

文章编号:1009-9603(2023)03-0152-07

DOI:10.13673/j.pgrec.202208019

普通稠油原位乳化降黏驱微观渗流特征可视化研究

张 民,孙志刚,于春磊,吴光焕,孙宝泉,吴秀英
(中国石化胜利油田分公司 勘探开发研究院,山东 东营 257015)

摘要:普通稠油乳化降黏驱是表面活性剂驱和乳状液驱的综合过程,既包含表面活性剂的降低界面张力作用,又包含乳状液的调驱作用。为此,采用微观物理模拟可视化研究多孔介质中乳状液的形成机制和运移特征,利用天然露头长岩心并联驱替实验分别进行水驱+乳化降黏驱和直接乳化降黏驱实验,进一步验证乳化降黏驱渗流特征,对比分析乳化降黏驱的驱油效果。实验结果表明,乳化降黏驱在剪切和降低界面张力作用下原位形成乳状液,形成的乳状液通过卡封、架桥和吸附滞留3种封堵模式导致驱替介质的频繁绕流改道,起到扩大波及范围及提高驱油效率的作用。乳状液运移过程中与多孔介质相互作用,呈三快三慢的渗流特征。由此导致的渗滤作用,使乳状液分布沿着渗流路径和驱替倍数增加呈规律性变化。对比不同注入方式的岩心并联驱替实验结果,发现直接乳化降黏驱比水驱的启动压力低(分别为0.57和1.52 MPa),水驱后进行乳化降黏驱的注入压力由0.37 MPa升至1.17 MPa。随着乳化降黏剂溶液的注入,驱替压力波动式上升直至平衡。相同注入量下,直接乳化降黏驱比水驱+乳化降黏的驱油效率增加了16.69%,进一步证实乳化降黏驱扩大波及范围和提高驱油效率的有效性。

关键词:普通稠油;原位乳化;降黏;微观物理模拟;渗流特征

中图分类号:TE32

文献标识码:A

Visualization of microscopic flow characteristics for in-situ emulsification and viscosity reduction development in common heavy oil reservoirs

ZHANG Min, SUN Zhigang, YU Chunlei, WU Guanghuan, SUN Baoquan, WU Xiuying

(Exploration and Development Research Institute, Shengli Oilfield Company, SINOPEC,
Dongying City, Shandong Province, 257015, China)

Abstract: Emulsification viscosity reduction flooding in common heavy oil reservoirs is a comprehensive process of surfactant flooding and emulsion flooding, which includes both the interfacial tension reduction effect of surfactants and the control and flooding effect of emulsions. Therefore, the formation mechanism and migration characteristics of emulsions in porous media were first visualized by microphysical simulation. Then, the parallel experiments of natural outcrop long cores were used to conduct water flooding + emulsification viscosity reduction flooding and direct emulsification viscosity reduction flooding experiments. The effort was to further verify the flow characteristics of emulsification viscosity reduction flooding and comparatively analyze the oil displacement effects of emulsified viscosity reducer flooding. The experimental results show that emulsions are formed in situ under the action of shearing and interfacial tension reduction. These emulsions lead to frequent detour flow diversion of displacement media through clamping, bridging, and adsorption, which play the role of expanding swept volume and enhancing oil displacement. In the migration process, the emulsions interact with the porous media to demonstrate the flow characteristics of "slow and fast in respective three aspects." The resulting percolation causes the distribution of emulsions to change regularly along the flow path and with the increase in the displacement ratio. The results of parallel core displacement experiments under different injection modes were compared. The result indicates that the starting pressure of direct emulsification viscosity reduction

收稿日期:2022-08-12。

作者简介:张民(1983—),男,山东烟台人,高级工程师,博士,从事油气开发渗流机理研究。E-mail:zhangminupc@126.com。

基金项目:国家自然科学基金创业创新发展联合基金“难采稠油多元热复合高效开发机理与关键技术基础研究”(U20B6003),中国石化股份公司课题“浅薄层超稠油多元热复合开发关键技术研究与应用”(P21037-4)。

flooding (0.57 MPa) is lower than that of water flooding (1.52 MPa), and the injection pressure of emulsification viscosity reduction flooding after water flooding increases from 0.37 MPa to 1.17 MPa. The displacement pressure rises to an equilibrium in a fluctuating manner during the injection of the emulsified viscosity reducer solution. At the same injection ratio, the displacement efficiency of direct emulsification viscosity reduction flooding is increased by 16.69% than that of water flooding + emulsification viscosity reduction flooding. This further verifies that emulsification viscosity reduction flooding can effectively expand the swept volume and raise oil displacement efficiency.

