

特高含水期剩余油分布及形成机理

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摘要 目前我国东部老油区普遍进入特高含水阶段, 水驱开发效果变差, 采收率明显下降, 有效挖掘剩余油潜力是当前开发的重点所在. 特高含水期油相主要以非连续状态存在于孔隙空间内, 基于宏观认识的达西定律很难准确描述地下剩余油的真实流动状态. 为摸清特高含水期剩余油分布状况, 研究剩余油形成机理并挖掘剩余油潜力, 基于N-S方程模拟油水两相在微尺度多孔介质内流动, 运用相场方法实时追踪驱替过程中的两相界面, 建立微观流动模型. 研究特高含水期剩余油分布, 并从力学角度分析残余油形成机理. 结果表明特高含水期多孔介质内剩余油主要可以分为5种类型: 孤立油滴、孔喉残余油、簇状非均质残余油、油膜、盲端残余油. 毛管力, 孔隙结构以及壁面润湿性是影响特高含水期剩余油的分布与类型的主要因素. 孔隙尺度流动模拟得到的水驱曲线与矿场规律基本一致. 特高含水期增注与注入表面活性剂均是通过驱替出簇状非均质残余油, 孔喉残余油以及孤立油滴达到提高剩余油采收程度的目的. 簇状非均质残余油的减少是采收程度提高的主要原因. 矿场增注时机对经济开发有重要影响. 该研究初步揭示了特高含水期剩余油分布及形成机理, 为水驱油藏的后期开发提供有效指导.

关键词 特高含水期, N-S 方程, 相场, 微观流动, 剩余油

中国东部老油田普遍进入高含水甚至特高含水开发阶段, 平均采出程度约30%, 稳产难度加大^[1,2]. 以胜利油田为例, 整装和断块高含水单元有149个, 动用地质储量 2.5×10^8 吨, 占油区已动用地质储量29.8%, 因此相当一部分剩余可采储量要在特高含水阶段采出^[3,4].

中低含水期油相多以连续状态分布, 传统的达西定律可以很好地描述储层内流体流动. 进入特高含水期剩余油分布呈现“整体分散, 局部富集”的状态, 油相主要以非连续状态存在于孔隙空间内^[3~6], 此时基于宏观认识的达西定律很难从本质上准确描述与解释地下剩余油的真实流动状态. 当前形势下, 摸清剩余油分布状况^[7,8], 研究剩余油形成机理, 挖

掘剩余油潜力是开发的重点所在, 因此有必要采用新的方法研究特高含水期剩余油分布与流动. 近年来以CT扫描以及图像处理得到的孔隙尺度多孔介质图像为基础^[9~12], 通过数值求解N-S方程得到流体在多孔介质内的流动形态^[9,13~15]为模拟剩余油流动提供了一种新的研究方法. 目前这类方法拥有成熟的理论基础以及稳定的数值计算格式, 该类方法在孔隙尺度^[16,17]的单相流以及多相流模拟中得到广泛应用, 但是对于特高含水期剩余油流动模拟的研究基本未展开. 本文首次将传统的多相流模拟方法应用到当前棘手的特高含水后期剩余油问题, 基于N-S方程直接描述油水两相在微尺度多孔介质内流动, 运用相场方法实时追踪驱替过程中的两相界面, 建立

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Zhu G P, Yao J, Zhang L, et al. Pore-scale investigation of residual oil distributions and formation mechanisms at the extra-high water-cut stage (in Chinese). Chin Sci Bull, 2017, 62: 2553–2563, doi: 10.1360/N972017-00392

微观流动模型. 观察驱替后多孔介质内剩余油类型及分布, 从力学角度分析其形成机理. 同时探究矿场传统剩余油挖潜措施提高采收率的本质机理. 本文为特高含水期剩余油分布及形成机理研究提供一种新的切入点, 对于矿场开发具有重要的科学与工程意义.

1 微尺度多孔介质流动模型

1.1 流体运动模型

多孔介质内油水流动的连续性方程为^[9,18]

$$\nabla \cdot \mathbf{u} = 0, \quad (1)$$

对于微流道内不可压缩流体, 其运动方程为^[14,18]

$$\rho \left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right] = -\nabla \cdot \left(p \mathbf{I} + \mu \left[\nabla \mathbf{u} + (\nabla \mathbf{u})^T \right] \right) + \mathbf{F}_{st}, \quad (2)$$

式(2)中, $\mathbf{u}$ 为流体流速, m/s; ρ 为流体密度, kg/m³; μ 为流体动力黏度, Pa·s; p 为流体压力, Pa; $\mathbf{I}$ 为单位向量; t 为流动时间, s; $\mathbf{F}_{st}$ 为界面张力作用项.

1.2 界面追踪模型

微孔道内水驱油过程中, 两相界面不断变化, 为准确追踪油水界面, 需引入界面追踪方法. 常用的界面追踪方法包括流体体积法、水平集法、前缘追踪法和相场方法. 流体体积法^[19,20]可以追踪复杂相界面变化过程, 具有保持质量守恒的特性, 但是该方法难以准确计算曲率以及曲率有关的物理量, 对相界面处突变的物理量处理效果较差. 水平集法^[21]界面计算精度高, 不需要重构界面, 可以描述界面复杂的拓扑变化, 但是该方法质量守恒性较差. 前缘追踪法^[18]使用网格点追踪界面, 界面位置可以精确确定, 但是当界面拓扑变化较大时, 需要对网格进行大调整或者对网格进行重建, 计算复杂度高. 相场方法^[14,15,22]通过引入相变量将尖锐的界面处理成具有一定厚度的扩散界面层, 界面的运动和变形不仅受到对流的作用, 而且也受到扩散的影响. 整个计算区域中所有变量都连续可微, 并且可以使用统一的控制方程描述, 不必区分各个相与界面, 不需要直接追踪两相界面的变化, 界面本身就是方程求解的一部分. 鉴于上述优点, 本文采用相场方法来追踪驱替过程中的油水界面. 引入相场变量 ϕ 来标识不同相区域, 以及不同相间的过渡区域. 在均匀相区域, 相场变量 ϕ 为常数(通常设定为-1和1); 而在界面处过渡

区域, 相场变量 ϕ 连续变化(介于-1和1之间). 控制界面轮廓演化的对流扩散方程^[22](Cahn-Hilliard方程)就是由基于 ϕ 定义的混合能引入的, 该方程表示相场变量 ϕ 随时间的变化量与对流和扩散影响下的变化量相互平衡,

$$\begin{cases} \frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \nabla \cdot \left(\frac{\gamma \lambda}{\varepsilon^2} \nabla \psi \right), \\ \psi = -\nabla \cdot \varepsilon^2 \nabla \phi + (\phi^2 - 1) \phi, \end{cases} \quad (3)$$

式(3)中, ϕ 为相场变量, 无因次; ε 表示界面厚度, m; γ 为迁移率, 表示单位驱动力作用下界面的迁移速度, m³ s/kg; λ 为混合自由能密度, N.

