基于界面追踪的黏弹性流体微观流动模拟

朱光普, 姚军*, 孙海, 张磊, 李爱芬

中国石油大学(华东)石油工程学院, 青岛 266580

* 联系人, E-mail: RCOGFR_UPC@126.com

2016-08-14 收稿, 2016-09-20 修回, 2016-09-21 接受, 2016-10-21 网络版发表

泰山学者建设工程专项经费、国家重大专项(2016ZX05011-001)、国家自然科学基金(41502131, 51504276, 51304232, 51274226)和中国博士后科学基金(2015M580621)资助

摘要 特高含水期后期, 地层剩余油主要以油膜、盲端残余油等形态存在, 水驱开发效果变差, 采用黏弹性流体驱替是当前提高采收率的有效方法. 为探索黏弹性流体驱替残余油的水动力学机理, 基于N-S方程模拟黏弹性流体在微孔道内流动. 采用Oldroyd-B本构方程描述流体的黏弹性, 运用相场方法实时追踪驱替过程中两相界面. 分别研究壁面油膜在黏弹性流体驱替下的运动和变形, 黏弹性流体对盲端残余油的驱替效果, 并分析残余油微观受力状况. 采用有限元方法对模型进行求解, 并验证模型与求解的正确性. 研究结果表明: 黏弹性流体可以有效驱动壁面油膜运动, 相同注入流量下, 黏弹性流体作用于壁面油膜上的水平应力差远大于水; 作用于油膜上的法向应力分布不均匀导致油膜发生较大变形. 同时黏弹性流体在盲端内的波及边界更深, 有利于引发盲端残余油的运动, 提高残余油采收率. 黏弹性流体驱替对水湿油藏开发增产效果更明显. 该研究初步揭示了黏弹性流体驱替残余油的水动力学机理, 为油田三次采油提供有效指导.

关键词 黏弹性流体, N-S 方程, Oldroyd-B, 相场, 残余油

目前我国东部老油区已进入特高含水后期, 剩余油分布呈现“高度分散, 局部富集”的特征, 水驱开发效果变差, 采收率明显下降^[1,2]. 地层剩余油主要以5种形态^[3]存在: 孤立油滴、油膜、盲端残余油、孔喉残余油、簇状油. 有效挖掘残余油潜力是提高采收率的关键, 聚合物驱^[4,5]是当前推广应用较好的一种方法.

聚合物驱已成功用于大庆油田三次采油, 矿场实践表明具有黏弹性的聚合物溶液可以提高水驱后的采油效率. 对于黏弹性流体的驱油机理, 王德民等人^[6,7]研究表明具有黏弹性的聚合物溶液驱替时表现出很强的“拉、拽”作用, 微观驱油效率的提高与聚合物溶液的弹性有关. 但由于实验尺度以及精度限制, 模拟微纳尺度黏弹性流体驱替仍存在巨大挑战. 张

立娟等人^[8~11]基于上随体Maxwell本构方程, 研究了黏弹性流体对微孔道中残余油滴驱替的水动力学机制, 该研究具有重要的参考与指导意义, 但相关研究仍局限于稳态, 同时也忽略了牛顿流体的黏度. 国外学者Alves等人^[12~14]对黏弹性流体圆柱管壁绕流及其在收缩孔道内流动问题做了深入研究, 但普遍局限于单相稳态流场以及管壁作用力分析, 对黏弹性流体提高原油采收率还未展开研究. Harvie等人^[15]基于Oldroyd-B模型精确描述了收缩孔道内黏弹性液滴在水驱过程中的运动与变形, 对黏弹性流体非稳态流动模拟具有重要参考意义.

为探索黏弹性流体驱替残余油的水动力学机理, 基于N-S方程^[16~19]考虑壁面润湿状况^[20,21], 模拟黏弹性流体在微孔道内流动^[22~26]. 采用Oldroyd-B本构方

引用格式: 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

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, doi: 10.1360/N972016-00050

程^[15,27]描述流体的黏弹性,运用相场模型^[28,29]实时追踪驱替过程中两相界面.对比研究在水和黏弹性流体驱替下,壁面油膜的运动及变形,分析油膜的微观受力状况^[30],揭示黏弹性流体提高采收率的本质机理;研究黏弹性流体对盲端残余油的驱替效果,推动聚合物驱油理论的发展,为油田的实际开发提供指导.