Key words: common heavy oil reservoir; in-situ emulsification; viscosity reduction; microphysical simulation; flow characteristics

一直以来,稠油热采是稠油油藏开发的主导技术,例如蒸汽吞吐和蒸汽驱,在矿场也取得了较好的开发效果^[1-3]。但是,在稠油热采过程中存在蒸汽超覆和窜流问题,加之地层的非均质性强,导致采收率不高^[4-6]。另外,许多稠油油藏类型不适用于采用热采开发^[7-12],对于这些稠油油藏,特别是黏度低于2 000 mPa·s的普通稠油,通常采用水驱进行开发^[13-16]。然而,由于油藏的渗透率、稠油黏度和含水饱和度均普遍存在非均质性导致水驱采收率也不高。为此,越来越多的学者采用直接注乳状液或者表面活性剂进行原位乳化的方法抑制油藏非均质性,提高水驱普通稠油油藏的采收率^[17-23]。对于普通稠油油藏乳化降黏开采的机理,中外学者已进行大量物理模拟实验^[24-31],提出许多乳状液在多孔介质中渗流的数学模型^[32-36],充分显示了普通稠油原位乳化降黏开采在提高采收率方面的潜力。目前针对稠油乳化降黏驱过程中剂、油、多孔介质间相互作用导致的原位乳状液的形成机制、渗流特征仍缺乏系统深入研究。尤其是乳状液在多孔介质中的渗流特征是建立渗流数学模型须考虑的重点问题,其决定模型的适用性。

为此,借助于微观模型驱替实验在可视化研究方面无可比拟的优势,研究稠油与乳化降黏剂相互作用原位形成乳状液的机制,乳状液与多孔介质相互作用产生的堵调模式,以及多孔介质对乳状液运移的渗流作用导致乳状液分布的时空变化特征。最终,借助于长岩心并联驱替实验研究水驱+乳化降黏

驱和乳化降黏驱的驱替特征,并分析驱油效果,进一步验证乳状液在多孔介质中的渗流特征。将微观与宏观物理模拟实验相结合,分析由微观渗流特征导致的宏观驱替效果,研究成果为普通稠油乳化降黏开发技术的应用提供了室内实验依据。

1 实验器材与步骤

1.1 实验器材

实验用仪器为微观物理模拟驱替实验装置和长岩心并联驱替实验装置。微观物理模拟驱替实验装置主要由高精度泵、恒温箱、高温高压可视釜等组成(图1),长岩心并联驱替实验装置由驱替泵、围压泵、长岩心夹持器、压力采集系统和压力数据处理系统等组成(图2)。

实验用乳化型降黏剂为胜利某化工厂的烷基苯磺酸盐。地层温度为42℃,质量分数为0.3%的降黏剂溶液与稠油间界面张力为 1.68×10^{-3} mN/m。

实验用水为胜利油田金8区块模拟地层水,矿化度为3 070 mg/L。

实验用油为金8区块脱水原油,42℃时脱水原油黏度为900 mPa·s。

实验用微观模型呈条带状,尺寸为2.5 cm×7.5 cm,渗透率为468.5 mD,面孔率为34.7%。水驱+乳化降黏驱及乳化降黏驱所用并联岩心的物性参数见表1。