由于界面区域对流与扩散的存在, 引起界面自由能的变化, 因此界面张力作用项可定义为

$$\mathbf{F}_{st} = w \nabla \phi, \quad (4)$$

式(4)中, w 为化学势, J/m³, 可表示为

$$w = \lambda \left[-\nabla^2 \phi + \frac{\phi(\phi^2 - 1)}{\varepsilon^2} \right] = \frac{\lambda}{\varepsilon^2} \psi. \quad (5)$$

当系统处于平衡状态时, 界面区域混合自由能最小, 通过对单位长度界面曲线上的能量进行积分得到界面张力^[23],

$$\sigma = \frac{3\sqrt{2}\lambda}{3\varepsilon}. \quad (6)$$

流体在不渗透岩石表面无滑移, 且存在一定的润湿角^[24,25],

$$\mathbf{u} = \mathbf{u}_w, \quad (7)$$

$$\mathbf{n} \cdot \frac{\lambda \gamma}{\varepsilon^2} \nabla \psi = 0, \quad (8)$$

$$\mathbf{n} \cdot \varepsilon^2 \nabla \phi = -\varepsilon^2 \cos(\theta) |\nabla \phi|, \quad (9)$$

式(7)表示流体相对岩石壁面无滑移, $\mathbf{u}_w$ 表示壁面滑移速度, m/s; 式(8)表示相场变量的法向流量为0; 壁面润湿角 θ 可由相场变量给出, 如式(9)所示.

驱替过程中的流体物性参数如动力黏度和密度也定义为关于相变量的函数:

$$\begin{cases} \rho = \frac{1+\phi}{2} \rho_w + \frac{1-\phi}{2} \rho_o, \\ \mu = \frac{1+\phi}{2} \mu_w + \frac{1-\phi}{2} \mu_o, \end{cases} \quad (10)$$

式(10)中, ρ_w 与 ρ_o 分别表示水油密度, kg/m³; μ_w 与 μ_o 分别表示水油动力黏度, Pa s.

基于上述N-S方程与界面追踪方法直接描述微尺度多孔介质内油水两相流动.

2 结果与分析

2.1 模型验证

采用基于有限元的多物理场耦合软件COMSOL Multiphysics^[26~28]对N-S与相场模型进行耦合求解,为验证模型数值求解的正确性,采用平行板分层两相流模型进行对比。如图1所示,两个相互平行的无限大平板组成的流道间有两种非混相流体, y 方向流道高度为 $2b$,流道中心位于 $y=0$ 处。流体1位于中央区域 $0<|y|<a$,流体2与平行板接触,位于 $a<|y|<b$ 区域。沿着 x 方向分别在流体1与流体2两端施加恒定压力梯度 G_1 和 G_2 。若无限大平行板间流体运动稳定后满足泊肃叶流动,则两平行板间沿 y 方向任一截面上的速度分布存在解析解:

$$u_x(y) = \begin{cases} A_1 y^2 + C_1 & (0 \leq |y| \leq a), \\ A_2 y^2 + B_2 y + C_2 & (a \leq |y| \leq b), \end{cases} \quad (11)$$

式(6)中系数 A_1, A_2, B_2, C_1, C_2 分别为

$$A_1 = -\frac{G_1}{2\mu_1}, \quad A_2 = -\frac{G_2}{2\mu_2}, \quad B_2 = 2(A_1 M - A_2)a,$$

$C_1 = (A_2 - A_1)a^2 - B_2(b-a) - A_2 b^2, \quad C_2 = -A_2 b^2 - B_2 b,$ 其中 $M = \mu_1/\mu_2$ 为动力黏度比。

求解域大小为 $10 \mu\text{m} \times 200 \mu\text{m}$,两种流体密度相同均为 $\rho_1 = \rho_2 = 1000 \text{ kg/m}^3$,流体1动力黏度为 $\mu_1 = 2 \text{ mPa} \cdot \text{s}$,流体2动力黏度 $\mu_2 = 25 \text{ mPa} \cdot \text{s}$,两相界面张力 $\sigma = 0.072 \text{ N/m}$ 。平行板间距离为 $2b = 4a = 200 \mu\text{m}$ 。沿 x 方向在平行板两端施加周期性边界条件,壁面采用无滑移边界条件。在流体1和流体2两端分别施加不

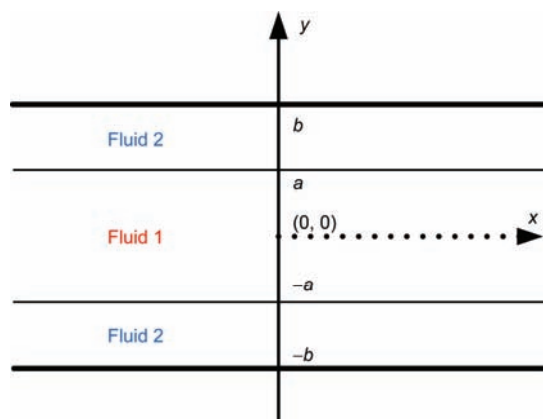


图1 (网络版彩色)平行板间分层两相流示意图

Figure 1 (Color online) Schematic of layered two-phase flow between two parallel plates

同的压力梯度 $G_1 = 1 \times 10^5 \text{ Pa/m}$ 和 $G_2 = 1 \times 10^6 \text{ Pa/m}$ 。由图2可知,数值解与基于泊肃叶定律推导得到的解析解^[29]基本一致,验证了本文模型与数值求解的正确性。