1 黏弹性流体微观流动数学模型

1.1 流体运动模型

黏弹性的聚合物溶液具有复杂的流变特性,须采用黏弹性本构方程描述.本构方程描述了聚合物分子拉伸变形与弹性应力的关系,经实践研究表明,Oldroyd-B模型可以很好地描述黏弹性连续介质.

黏弹性流体流动的连续性方程^[13,15]为

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

对于微流道内不可压缩流体,其运动方程^[12,15,19]为

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

式(2)中, $\mathbf{u}$ 为流体流速, m/s; ρ 为流体密度, kg/m³; μ_s 为牛顿流体黏度, Pa·s; p 为流体压力, Pa; $\mathbf{I}$ 为单位向量; t 为流动时间, s; 流场的总应力分布^[31]可表示为

$$\boldsymbol{\sigma} = -p \mathbf{I} + \mu_s \left[\nabla \mathbf{u} + (\nabla \mathbf{u})^T \right] + \mathbf{T}. \quad (3)$$

由牛顿流体引起的基础应力为

$$\boldsymbol{\sigma}_s = -p \mathbf{I} + \mu_s \left[\nabla \mathbf{u} + (\nabla \mathbf{u})^T \right]. \quad (4)$$

聚合物引起的额外应力张量 $\mathbf{T}$,可采用Oldroyd-B本构方程^[12,13,31]描述

$$\begin{cases} \mathbf{T} + \lambda_p \frac{\Delta \mathbf{T}}{\Delta t} = \mu_p \left[\nabla \mathbf{u} + (\nabla \mathbf{u})^T \right], \\ \frac{\Delta \mathbf{T}}{\Delta t} = \frac{\partial \mathbf{T}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{T} - \left[(\nabla \mathbf{u}) \mathbf{T} + \mathbf{T} (\nabla \mathbf{u})^T \right], \end{cases} \quad (5)$$

式(5)中, λ_p 为聚合物松弛时间, s; μ_p 为上随体Maxwell流体的黏度, Pa·s.

1.2 界面追踪模型

黏弹性流体在微孔道内驱替油相过程中,两相界面不断变化,为准确追踪黏弹性流体与油相界面,本文引入相场方法.相场法^[32~34]的核心思想是两相交界面不是非常锐利的间断,而是具有一定厚度扩

散的界面层,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.该方法引入相场变量 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(Cahn-Hilliard方程^[32~34])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

$$\begin{cases} \frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \nabla \cdot \left(\frac{\gamma \lambda}{\varepsilon^2} \nabla \psi \right), \\ \psi = -\nabla \cdot \varepsilon^2 \nabla \phi + (\phi^2 - 1) \phi, \end{cases} \quad (6)$$

式(6)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,因此把界面张力^[34]作为体积力添加到N-S方程中

$$\mathbf{F}_{st} = G \nabla \phi, \quad (7)$$

式(8)中, G 为化学势, J/m³, 可表示为

$$G = \lambda \left[-\nabla^2 \phi + \frac{\phi(\phi^2 - 1)}{\varepsilon^2} \right] = \frac{\lambda}{\varepsilon^2} \psi. \quad (8)$$

1.3 模型的无因次化

取流道入口的平均速度 U_{in} ,作为特征速度,流道入口直径 D 作为特征长度,定义如下无因次参数:

$$\begin{aligned} x_D &= \frac{x}{D}, \quad y_D = \frac{y}{D}, \quad \mathbf{u}_D = \frac{\mathbf{u}}{U_{in}}, \quad T_D = \frac{D \mathbf{T}}{\mu U_{in}}, \\ p_D &= \frac{D p}{\mu U_{in}}, \quad t_D = \frac{t}{D/U_{in}}, \quad Re = \frac{\rho U_{in} D}{\mu}, \\ We &= \frac{\lambda U_{in}}{D}, \quad \mu_{Ds} = \frac{\mu_s}{\mu}, \quad \mu_{Dp} = \frac{\mu_p}{\mu}, \quad \varepsilon_D = \frac{\varepsilon}{D}, \\ Ca &= \frac{\mu_s U_{in} \varepsilon}{\lambda}, \quad \lambda_D = \frac{\varepsilon_D}{Ca}, \end{aligned}$$