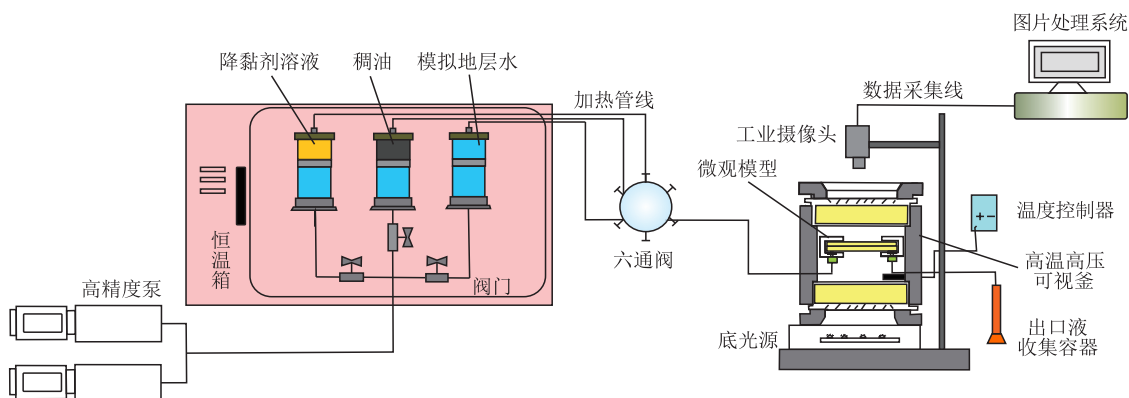


图1 微观物理模拟驱替实验装置

Fig.1 Experimental devices for microphysical simulation of displacement

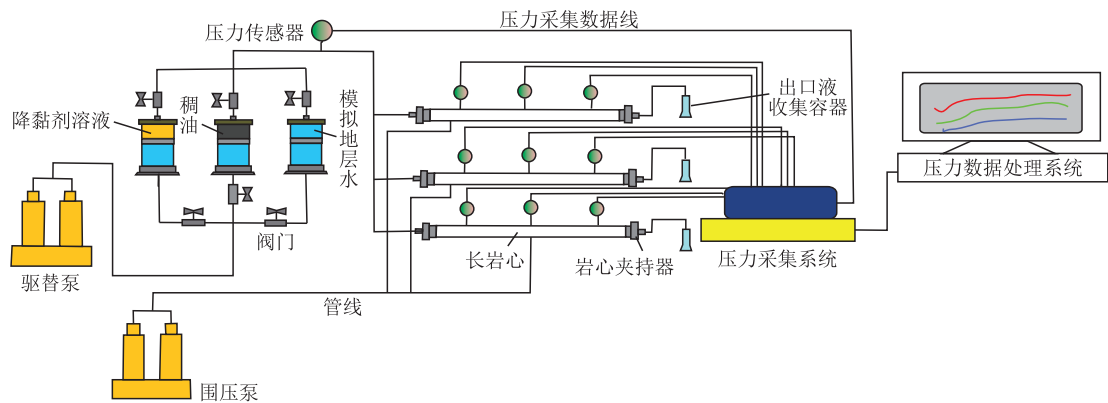


图2 长岩心并联驱替实验装置

Fig.2 Experimental devices for parallel long core displacement

1.2 实验步骤

1.2.1 微观物理模拟驱替实验

实验步骤主要包括:①微观模型抽真空饱和模拟地层水。②饱和油。③乳化降黏剂溶液驱油至模型不出油为止。实验温度为42℃,驱替速度为0.003 mL/min,实验过程中进行模型整体和局部的图像及视频采集。

1.2.2 长岩心并联驱替实验

水驱+乳化降黏驱实验步骤主要包括:①取3根岩心分别采用驱替法饱和和模拟地层水。②每根岩心分别采用驱替法饱和油。③并联岩心夹持器,进行乳化降黏驱油至含水率为98%。实验过程中,驱替速度为0.5 mL/min,实验温度恒定为42℃。