2.2 特高含水期剩余油类型及形成机理

为研究特高含水期剩余油分布及形成机理,选取尺寸为 $1000 \mu\text{m} \times 500 \mu\text{m}$ 的人造二维多孔介质作为研究对象。实际地层的孔隙尺度多孔介质一般通过CT扫描岩心,获得数字岩心,通过图像处理,获得真实地层的二维多孔介质。本文所采用的多孔介质是一个经过多次流动测试修正得到的结构复杂的概念模型,目的是向读者展示类型全面的剩余油分布。初始多孔介质内饱和油相,左端作为注入端,恒速注入水相,右端作为采出端,压力为0。油相与水相的密度分别为 $\rho_o = 870 \text{ kg/m}^3$, $\rho_w = 1000 \text{ kg/m}^3$ 。油相与水相动力黏度分别为 $\mu_o = 5 \text{ mPa} \cdot \text{s}$, $\mu_w = 1 \text{ mPa} \cdot \text{s}$ 。油水界面张力 $\sigma = 0.072 \text{ N/m}$,岩石壁面油湿,与油相接触角为 $\theta = 60^\circ$,上下固壁采用无滑移边界条件。采用Delaunay三角网格对多孔介质进行剖分,通过网格无关性检验确定的网格单元数为44755(网格无关性检验见附录)。界面厚度设置为最大网格单元尺寸的四分之一,初始时间步为 $1 \times 10^{-10} \text{ s}$,时间步长采用向后差分法(BDF)确定,相对误差0.001。采用PARDISO求解器对模型进行求解。初始在多孔介质左端入口处以平均速度 $U_{in} = 0.015 \text{ m/s}$ 恒速注入水,对应毛细数 Ca 为 2.08×10^{-4} 。待驱替稳定后(多孔介质内含水饱和度基本不再变化)计算多孔介质内采收程度(采收程度,表示出口累计产油量与多孔介质孔隙体积之比)

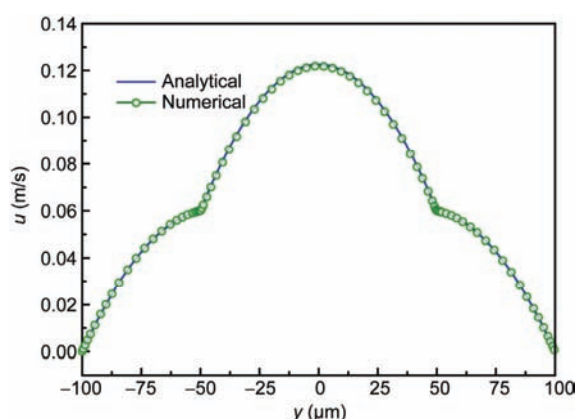


图2 (网络版彩色)平行板截面流速分布

Figure 2 (Color online) Numerical and analytical velocity profiles between two parallel plates

与出口端含水率(含水率是反应油田开发潜力的重要指标, 定义为 $f_w = Q_w / (Q_w + Q_o)$, Q_w 为出口端水相流量, Q_o 为出口端油相流量), 结果图3所示。

由图3(a)可知, 注水后多孔介质内采收程度迅速上升, 出口端突破后(水流到出口端), 注入水开始沿着形成的高渗通道流动, 波及效率变低, 采收速率下降。驱替0.011 s后多孔介质内剩余油量基本不变, 此时采收程度为73.47%。由图3(b)可知, 早期注入水未突破, 出口端含水率为0, 称为无水采油期。出口端突破后, 含水率开始大幅上升, 驱替0.00323 s后, 出口端含水率达到90%, 进入特高含水期, 最终驱替稳定后, 出口端含水率约为98.62%, 达到常规开发的经济极限。

在水驱油田的动态分析和预测工作中, 水驱曲线被广泛用于描述生产过程中的含水变化, 最终采收率以及可采储量。计算采出端不同时刻的累产水量 $\log W_p$ 与累产油量 N_p , 可得图4所示甲型水驱曲线。由图4可知, 早期含水率较低时含水上升速度较快, 含水率到达42.5%后, 水驱曲线基本呈一条直线。当含水率到达91.14%, 进入特高含水期, 水驱曲线上翘^[30,31], 含水上升率迅速增大, 出口端采出油量大幅减少。孔隙尺度流动模拟得到的水驱曲线与矿场规律基本一致。

图5是基于孔隙尺度流动模拟得到的相对渗透率曲线^[32]。相对渗透率是多相流体在多孔介质中共存时, 每一相的有效渗透率与绝对渗透率的比值, 反映每一相流体的流体能力。图5中反映的特高含水后期(含水率大于98%)最重要的渗流特征是水相相渗曲线上翘, 其在多孔介质中的流动能力急剧上升, 这一规律与矿场生产得到的相渗曲线规律基本一致, 也从

侧面反映本文模型的适用性。而油相相对渗透率基本持续下降, 接近为0, 油基本被束缚在孔隙内。

图6表示驱替稳定之后, 多孔介质内剩余油分布状况及类型(包括注入水, 剩余油, 岩石骨架)。观察可知, 特高含水期多孔介质内剩余油共有5种类型: (1) 孤立油滴; (2) 孔喉残余油; (3) 簇状非均质剩余油; (4) 岩石表面油膜; (5) 盲端残余油。剩余油总体分布呈现“高度分散, 局部富集”的特征。

(i) 孤立油滴。选取图6中标记为1的典型孤立油滴为例, 解释其形成机理。为有效观察油滴形成过程, 对1处进行局部放大。

图7给出驱替过程中孤立油滴的形成过程。特定的孔隙结构是形成孤立油滴的必要条件。如图7(b)所示初始注入水沿 f_1 和 f_3 (标示见图8)方向的两条流动突破喉道毛管阻力流入孔隙并驱替油相, 同时注入水沿 f_2 方向驱动油相。图8给出了形成孤立油滴过程中 p_1 与 p_2 两点的压力差。0.0011 s左右, 注入水流过 p_1 点, 该处压力上升, 但 p_2 处注入水未波及, 导致两点压力差急剧上升, 此时 f_1 处水驱前缘推进速度相对较快。0.0012 s左右, 注入水波及到 p_2 处(图7(c)), 压力上升, 导致图8中两点压力差的急剧下降, 也减缓了 f_1 处水驱前缘推进速度。此后注入水沿 f_2 方向继续往前顺利推进, 而 f_1 处流动较慢, p_1 处压力升高, 因而在0.0012 s后 p_1 与 p_2 两点压力差上升。随后 f_2 方向, 油相发生断裂(图7(f)), 部分残余油被滞留在孔隙内。滞留油滴在壁面润湿性等因素影响下, 形态发生变化, 直到最终孔隙内压力达到平衡, 油滴形态不再变化。孤立油滴的形成是孔隙结构, 毛管力以及壁面润湿性共同作用的结果。