其中, $\mu = \mu_s + \mu_p$.黏弹性流体在微孔道流动过程中,流速较低,雷诺数 Re 较小,处于层流流动.韦森伯格数 We 是反应流体弹性的要素,与松弛时间成正相关, We 越大,流体弹性越强.对连续性方程,运动方程以及黏弹性本构方程进行无因次化可得

$$\nabla \cdot \mathbf{u}_D = 0, \quad (9)$$

$$\begin{aligned} & Re \left[\frac{\partial \mathbf{u}_D}{\partial t_D} + (\mathbf{u}_D \cdot \nabla) \mathbf{u}_D \right] \\ &= \nabla \cdot \left(-p_D \mathbf{I} + \mu_{Ds} \left[\nabla \mathbf{u}_D + (\nabla \mathbf{u}_D)^T \right] + \mathbf{T}_D \right) \\ &+ \lambda_D \left[-\nabla^2 \phi + \frac{\phi(\phi^2 - 1)}{\varepsilon_D} \right] \nabla \phi, \end{aligned} \quad (10)$$

$$\begin{aligned} We \frac{\partial \mathbf{T}_D}{\partial t_D} &= \mu_{Dp} \left[\nabla \mathbf{u}_D + (\nabla \mathbf{u}_D)^T \right] - \mathbf{T}_D \\ &- We \left\{ (\mathbf{u}_D \cdot \nabla) \mathbf{T}_D - \left[(\nabla \mathbf{u}_D) \mathbf{T}_D + \mathbf{T}_D (\nabla \mathbf{u}_D)^T \right] \right\}. \end{aligned} \quad (11)$$

1.4 油膜受力分析

流场总应力分布 σ 可由式(3)表示, 则流场中任意曲面上一点处的应力 σ_n 可表示为

$$\sigma_n = \mathbf{n} \cdot \sigma, \quad (12)$$

式(12)中, $\mathbf{n}$ 为曲面单位法向量. 壁面油膜上任意一点受力如图1所示.

由油膜表面任意一点的水平偏应力 σ_{nh} , 可得流体对液滴的水平拖拽力^[31]

$$F_d = \int_{\partial\Omega} \sigma_{nh} d\Omega = \int_{\partial\Omega} (\mathbf{n} \cdot \sigma) \cdot \mathbf{e}_x d\Omega, \quad (13)$$

式(13)中, $\mathbf{e}_x$ 为流动方向上的单位向量(x方向).

图1 (网络版彩色)油膜受力分解示意图. (a) 应力的切向与法向分解; (b) 应力的垂向与水平分解. σ_{nn} 为法向偏应力, Pa; σ_{nt} 为切向偏应力, Pa; σ_{nh} 为水平偏应力, Pa; σ_{nv} 为垂直偏应力, Pa

Figure 1 (Color online) The decomposition of stress on oil film. (a) Tangential and normal decomposition of stress; (b) vertical and horizontal decomposition of stress. σ_{nn} is normal stress component, Pa; σ_{nt} is tangential stress component, Pa; σ_{nh} is horizontal stress component, Pa; σ_{nv} is vertical stress component, Pa

1.5 模型求解

采用基于有限元的多物理场耦合软件COMSOL^[35]的多相流模块(运动方程)和PDE模块(黏弹性本构方程)对模型进行求解. 采用自由剖分的三角网格, 通过网格无关性检验确定的网格参数为: 最小单元尺寸 $0.008 \mu\text{m}$, 最大网格生长率1.15, 曲率解析度0.3. 初始时间步为 $5 \times 10^{-6} \text{ s}$, 时间步长采用向后差分法(BDF)确定, 相对误差0.005. 采用PARDISO求解器对两个模块进行同时求解.

