗流时，其含水率上升相对平缓，产量下降的慢。由此可见，对碳酸盐岩油藏来说，如果溶洞彼此连接，而不是孤立的，则对开发有积极的影响。应根据油田实际油藏地质情况，选择合适的模型进行模拟。

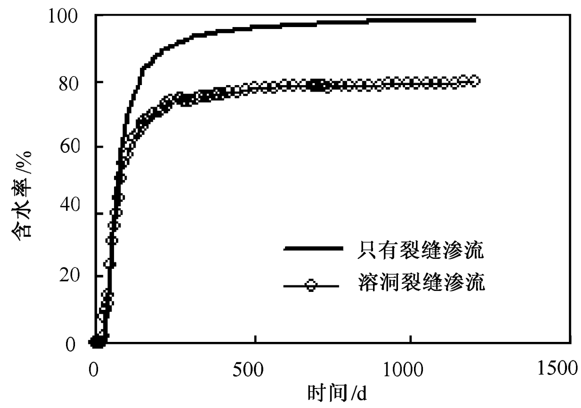

图 7　含水率对比曲线

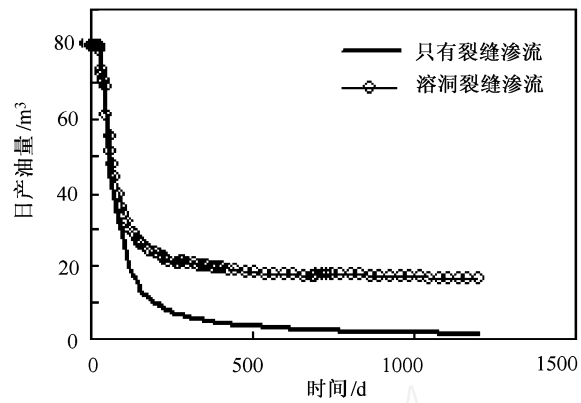

图 8　单井日产油对比曲线

5　结　　论

1) 给出了三重介质三维油藏油、气、水三相的渗流模型。

2) 在借鉴国内外公开发表的文献资料的基础上，建立了介质间窜流量的计算模型。

3) 建立了考虑溶洞和裂缝同时向井底供液时产量的全隐式求解方法。

4) 基于现代软件设计的基本思想，开发了既可模拟双孔双渗、双孔单渗的普通裂缝性油藏，又可模拟复杂碳酸盐岩三重介质油藏的三维三相全隐式数值模拟软件。

5) 通过模拟双孔双渗五点法理论模型，所计算的结果与国外商业软件 ECLIPSE 计算的结果相近，验证了本文模型与模拟器的正确性。

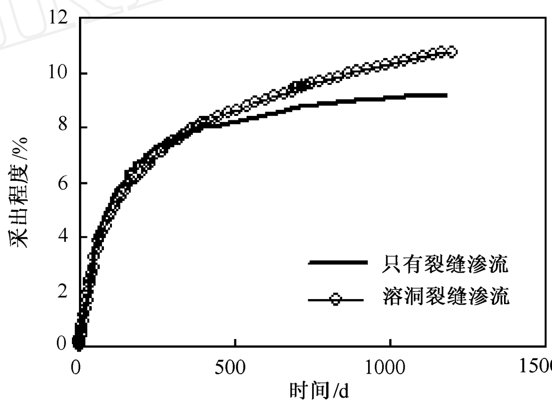

图 9　采出程度对比曲线

6) 对三重介质理论五点法模型，对溶洞间和裂缝间均可渗流、基岩间不能渗流和只有裂缝间可以渗流、溶洞间和基岩间不能渗流两种情况进行了模拟，由于目前国内外尚未有商业性的三重介质模拟软件，故本文只给出计算结果。

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Abstract: The influencial factors of gas leakage and diffusion were analyzed, models used for calculating gas diffusion were introduced. By using well blowout containing hydrogen sulfide for example, Gaussian plume model was chosen to calculate the diffusion extent of well blowout of natural gas containing sulfide hydrogen under conditions different climates and geologic situations, in combination with typical geomorphology in sulfide gas reservoirs. The correlation between H_2S diffusion concentration and radius and outcomes induced after well blowout was analyzed, factors influencing the gas diffusion were discussed. The result shows that to accurately calculate the gas diffusion extent, calculating models should be strictly chosen, while uncertain factors would influence the gas diffusion, measures should be taken from the aspects of safe operation, prewarning, emergency measures as well as safety spacing for the purposes of inducing the hazards of well blowout.
Key words: hydrogen sulfide; natural gas; well blowout; diffusion model; countermeasures; safety