(ii) 孔喉残余油。孔喉残余油的形成主要有两

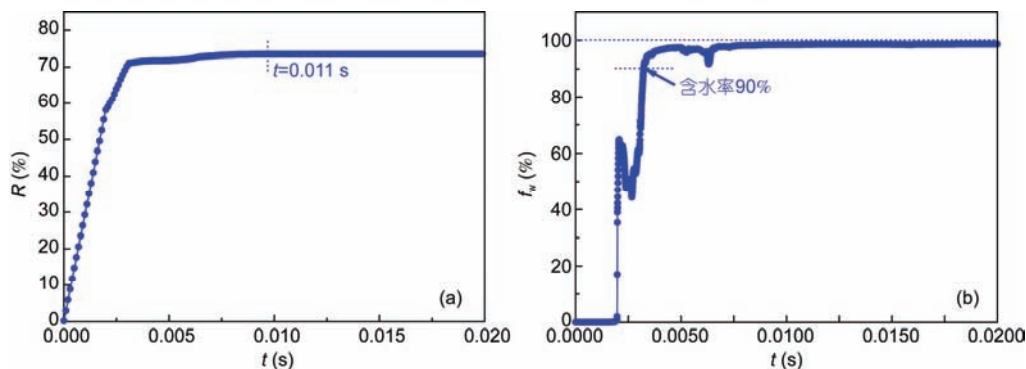


图3 (网络版彩色)采出程度与含水率曲线。(a) 多孔介质采收程度;(b) 出口端含水率

Figure 3 (Color online) Oil recovery of porous media and water cut at the outlet. (a) Oil recovery of porous media; (b) water cut at the outlet

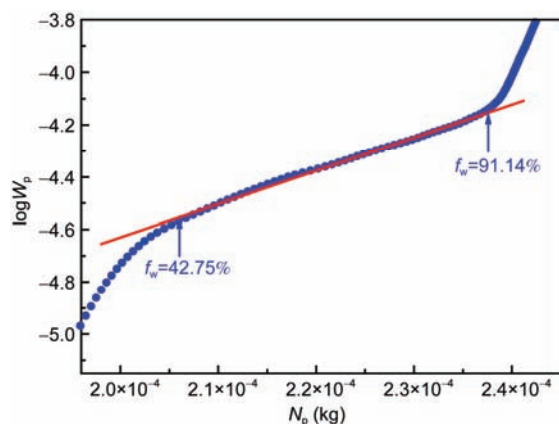


图4 (网络版彩色)特高含水期甲型水驱曲线

Figure 4 (Color online) Water displacement curve at the extra-high water-cut stage

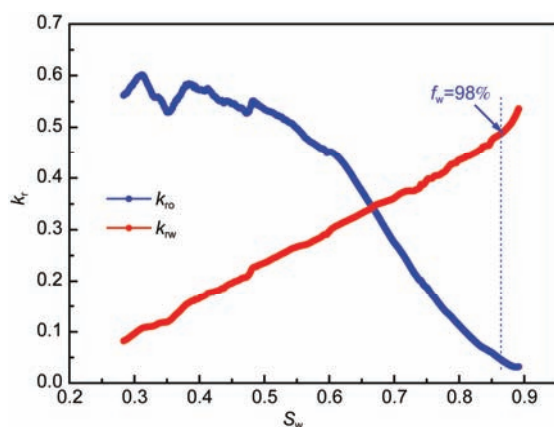


图5 (网络版彩色)相对渗透率曲线

Figure 5 (Color online) Relative permeability curve

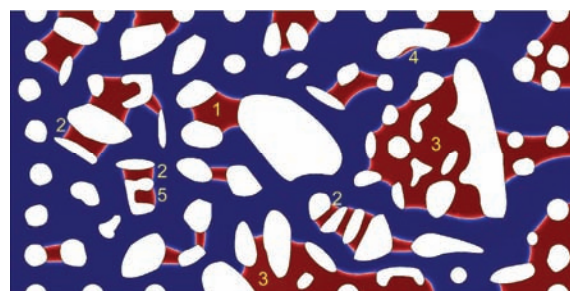


图6 (网络版彩色)特高含水期多孔介质内剩余油分布($t=0.02$ s)

Figure 6 (Color online) Residual oil distribution in the porous media at extra-high water-cut stage ($t=0.02$ s)

种原因,根据其形成机理的不同,分别将其命名为A类和B类孔喉残余油.以图6中靠近注入端处标记为2的两处典型孔喉残余油为例,解释其形成机理.

图9为典型的A类孔喉残余油,水驱过程中油相始终滞留于岩石颗粒间.驱替过程中 V_1 与 V_2 两点处的压差如图10所示,水驱波及到 V_1 处后且未波及到 V_2 处时两点的压力差不断增大,但整个过程中两点的最大压差始终小于孔喉最窄处毛管力(极限毛管力,图10中水平线),因此不能驱替出孔喉内残余油.当注入水波及到 V_2 处后,孔喉两端压差剧烈下降,孔喉内的残余油被滞留其中.孔喉毛管力是形成A类孔喉残余油的本质机理.

图11为靠近盲端的B类孔喉残余油,图12揭示了其形成机理.驱替过程中注入水沿 f_4 方向突破喉道的毛管压力,驱替出喉道内油相,如图12(a)所示.毛管力是水驱替孔喉内油相的阻力.当孔喉内全部残余