2 结果与分析

2.1 模型的验证

为验证流动方程与黏弹性本构方程求解的正确性, 模拟Oldroyd-B流体流过平行板间圆柱管壁, 平行板及流体相关参数见文献[27]. 求解作用于管壁上的水平拖拽力, 并与其他学者的研究结果进行对比, 如图2所示. 本文求解的水平拖拽力与Sun等人^[27,36]的结果基本一致, 不同 We 数下, 差别均小于1%, 验证了本文模型求解的正确性.

为探索黏弹性流体驱油的水动力学机理, 以油膜及盲端残余油为研究对象, 研究在黏弹性流体驱动下壁面油膜的运动与变形, 分析其微观受力状况, 以及黏弹性流体对盲端残余油的驱替效果.

2.2 油膜的运动与变形

微流道内油膜物理模型如图3所示, 流道直径 $D=4 \mu\text{m}$, 长 $L=16 \mu\text{m}$, 流道底部有残余油, 残余油半

图2 (网络版彩色)不同 We 数下的流体对管壁的水平拖拽力
Figure 2 (Color online) The drag force acting on the cylinder for different Weissenberg numbers

图3 (网络版彩色)油膜物理模型

Figure 3 (Color online) The schematic of oil film on the wall

径为 $R=1.5\ \mu\text{m}$, 距入口 $4.5\ \mu\text{m}$ 处. 流道左端为入口, 入口流量 $Q=2.52\times 10^{-15}\ \text{m}^3$. 右端为出口, 压力为0. 考虑壁面润湿性, 润湿相与壁面接触角 θ 为 60° . 水的黏度 $\mu_s=1\ \text{mPa}\cdot\text{s}$, 聚合物黏度 $\mu_p=32\ \text{mPa}\cdot\text{s}$, 取 $Re=1\times 10^{-3}$, $We=0.3$, 分别模拟在水、与黏弹性流体黏度相同的牛顿流体、黏弹性流体驱替下油膜的运动与变形. 图3也是油膜的初始模拟状态.

考虑壁面水湿, 对比在3种流体驱替下, 不同时刻液滴的运动与变形, 如图4所示.

由图4可知, 相同注入流量下, 水驱时, 油膜基本不动; 高黏度牛顿流体驱替 $0.002\ \text{s}$, 油膜移动 $1.3\ \mu\text{m}$, 平均移动速度为 $650\ \mu\text{m/s}$; 黏弹性流体驱替 $0.002\ \text{s}$, 油膜移动 $6.3\ \mu\text{m}$, 平均移动速度约为 $3150\ \mu\text{m/s}$.

考虑壁面油湿, 对比在3种流体驱替下, 不同时刻液滴的运动与变形, 如图5所示.

由图5可知, 相同注入流量下, 水驱时, 油膜基本不动; 高黏度牛顿流体驱替 $0.002\ \text{s}$, 油膜移动约 1

μm , 平均移动速度为 $500\ \mu\text{m/s}$; 黏弹性流体驱替 $0.002\ \text{s}$, 油膜移动 $4.6\ \mu\text{m}$, 平均移动速度约为 $2300\ \mu\text{m/s}$. 壁面油湿时, 油膜的移动速度明显低于水湿.

由图4和5可知, 与低黏度的水相比, 高黏度的牛顿流体可以驱动壁面油膜, 但驱动效果不明显, 效率较低. 黏弹性流体可以有效地驱动壁面油膜, 同时油膜发生较大程度的变形, 提高驱油效率. 与油湿壁面相比, 注入流量相同时, 水湿壁面油膜更易驱动, 变形程度更大. 对比3种流体驱替效果可知, 黏弹性流体驱动油膜, 不仅仅依靠其高黏度, 同时也依靠其“弹性”驱动壁面油膜. 为进一步探究黏弹性流体驱动油膜运动与变形的内在机理, 分析油膜在驱动过程中的微观受力状况, 如图6所示.