119 **Reservoir Numerical Simulation with Triple Media in Carbonate Reservoirs**

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Abstract: Based on the theory of percolating dynamics and by collecting the data both from the home and abroad, a model for triple-medium reservoir simulation was established for carbonate reservoirs, the situations of fluids provided to downhole from fractures, cavities and fractures were considered in modeling production. A method for calculating the channeling rate between cavities, fractures and matrix was provided. C++ is used to establish a software for triple medium simulation by using five-spot well pattern simulation with dual-porosity and dual permeability model, the result is compared with that of commercial simulator ECLIPSE, the correctness of the model and software is proven. Also 2 results of five-spot well pattern simulation are given.
Key words: carbonate reservoir; triple media; reservoir numerical simulation; channeling

124 **Technique for Tapping the Potential of Remaining Oil in Narrow-strip Faulted Reservoirs**

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Abstract: To further improve the level of trapping the potential of remaining oil in narrow-strip faulted reservoirs at the mid-late stages of development, the methods of quantitative evaluation of remaining oil and techniques of old well sidetracking with horizontal well combination were studied. On the basis of quantitative study of remaining oil, the characteristics of reservoir development and remaining oil distribution at the mid-late stage were analyzed from the aspects of geologic characters of narrow-strip faulted reservoirs, the new methods of remaining oil quantitative evaluation and the main methods of old well sidetracking with horizontal well combination which were satisfied with the reservoir geologic conditions and its development characters and matching techniques were emphatically described. These methods are used in AF Oilfield. It is further proven the method of tapping the potential with old-well sidetracking with horizontal well combination is an effective means of improving the production of narrow-strip faulted reservoirs and it has good prospects of application.
Key words: Subei Basin; narrow-strip faulted reservoir; remaining oil; technique of tapping the potential

127 **Influential Factor of Upwarping Moment of Water-flooding Characteristic Curve at High Water-cut Stage**

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Abstract: By taking the typical relative permeability curves of mid-high permeability integrity reservoirs in Shengli Oilfield for an example, the upwarping features of Type I and II water-flooding characteristic curves at high water-cut stage were analyzed in combination with stream tube method. The effects of oil-water viscosity ratio, permeability, irreducible water saturation, residual oil saturation and endpoint ratio of water-oil relative permeability on both the occurrence of upwarping and prediction error of oil recovery were also discussed. Study indicates that the major influential factors of water-cut variation moment are oil-water viscosity ratio and relative permeability. Among the several influential factors of relative permeability, endpoint ratio of water-oil relative permeability is the main factor affecting the water-cut variation moment within the influencing factors.
Key words: water-flooding curve; relative permeability; oil-water viscosity ratio; influential factor

132 **Well Production Characteristics in Different Positions of Ordovician Carbonate Reservoirs in Tahe Oilfield**

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Abstract: On the basis of production characteristics of 6wells in an Ordovician carbonate reservoir of Tahe Oilfield, water producing charactrs of wells in different positions were studied. It was considered that there existed 4 water production types, such as water yielding in natural oil production, water yielding in acidic fracturing, water yielding after a period of natural production and water yielding after a period of acidic fracturing. The effects of different well locations on single well production characters are analyzed, it is considered that wells in different positions have different influences on water producing characters. In fracture position water is produced in fractures, wells in encountered dissolved cavities, water is produced in cavities. For wells in encountered cavities and with natural fractures grown in open holes, its water producing character is the combination of fracture and cavity. Water content increases quickly in fracture-produced water, while water content increases steadily and without water-free oil production period in cavity produced water.
Key words: carbonate reservoir; production performance; water producing fracture; rock dissolved position; Tahe Oilfield

135 **Characteristic Study on the Performance Response of Fracture System in Oil Formation II in Block Baobei of Baolang Oilfield**

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