乳化降黏驱实验步骤主要包括:①—②步骤同上。③并联岩心夹持器,进行水驱油至含水率为98%。④进行水驱后乳化降黏驱至含水率为98%。实验条件同上。

2 实验结果与分析

2.1 普通稠油乳化降黏驱微观渗流特征可视化分析

2.1.1 稠油原位乳化形成乳状液的机制

稠油与乳化降黏剂溶液接触后,在流动溶液的切削作用下不断拉伸变形,当拉伸至一定程度后从稠油某处断裂,形成水包油乳状液。从乳化过程可

见,乳化降黏剂降低界面张力作用使稠油更易被拉伸、变形,在驱替液的剪切作用下稠油从本体剥离进入孔喉与驱替溶液充分接触并继续被剪切,当剪切力大于界面张力时,原油进一步被扯断,形成乳状液。实验过程中也存在稠油从本体剥离后直接形成乳状液的现象。稠油被乳化为水包油乳状液至形成乳状液的过程见图3。

2.1.2 多孔介质中乳状液的封堵模式

随着乳化降黏剂的注入,乳化程度增加,乳化降黏驱由表面活性剂驱变为表面活性剂驱+乳状液驱。由于乳状液与多孔介质的相互作用,使大小不同的乳状液滴在孔喉不同位置产生了类似于弱凝胶颗粒的封堵作用,变为卡封、架桥、吸附滞留3种不同的封堵模式(图4)。

卡封模式是由于单个乳状液颗粒大于喉道,乳状液卡在喉道处,产生贾敏效应;架桥模式是由于小于孔喉的乳状液颗粒,无序拥挤在喉道处,形成了拥堵;吸附滞留模式则是由于乳状液在孔喉壁产生二次吸附,或者运移速度减慢后滞留在孔壁的边缘,使渗流通道变窄。不同的封堵模式均可降低乳化降黏剂的局部渗透率,导致乳化降黏剂溶液在多孔介质内频繁发生绕流改道,扩大孔隙体积的波及,起到边调边驱的效果,从而提高微观驱油效率。

2.1.3 乳状液在多孔介质中的渗流特征

多孔介质中稠油以油包水乳状液的形式被携带

表1 岩心物性参数

Table1 Physical property parameters of cores

实验类型	样品编号	长度/cm	直径/cm	孔隙度/%	渗透率/mD
水驱+乳化降黏驱	1	30.0	2.46	17.5	174.56
	2	30.0	2.50	18.9	327.79
	3	30.2	2.52	18.7	589.40
	4	29.9	2.50	17.6	149.95
乳化降黏驱	5	30.0	2.50	17.9	378.98
	6	30.0	2.50	19.4	529.98



图3 多孔介质中稠油的原位乳化

Fig.3 In-situ emulsification of heavy oil in porous media

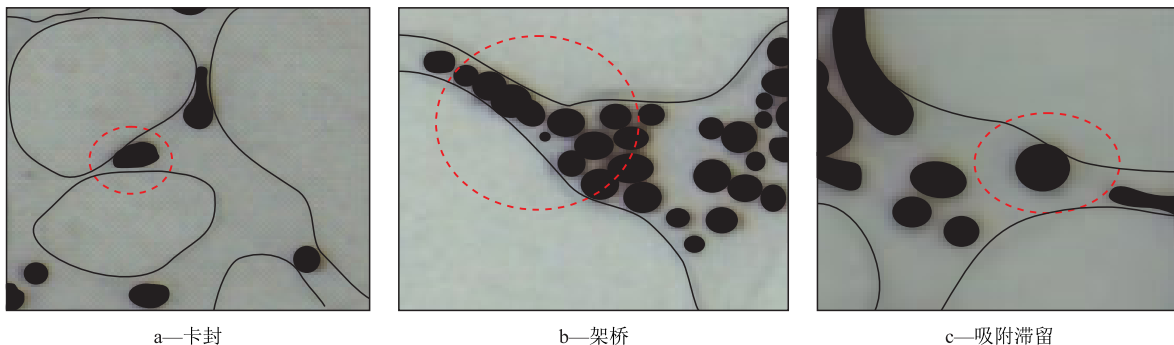


图4 多孔介质中乳状液的封堵模式

Fig.4 Plugging mode of emulsions in porous media

运移,为进一步研究多孔介质中乳状液的渗流特征,对渗流过程进行视频采集,发现渗流状态下不同大小的乳状液颗粒在多孔介质不同部位的运移呈三快三慢的渗流特征,多孔介质对乳状液具有渗滤作用,视频截图如图5所示。