图6(a)是不同流体驱替时, 作用于油膜同一水平高度上的两点的水平应力差. 黏弹性驱替时, 作用于油膜上每一点的水平应力差均远大于水驱. 由式(13)分别计算不同流体对油膜的水平拖拽力, 可知黏弹

图4 (网络版彩色)不同流体驱替下油膜的运动与变形(水湿). (a) 水驱; (b) 高黏牛顿流体驱替; (c) 黏弹性流体驱替

Figure 4 (Color online) The movement and deformation of oil film with respect to the displacement of different fluids (water-wet). (a) Water flooding; (b) Newtonian fluid flooding; (c) viscoelastic flooding

图5 (网络版彩色)不同流体驱替下油膜的运动与变形(油湿). (a) 水驱; (b) 高黏牛顿流体驱替; (c) 黏弹性流体驱替

Figure 5 (Color online) The movement and deformation of oil film with respect to the displacement of different fluids (oil-wet). (a) Water flooding; (b) Newtonian fluid flooding; (c) viscoelastic flooding

图6 (网络版彩色)油膜受力状况. (a) 油膜表面水平应力差; (b) 油膜表面的法向应力

Figure 6 (Color online) The stresses acting on the oil film. (a) The horizontal stress difference on the oil film; (b) the normal stress on the oil film

性流体对油膜的水平拖拽力是水的32.24倍, 水平应力差先增大后减小. 图6(b)是黏弹性流体作用于油膜表面的法向应力, 可知液滴前半部分所受法向应力较大, 后半部分所受应力较小, 不对称的应力分布导致油膜产生相应的变形. 水湿壁面, 油膜形变更大.

2.3 盲端残余油

盲端残余油物理模型如图7所示, 流道直径 $D=4\ \mu\text{m}$, 长 $L=16\ \mu\text{m}$, 盲端距入口距离为 $d=6\ \mu\text{m}$, 盲端近似边长为 $2\ \mu\text{m}$ 的正方形, 盲端内为残余油. 流道左端为入口, 入口流量 $Q=5.04\times 10^{-15}\ \text{m}^3$. 右端为出口, 压力为0. 考虑壁面润湿性, 润湿相与壁面接触角 θ 为 60° . 取 $Re=2\times 10^{-3}$, $We=0.3$, 研究黏弹性流体的驱替效果. 图7也是盲端残余油的初始模拟状态.

考虑壁面不同润湿状况, 比较在水和黏弹性流体驱替下, 盲端的残余油变化, 如图8所示.

由图8可知, 水驱时, 水湿油藏的驱替效率更高. 与水驱相比, 黏弹性流体可以驱替出更多的盲端残余油. 如图9所示, 驱替0.02 s, 壁面水湿, 水驱采收程度约为15.8%, 采用黏弹性流体驱替, 采收程度约为27.9%, 采收程度提高12.1%; 壁面油湿, 水驱采收程度约为2.8%, 黏弹性流体驱替采收程度约为8.3%, 采收程度提高5.5%. 因此在特高含水开发后期, 注入黏弹性流体驱替可以提高驱油效率, 水湿油藏采用黏弹性流体驱替, 开发效果更好.

为进一步探究黏弹性流体驱替盲端残余油的机

图7 (网络版彩色)盲端残余油物理模型

Figure 7 (Color online) The schematic of residual in the dead end

图8 (网络版彩色)驱替后盲端残余油。(a) 水驱(水湿); (b) 黏弹性流体驱替(水湿); (c) 水驱(油湿); (d) 黏弹性流体驱替(油湿)

Figure 8 (Color online) The residual oil in the dead end after flooding. (a) Water flooding (water-wet); (b) viscoelastic flooding (water-wet) (c) water flooding (oil-wet); (d) viscoelastic flooding (oil-wet)

图9 (网络版彩色)不同流体驱替后盲端残余油量

Figure 9 (Color online) The residual oil in the dead end after water and viscoelastic fluid flooding

理, 定义无量纲速度^[5] $V_D = u/U_{in}$. $V_D = 0.05$, 即 $u = 2 \times 10^{-4}$ m/s, 设为流体在盲端的波及边界. 如图10所示, 蓝白交界处为驱替流体在盲端内的波及边界(白色区

图10 (网络版彩色)盲端内流体波及边界

Figure 10 (Color online) The sweep boundary of fluid in the dead end

域速度均大于 u). 对比水驱与黏弹性流体驱替的波及边界可知, 流体的黏弹性有利于引发盲端流体的运动, 减少孔隙盲端的滞留区.