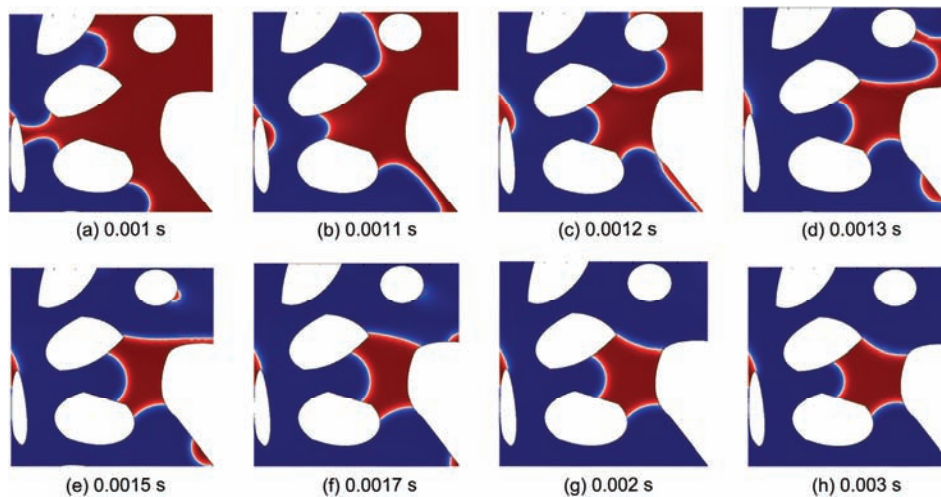


图7 (网络版彩色)孤立油滴形成过程

Figure 7 (Color online) Formation process of the isolated oil droplet

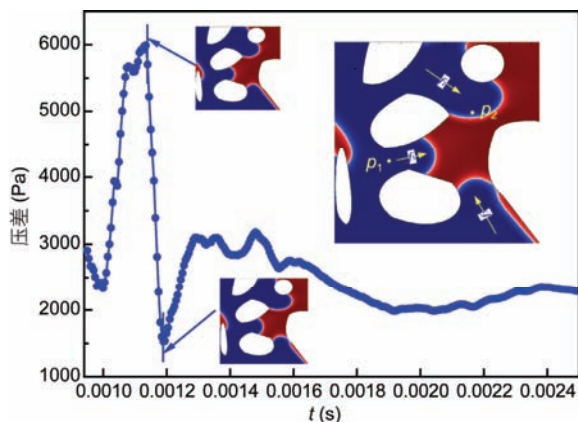
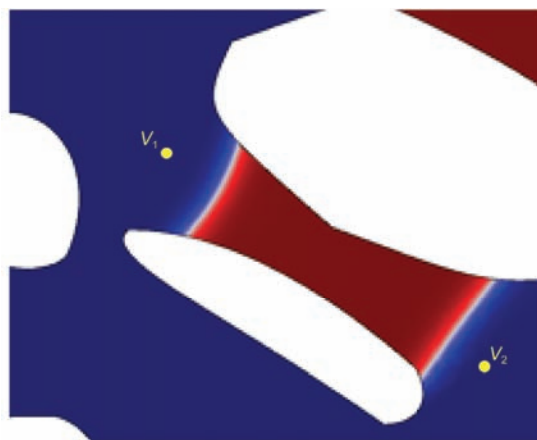
图8 (网络版彩色) p_1 点与 p_2 点压力差Figure 8 (Color online) The pressure difference between p_1 and p_2 

图9 (网络版彩色)A类孔喉残余油

Figure 9 (Color online) A-type residual oil in the pore throat

油要被驱出时, 注入水沿 f_5 方向突破, V_4 处压力升高部分导致部分油相滞留在孔喉内, 如图12(b)所示。

随后位于喉道末端的残余油在毛管力等作用下回流, 滞留在盲端上方的残余油在沿 f_5 与 f_6 方向流动的注入水共同作用下往孔喉处流动, 最终流入孔喉内, 达到水动力平衡, 形成束缚在喉道内的残余油。对于水湿油藏, 毛管力是水流入孔喉内的动力, 易于

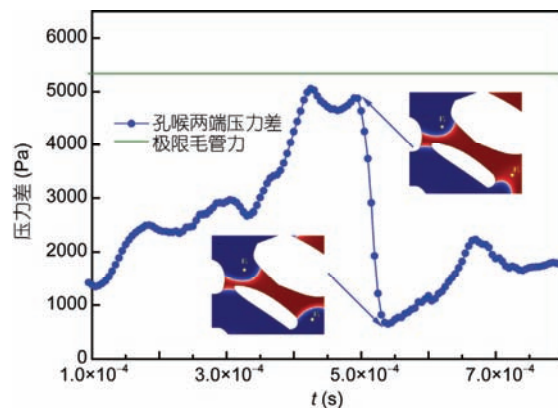
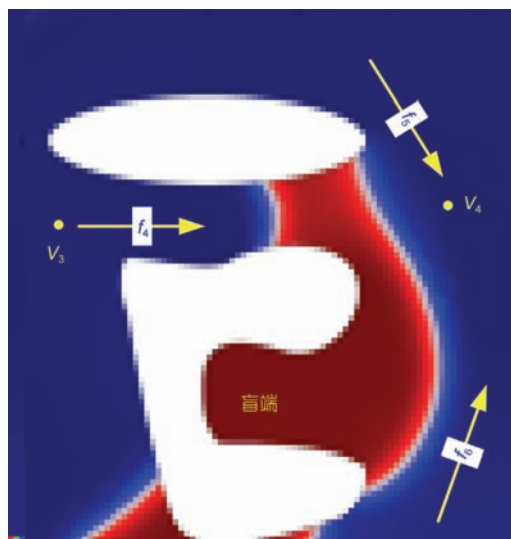
图10 (网络版彩色) V_1 与 V_2 两点压力差Figure 10 (Color online) The pressure difference between V_1 and V_2 

图11 (网络版彩色)第二类孔喉残余油

Figure 11 (Color online) B-type residual oil in the pore throat

驱替出孔喉内残余油, 同时也是油相重新流回孔喉内的阻力, 因此很难形成B类孔喉残余油。壁面润湿性是形成B类孔喉残余油的关键因素。

(iii) 簇状非均质剩余油。图6中标记为3的剩余油类型为典型的簇状非均质剩余油。形成簇状非均

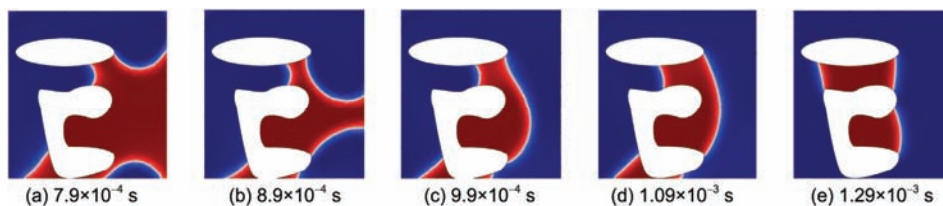


图12 (网络版彩色)B类孔喉残余油形成过程

Figure 12 (Color online) The formation process of B-type residual oil in the pore throat

质剩余油的主要原因是多孔介质非均质较强,局部区域较为致密,孔隙半径较小,且其周围喉道半径较大,注入水沿着大孔道流动并驱替出其中的油相(毛管阻力低),致密区域油相未被波及滞留下来(图13).毛管力与孔隙结构是形成簇状非均质剩余油的主要原因.