渗流过程中,多孔介质对乳状液的渗滤作用具体表现为:乳状液运移至孔隙中,会产生滞留聚集效应,喉道中乳状液较少(图5a),再次启动孔隙中乳状液需增加驱替压力。小液滴质量小、颗粒小、运移快,导致驱替前缘小液滴占优势,由于颗粒小,乳化捕集作用弱;大液滴质量大、颗粒大,运移相对慢,甚至在某些孔喉处产生封堵不运移(图5b)。孔喉中心驱替流速快,相同大小颗粒的乳状液,位于中心的先运移,甚至会出现小液滴由于偏离孔喉中心,比大

液滴运移慢的现象,如果改变驱替动力或方向,滞留液滴仍可有效启动。

2.1.4 乳状液在多孔介质中的时空分布规律

由于多孔介质对乳状液的渗滤作用,导致乳状液的颗粒大小及数量在多孔介质中的分布呈一定的规律性(图6)。在驱替初始阶段、驱油过程及驱油平衡阶段选取不同驱替时刻相同驱替部位(标记为1-1,2-1和3-1)进行乳状液时间分布规律分析,在驱油过程沿着驱替方向选取不同部位(标记为2-1,2-2和2-3)进行乳状液空间分布规律分析。

随着乳化降黏驱油过程的进行,相同部位乳状液的颗粒数量越来越少(图7a),这是由于随着驱替过程的进行,相同部位乳化降黏剂的驱替倍数增加,该部位稠油不断被乳化携带驱出模型;相同驱替时

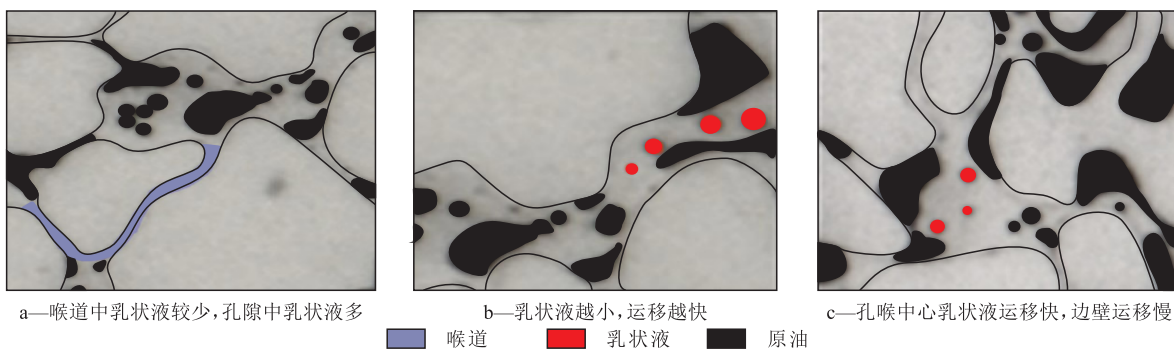


图5 多孔介质对乳状液的渗滤作用

Fig.5 Percolation effect on emulsions exerted by porous media

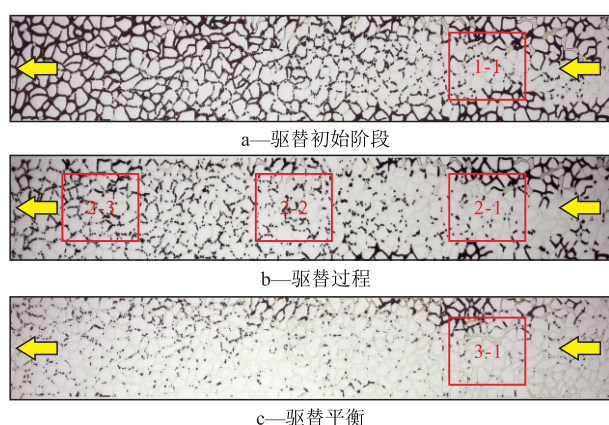


图6 不同驱替阶段乳状液在多孔介质中的分布

Fig.6 Distribution of emulsions in porous media at different displacement stages

刻,沿着乳状液的运移路径,乳状液的颗粒数量越来越多,液滴越来越小(图7b),这是由于随着乳状液在多孔介质中运移,与孔喉相互作用被分裂成小乳状液滴,小乳状液滴运移快,沿着驱替方向聚集,在驱替前缘聚集密度最大。