3 结论

本文基于N-S方程建立黏弹性流体微观流动数学模型. 采用Oldroyd-B本构方程描述流体的黏弹性,

运用相场方法实时追踪驱替过程中两相界面。分别研究壁面油膜在黏弹性流体驱替下的运动和变形,黏弹性流体对盲端残余油的驱替效果,并分析残余油微观受力状况。主要得到以下结论:

(1) 黏弹性流体可以有效驱动壁面油膜运动,相同注入流量下,黏弹性流体作用于壁面油膜上的拖

拽力远大于水;

(2) 作用于油膜上的法向应力分布不均匀导致油膜发生较大变形。

(3) 黏弹性流体在盲端内的波及边界更深,有利于引发盲端残余油的运动,提高残余油采收率。黏弹性流体驱替对水湿油藏开发增产效果更明显。

参考文献

- 1 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]
- 2 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]
- 3 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. In: Proceedings of SPE Asia Pacific Improved Oil Recovery Conference 2011. Kuala Lumpur: SPE, 2011. 72123
- 4 Liu G, Hou J R, Li Q Y, et al. Chemicals loss and effective distance of ASP flooding in second-class oil layers (in Chinese). J China Univ Petrol, 2015, 39: 171–177 [刘刚, 侯吉瑞, 李秋言, 等. 二类油层中三元复合驱体系的损耗及有效作用距离. 中国石油大学学报, 2015, 39: 171–177]
- 5 Song K P, He J G, Yang J. Influence of base asp flooding on the reservoir pore structure (in Chinese). J China Univ Petrol, 2015, 39: 164–172 [宋考平, 何金钢, 杨晶. 强碱三元复合驱对储层孔隙结构影响研究. 中国石油大学学报, 2015, 39: 164–172]
- 6 Wang D M, Chen J C, Yang Q Y, et al. Viscoelastic polymer can increase microp-scale displacement efficiency in cores (in Chinese). Acta Petrol Sin, 2000, 21: 45–51 [王德民, 程杰成, 杨清彦. 黏弹性聚合物溶液能够提高岩心的微观驱油效率. 石油学报, 2000, 21: 45–51]
- 7 Wang D M, Chen J C, Xia H F, et al. Improvement of displacement efficiency of cores by driving forces parallel to the oil-water interface of viscoelastic fluid (in Chinese). Acta Petrol Sin, 2002, 23: 48–52 [王德民, 程杰成, 夏惠芬, 等. 黏弹性流体平行于界面的力可以提高驱油效率. 石油学报, 2002, 23: 48–52]
- 8 Zhang L J, Yue X A, Liu Z C, et al. Flow field of viscoelastic fluid in pores with dead ends (in Chinese). J Hydrodyn (Ser A), 2002, 17: 748–755 [张立娟, 岳湘安, 刘中春, 等. 黏弹性流体在盲端孔隙中的流场. 水动力学研究与进展(A 辑), 2002, 17: 748–755]
- 9 Wang C S, Yang S R, Liu L L, et al. Micro-force calculation in residual oil displacement by viscoelastic fluid (in Chinese). J Southwest Petrol Univ, 2011, 22: 135–138 [王春生, 杨树人, 刘丽丽. 黏弹性流体驱替残余油微观力计算. 西南石油大学学报, 2011, 33: 135–138]
- 10 Yang S R, Wang D M, Xia H F, et al. Hydrodynamics mechanism of viscoelastic fluids displacing residual oil droplets in micro pores (in Chinese). J China Univ Petrol, 2011, 35: 139–142 [杨树人, 王德民, 夏惠芬, 等. 黏弹性流体驱替微孔道中残余油滴的水动力学机制. 中国石油大学学报, 2011, 35: 139–142]
- 11 Liu Y, Liu C Z. Mechanism of enhancing oil displacement efficiency by viscoelastic polymer solution (in Chinese). J China Univ Petrol, 2007, 31: 91–94 [刘洋, 刘春泽. 黏弹性聚合物溶液提高驱油效率机理研究. 中国石油大学学报, 2007, 31: 91–94]
- 12 Alves M, Pinho F, Oliveira P. The Flow of viscoelastic fluids past a cylinder: Finite-volume high-resolution methods. J Non-Newtonian Fluid Mech, 2001, 97: 207–232
- 13 Kim J M, Kim C, Kim J H, et al. High-resolution finite element simulation of 4: 1 Planar contraction flow of viscoelastic fluid. J Non-Newtonian Fluid Mech, 2005, 129: 23–37
- 14 Oliveira M S, Oliveira P J, Pinho F T, et al. Effect of contraction ratio upon viscoelastic flow in contractions: The axisymmetric case. J Non-Newtonian Fluid Mech, 2007, 147: 92–108
- 15 Harvie D, Cooper-White J, Davidson M. Deformation of a viscoelastic droplet passing through a microfluidic contraction. J Non-Newtonian Fluid Mech, 2008, 155: 67–79
- 16 Molins S, Trebotich D, Ligocki T J, et al. A highly resolved direct numerical simulation model of reactive transport at the pore scale. AGU Fall Meet Abstracts, 2014, 1: 0836
- 17 Peszynska M, Trykozko A. Pore-to-core simulations of flow with large velocities using continuum models and imaging data. Comput Geosci, 2013, 17: 623–645