(iv) 壁面油膜. 壁面油湿时,壁面对残余油作用力较强,且随着接触角的减小而增大.当水动力作用较弱时,在壁面易于形成油膜.图6中标记为4的残余油为典型油膜.而水湿油藏由于对油相作用力较弱,一般在驱替过程中很难出现油膜.壁面润湿性是形成油膜的主要原因.

(v) 盲端残余油. 由图6中标记为5的残余油为典型的盲端残余油.形成盲端残余油的主要原因是由于孔隙结构的束缚.同时驱替过程中盲端前端不是主流道,流速较低,注入水对盲端内残余油波及作用较弱,导致残余油在盲端富集.对于该类残余油,具有黏弹性的聚合物流体一般具有较好的驱替效果^[7,8].

在实际矿场开发中,地层中的流动是在三维空间尺度下进行的,重力等因素对剩余油分布及形成机理具有一定影响,因此本文基于二维流动模拟得到的结果存在一定局限性.但对于每一类剩余油的形成过程的阐述及机理分析方法上,三维尺度与二维基本一致,本文对于二维多孔介质的研究为三维复杂多孔介质剩余油的分布及形成机理研究打下了坚实的基础.

2.3 特高含水期剩余油挖潜研究

特高含水期提高采收率的本质是挖掘多孔介质内五类残余油的潜力.对于残余油形成过程和机理的研究,为矿场各类增产措施提供了理论基础及指导.

(i) 增注及增注时机的选择. 提高注水强度是矿场常用的一种增产措施^[4,33],为研究特高含水期增注提高采收率的机理,从 $t=0.011$ s开始分别将平均注入速度由 0.015 m/s提高至 0.025 m/s,观察驱替稳定后剩余油分布.

由图14剩余油分布可知,簇状非均质剩余油的减少是增注提高采收程度的主要原因.随着注入速度的提高,毛细数增大($Ca=\mu_w U_{in}/\sigma$,反应黏性力与毛管力相对强弱),黏性力作用增强,使得注入水克服致密区域小孔隙毛管力并将油相驱替出.此外孤立油滴以及部分受毛管力束缚的A类孔喉残余油也

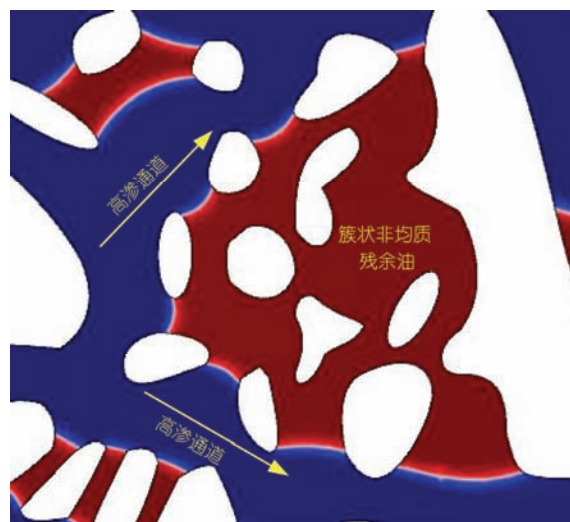


图13 (网络版彩色)簇状非均质残余油
Figure 13 (Color online) Cluster residual oil

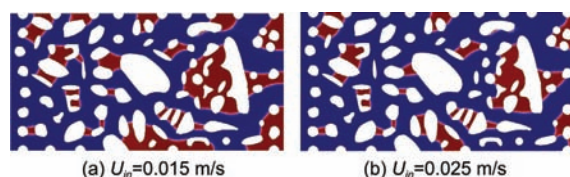


图14 (网络版彩色)增注后多孔介质内剩余油分布
Figure 14 (Color online) Residual oil distribution in porous media after increasing velocity of injection

被驱替出.

为进一步研究增注的时机对采收程度的影响,在三个不同时刻进行增注(注入速度由 0.015 m/s提高到 0.02 m/s,界面张力 $\sigma=0.072$ N/m): (1) 开发初期增注($t=0$); (2) 刚进入特高含水期进行增注(含水率为90%, $t=0.00323$ s); (3) 特高含水后期增注(驱替稳定, $t=0.011$ s),观察并对比较开发效果.

由图15可知,开发初期($t=0$ s)增注,采收程度较高,但采收速度逐渐下降,约 $t=0.012$ s时,采收程度达到78.2%后,基本不变.第二种增注方案,含水率达到90%时增注,采收速度迅速增加,约 $t=0.008$ s时达到采收极限.特高含水后期增注,约 $t=0.0185$ s时,采收程度达到最终的78.2%.对比三种增注方案可知,三者最终采收率基本一致,但是开发时间长短存在差别,含水率达到90%时增注,达到采收极限时间较短,注水量低,经济成本低,是较优的一种增注方案.

(ii) 降低界面张力. 注入表面活性剂提高采收

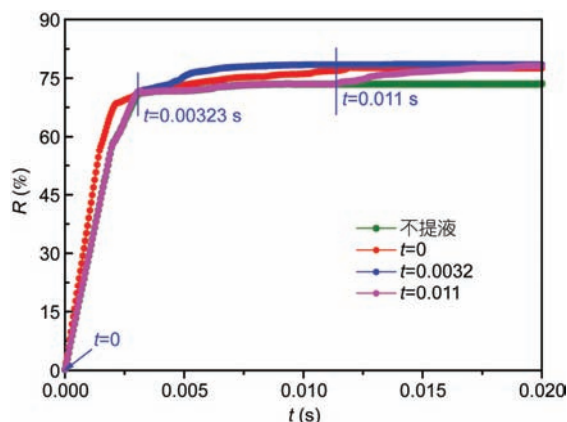


图15 (网络版彩色)不同增注时机采收率比较

Figure 15 (Color online) Oil Recoveries after increasing injection velocity at different times

率也是矿场常用的一种增产措施^[34]。降低油水界面张力是表面活性剂驱提高采收率最为突出的机理。为研究特高含水期注入表面活性剂对各类剩余油的驱替效果,将油水界面张力从0.072 N/m降低至0.02 N/m,观察驱替稳定后多孔介质内剩余油分布。

由图16可知,低界面张力下,毛细数增大,毛管力作用削弱,注入水突破小孔隙毛管力易于驱替出簇状非均质剩余油,孔喉残余油以及油滴,从而达到提高采收率的目的。簇状非均质剩余油的减少是增注提高采收率的主要原因。综上可知,簇状非均质剩余油的减少是增注与注入表面活性剂提高采收率的主要原因。