- 18 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 Resources*, 2014, 74: 116–126
- 19 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
- 20 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
- 21 Zhao X, Blunt M J, Yao J. Pore-scale modeling: Effects of wettability on waterflood oil recovery. *J Petrol Sci Eng*, 2010, 71: 169–178
- 22 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, 59: 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, 59: 3197–3203]
- 23 Yao J, Sun H, Fan D Y, et al. Numerical simulation of gas transport mechanisms in tight shale gas reservoirs. *Petrol Sci*, 2013, 10: 528–537
- 24 Chen L, Luan H B, He Y L, et al. Pore-scale flow and mass transport in gas diffusion layer of proton exchange membrane fuel cell with interdigitated flow fields. *Int J Therm Sci*, 2012, 51: 132–144
- 25 Chen L, Kang Q, Mu Y, et al. A critical review of the pseudopotential multiphase lattice boltzmann model: Methods and applications. *Int J Heat Mass Transfer*, 2014, 76: 210–236
- 26 Zhu B, Cheng H, Qiao Y, et al. Porosity and permeability evolution and evaluation in anisotropic porosity multiscale-multiphase-multi-component structure. *Chin Sci Bull*, 2012, 57: 320–327
- 27 Sun J, Smith M, Armstrong R, et al. Finite element method for viscoelastic flows based on the discrete adaptive viscoelastic stress splitting and the discontinuous galerkin method: Davss-G/Dg. *J Non-Newtonian Fluid Mech*, 1999, 86: 281–307
- 28 Jacqmin D. Calculation of two-phase navier-stokes flows using phase-field modeling. *J Comput Phys*, 1999, 155: 96–127
- 29 Cui H H, Feng H C, Xu L, et al. Numerical simulation about the movement of W/O droplet flowing over micropillar barrier (in Chinese). *Chin J Appl Mech*, 2015, 32: 76–82, 173–174 [崔海航, 冯换春, 许琳, 等. W/O 液滴绕流微柱阵列的数值模拟研究. *应用力学学报*, 2015, 32: 76–82, 173–174]
- 30 Yao J, Sun H, Huang Z Q, et al. Key mechanical problems in the development of shale gas reservoirs (in Chinese). *Sci Sin-Phys Mech Astron*, 2013, 43: 1527–1547 [姚军, 孙海, 黄朝琴, 等. 页岩气藏开发中的关键力学问题. *中国科学: 物理学 力学 天文学*, 2013, 43: 1527–1547]
- 31 Craven T J, Rees J M, Zimmerman W B. Stabilised finite element modelling of oldroyd-B Viscoelastic flows. In: *Proceedings of COMSOL users Conference 2006*. Birmingham: COMSOL Inc, 2006
- 32 Boyer F, Lapuerta C, Minjeaud S, et al. Cahn-Hilliard/Navier-Stokes model for the simulation of three-phase flows. *Transport Porous Media*, 2010, 82: 463–483
- 33 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
- 34 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: 47–67
- 35 Zhu G, 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
- 36 Liu A W, Bornside D E, Armstrong R C, et al. Viscoelastic flow of polymer solutions around a periodic, linear array of cylinders: Comparisons of predictions for microstructure and flow fields. *J Non-Newtonian Fluid Mech*, 1998, 77: 153–190