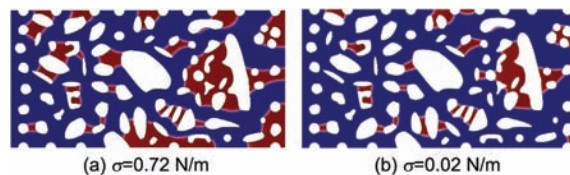


图16 (网络版彩色)注入表面活性剂后多孔介质内剩余油分布

Figure 16 (Color online) Residual oil distributions in the porous media after injecting surfactant

3 结论

本文将传统多相流模拟方法的应用拓展到矿场特高含水期剩余油研究领域,基于N-S方程建立特高含水期剩余油微观流动模拟模型,运用相场方法实时追踪驱替过程中的两相界面。研究特高含水期剩余油分布及形成机理,并探究特高含水期剩余油的挖潜措施。主要得到以下结论:

(1) 特高含水期多孔介质内剩余油主要可以分为5种类型:孤立油滴、孔喉残余油、簇状非均质剩余油、油膜、盲端残余油。毛管力,孔隙结构以及壁面润湿性等因素决定特高含水期剩余油的分布与类型。

(2) 孔隙尺度流动模拟得到的水驱曲线与矿场规律基本一致。

(3) 特高含水期增注与注入表面活性剂均是通过驱替出簇状非均质剩余油,孔喉残余油以及孤立油滴达到提高剩余油采收程度的目的。簇状非均质剩余油的减少是采收程度提高的主要原因。矿场增注时机对经济开发有重要影响。

参考文献

- Bing S X. Study on water drive development characteristics based on the oil-water two phase flow of ultra-high water cut stage (in Chinese). Dissertation for Doctoral Degree. Chengdu: Southwest Petroleum University, 2013 [邴绍献. 基于特高含水期油水两相渗流的水驱开发特征研究. 博士学位论文. 成都: 西南石油大学, 2013]
- Zhu L H, Du Q L, Jiang X Y, et al. Characteristic and strategies of three major contradictions for continental facies multi-layered sandstone reservoir at ultra-high water cut stage (in Chinese). Acta Petrol Sin, 2015, 36: 210–216 [朱丽红, 杜庆龙, 姜雪岩, 等. 陆相多层砂岩油藏特高含水期三大矛盾特征及对策. 石油学报, 2015, 36: 210–216]
- Zhu G P, Yao J, Sun H, et al. Microscopic flow simulation of viscoelastic fluid based on interface tracking method (in Chinese). Chin Sci Bull, 2016, 61: 3973–3981 [朱光普, 姚军, 孙海, 等. 基于界面追踪的黏弹性流体微观流动模拟. 科学通报, 2016, 61: 3973–3981]
- Han D K. Discussions on concepts, countermeasures and technical routes for the redevelopment of high water-cut oil fields (in Chinese). Petrol Explor Devel, 2010, 37: 584–591 [韩大匡. 关于高含水油田二次开发理念, 对策和技术路线的探讨. 石油勘探与开发, 2010, 37: 583–591]
- Jiang H Q. Early-warning and differentiated adjustment methods for channeling in oil reservoirs at ultra-high water cut stage (in Chinese). J China Univ Petrol, 2013, 37: 114–119 [姜汉桥. 特高含水期油田的优势渗流通道预警及差异化调整策略. 中国石油大学学报, 2013, 37: 114–119]
- Janssen P, Van Den Broek W, Harris C. Laboratory study investigating emulsion formation in the near-wellbore region of a high water-cut oil well. SPE J, 2001, 6: 71–79