Microscopic flow simulation of viscoelastic fluid based on interface tracking method

ZHU GuangPu, YAO Jun, SUN Hai, ZHANG Lei & LI AiFen

School of Petroleum Engineering, China University of Petroleum (East China), Qingdao 266580, China

Microscopic residual oil in reservoirs after water flooding can be classified into four types: oil films, oil in the dead end, oil in pores throat, and oil clusters. The oil is trapped in pores throat when the viscous force is not sufficiently large to overcome the capillary forces with water flooding. The oil in the dead end is constrained by the rock configuration. The oil clusters mainly exist in the lower permeability portion of the porous media, which is constrained by the capillary force and rock configuration. In particular, the efficiency of water flooding is extremely low at the high water cut period. Recently, viscoelastic fluid flooding (polymer flooding) was widely applied to improve the recovery after water flooding in the petroleum industry, and the displacement efficiency was greatly improved. However, the poor understanding of viscoelastic fluid flooding restricts its further progress. The investigation of how the viscoelastic fluid mobilizes the residual oil is warranted. In this study, a direct numerical simulation method is employed to simulate immiscible two-phase flows in a micro channel. Viscoelastic effects are simulated using the Oldroyd-B rheological model. The position of the interface between two immiscible fluids is determined by using the phase field method. The model incorporates the wetting condition of the porous media. The dynamics of oil film and residual oil in the dead end are explored under the displacement of water and viscoelastic fluid. The forces exerting on the oil film in the micro channel are analyzed, which contribute to the difference of oil film movement and deformation between the water flooding process and viscoelastic fluid process. Moreover, the sweep efficiencies of water and viscoelastic fluid in the dead end are observed and compared. The concept of dimensionless velocity is introduced as the sweep boundary in the dead end to explain the discrepancy of recovery between water and viscoelastic fluid. The numerical solution used for the simulation is performed using a finite element method. Additionally, a benchmark of the flow of Oldroyd-B fluid past a cylinder between two parallel plates is given to validate the correction of the model and solution. Compared with water, viscoelastic fluid can more easily mobilize the residual oil which can greatly improve the displacement efficiency. The viscosity is not the only one mechanism of the viscoelastic fluid's mobilization of the oil film; 'elasticity' of the fluid is another key driving mechanism which is reflected by the Weissenberg number. The horizontal stress difference of viscoelastic fluid acting on the residual oil film is considerably larger than that of water. The uneven distribution of normal stress caused by the viscoelastic fluid leads the residual oil film to deform significantly. Viscoelastic fluid can greatly improve the sweep efficiency in the dead end and this phenomenon is more obvious in the water-wet reservoir. The sweep boundary of viscoelastic fluid in the dead end is deeper than that of water which explain the reason why less residual oil trapped in the dead end with viscoelastic fluid flooding. The study provides effective guidance for tertiary oil recovery.

viscoelastic fluid, N-S equation, Oldroyd-B, phase field method, residual oil

doi: 10.1360/N972016-00050