- 7 Wang D, Cheng J, Yang Q, et al. Viscous-elastic polymer can increase microscale displacement efficiency in cores. SPE Annual Technical Conference and Exhibition, 2000
- 8 Wang D, Cheng J, Xia H, et al. Viscous-elastic fluids can mobilize oil remaining after water-flood by force parallel to the oil-water interface. SPE Asia Pacific Improved Oil Recovery Conference, 2001
- 9 Gunde A C, Bera B, Mitra S K. Investigation of water and CO₂ (carbon dioxide) flooding using micro-CT (micro-computed tomography) images of Berea sandstone core using finite element simulations. *Energy*, 2010, 35: 5209–5216
- 10 Raeini A Q, Blunt M J, Bijeljic B. Direct simulations of two-phase flow on micro-CT images of porous media and upscaling of pore-scale forces. *Adv Water Res*, 2014, 74: 116–126
- 11 Zhang L, Kang Q, Yao J, et al. Pore scale simulation of liquid and gas two-phase flow based on digital core technology. *Sci China Tech Sci*, 2015, 58: 1375–1384
- 12 Zhang L, Kang Q J, Yao J, et al. The explanation of low recovery of fracturing fluid in shale hydraulic fracturing by pore-scale simulation (in Chinese). *Chin Sci Bull*, 2014, 32: 3197–3203 [张磊, 康钦军, 姚军, 等. 页岩压裂中压裂液返排率低的孔隙尺度模拟与解释. *科学通报*, 2014, 32: 3197–3203]
- 13 Shen J, Yang X. Decoupled, energy stable schemes for phase-field models of two-phase incompressible flows. *SIAM J Numer Anal*, 2015, 53: 279–296
- 14 Yue P, Feng J J, Liu C, et al. A diffuse-interface method for simulating two-phase flows of complex fluids. *J Fluid Mech*, 2004, 515: 293–317
- 15 Yue P, Zhou C, Feng J J, et al. Phase-field simulations of interfacial dynamics in viscoelastic fluids using finite elements with adaptive meshing. *J Comput Phys*, 2006, 219: 147–167
- 16 Liu P, Yao J, Couples G D, et al. Numerical modelling and analysis of reactive flow and wormhole formation in fractured carbonate rocks. *Chem Eng Sci*, 2017, doi: <https://doi.org/10.1016/j.ces.2017.06.027>
- 17 Liu H, Valocchi A J, Werth C, et al. Pore-scale simulation of liquid CO₂ displacement of water using a two-phase lattice Boltzmann model. *Adv Water Res*, 2014, 73: 144–158
- 18 Tryggvason G, Bunner B, Esmaeili A, et al. A front-tracking method for the computations of multiphase flow. *J Comput Phys*, 2001, 169: 708–759
- 19 Saha A A, Mitra S K. Effect of dynamic contact angle in a volume of fluid (VOF) model for a microfluidic capillary flow. *J Colloid Interface Sci*, 2009, 339: 461–480
- 20 Hirt C W, Nichols B D. Volume of fluid (VOF) method for the dynamics of free boundaries. *J Comput Phys*, 1981, 39: 201–225
- 21 Sussman M, Smereka P, Osher S. A level set approach for computing solutions to incompressible two-phase flow. *J Comput Phys*, 1994, 114: 146–159
- 22 Boyer F, Lapuerta C, Minjeaud S, et al. Cahn-Hilliard/Navier-Stokes model for the simulation of three-phase flows. *Transport Porous Med*, 2010, 82: 463–483
- 23 Shen J. Modeling and numerical approximation of two-phase incompressible flows by a phase-field approach. *Multisc Model Anal Mater Simul*, 2011, 22: 147–195
- 24 Hizir F E, Hardt D E. Phase-field modeling of liquids splitting between separating surfaces and its application to high-resolution roll-based printing technologies. *Phys Fluids*, 2017, 29: 052007
- 25 Zhao Y P. Surface and Interface Physical Mechanics (in Chinese). Beijing: Science Press, 2012 [赵亚溥. 表面与界面物理力学. 北京: 科学出版社, 2012]
- 26 Zhu G P, Yao J, Sun H, et al. The numerical simulation of thermal recovery based on hydraulic fracture heating technology in shale gas reservoir. *J Nat Gas Sci Eng*, 2016, 28: 305–316
- 27 Zhu G P, Yao J, Ai F L, et al. Pore-scale investigation of carbon dioxide enhanced oil recovery. *Energy Fuels*, 2017, doi: 10.1021/acs.energyfuels.7b00058
- 28 Zhu G P, Yao J, Zhang L, et al. Investigation of the dynamic contact angle using a direct numerical simulation method. *Langmuir*, 2016, 32: 11736–11744
- 29 Huang H, Lu X. Relative permeability and coupling effects in steady-state gas-liquid flow in porous media: A lattice Boltzmann study. *Phys Fluids*, 2009, 21: 092104
- 30 Song Z J, Li Z P, Lai F P, et al. Derivation of water flooding characteristic curve for high water-cut oilfields. *Petrol Explor Devel*, 2013, 40: 216–223
- 31 Cui C Z, Xu J P, Wang D P, et al. A new water flooding characteristic curve at ultra-high water cut stage (in Chinese). *Acta Petrol Sin*, 2015, 36: 1267–1271 [崔传智, 徐建鹏, 王端平, 等. 特高含水阶段新型水驱特征曲线. *石油学报*, 2015, 36: 1267–1271]
- 32 Arrufat T, Bondino I, Zaleski S, et al. Developments on relative permeability computation in 3d rock images. Abu Dhabi International Petroleum Exhibition and Conference. Society of Petroleum Engineers, 2014

- 33 Zhu Y W, Meng H L, Ma B D, et al. Factors effecting decompression and augmented injection by surfactant in low permeability reservoir (in Chinese). *Petrol Geol Recov Eff*, 2016, 23: 74–78 [祝仰文, 孟红丽, 马宝东, 等. 低渗透油藏表面活性剂降压增注效果影响因素. *油气地质与采收率*, 2016, 23: 74–78]
 - 34 Han M, Kang X D, Zhang J, et al. Process in EOR by means of surfactants (in Chinese). *China Offshore Oil Gas*, 2006, 18: 408–412 [韩明, 康晓东, 张健, 等. 表面活性剂提高采收率技术的进展. *中国海上油气*, 2006, 18: 408–412]
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补充材料

图 S1 三种不同网格精度下采收程度曲线对比

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Summary for “特高含水期剩余油分布及形成机理”

Pore-scale investigation of residual oil distributions and formation mechanisms at the extra-high water-cut stage

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Water flooding has been widely applied in the oilfield development as a secondary recovery method due to its effectiveness and economic feasibility. After several decades of production, numerous oil fields are normally entering into the extra-high water-cut stage (water cut higher than 90%). The extra-high water-cut stage takes an extremely important role in the whole development process since a large amount of residual oil remains trapped in reservoirs (approximately 50% to 60% of initial oil in place) at this stage. The extensively continuous distribution of subsurface oil at the low water-cut stage has changed greatly after the water cut of mature oilfields becomes over 90%. The residual oil distributes mainly in a scattered state at the extra-high water-cut stage, while water flows in a continuous state. Oilfields with high water cut are normally suffering from poor flooding efficiency, to improve water flooding efficiency, it is necessary to understand distributions and formation mechanisms of residual oil at the extra-high water-cut stage. In this study, a pore-scale simulation model is developed to exploit the potential of residual oil in a porous media. A direct numerical simulation method is employed to simulate fluid flow in a porous media, the position of interface between water and oil is determined by the phase field method. The capacity and accuracy of the model is validated by a classical benchmark: a layered two-phase flow with a variable viscosity ratio. The formation processes of residual oil and mechanisms behind this are investigated in terms of mechanics. The results show that the residual oil in porous media at the extra-high water-cut stage can be classified as five types, namely, isolated oil droplet, residual oil in pore throats, cluster residual oil, oil film and residual oil in dead end. Rock configuration, wettability and capillary pressure play important roles in the formation of residual oil. The formation of isolated oil droplet is dominated by rock configuration, capillary pressure and wettability. Capillary pressure and wettability are key factors for the formation of residual oil in pore throats. Rock configuration and capillary pressure are responsible for the formation of cluster residual oil. Wettability is the dominant factor for the formation of oil film. The relationship between cumulative water production and cumulative oil production is consistent at the pore scale and Darcy scale. Relative permeability curve is obtained based on the pore-scale simulation and an upward turning is observed after the water cut reaches 98%. Increasing injection velocity and injection of surfactant can both displace cluster residual oil, residual oil in pore throats and isolated oil droplets, which leads to the increase in oil recovery at the extra-high water-cut stage. The decline in cluster residual oil is the main contributor to rise in oil recovery. Times of increasing injection velocity have an important pact on the field development. This study is only conducted in a two dimensional porous media, and more factors (e.g., gravity) should be incorporated into our model to investigate the formation process of residual oil in the three dimensional porous media.

extra-high water-cut stage, N-S equation, phase field, pore-scale flow simulation, residual oil

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