2.2 长岩心并联驱替结果

在乳化降黏驱渗流特征可视化研究的基础上,分别采用不同渗透率长岩心进行水驱+乳化降黏驱和乳化降黏驱油实验,通过注入压力和驱油效率分析,进一步验证普通稠油原位乳化降黏驱渗流特征和驱油效果。

2.2.1 不同驱替方式注入压力对比

在不同渗透率的长岩心并联进行水驱+乳化降

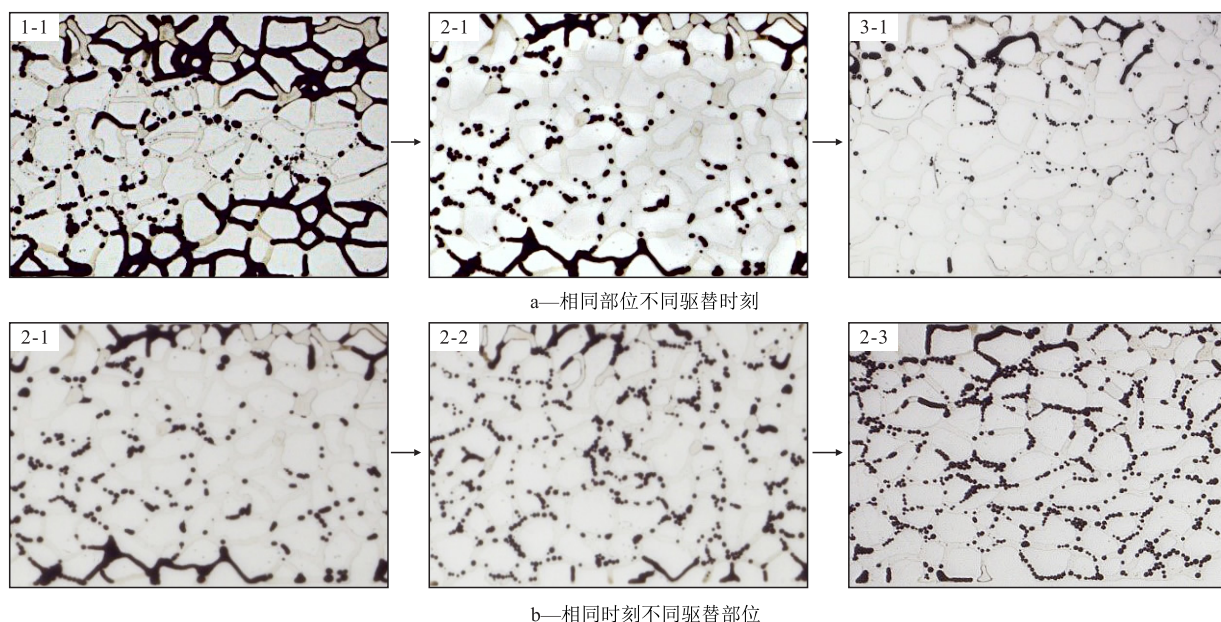


图7 乳状液在多孔介质中的时空分布规律

Fig.7 Temporal and spatial distribution laws of emulsions in porous media

黏驱和乳化降黏驱过程中,分析其注入端的压力变化情况(图8)。2种驱替方式的初始注入阶段注入压力均呈快速上升然后下降的规律,这是稠油被启动的过程;且直接乳化降黏驱比水驱的启动压力低(分别为0.57和1.52 MPa),说明驱替初始时刻乳化降黏驱由于降低界面张力和乳化作用,使稠油易于变形启动并运移。驱油过程中,随着乳化降黏剂溶液的注入与稠油广泛接触,乳化程度增加,注入压力快速升高,乳化降黏驱产生了乳状液驱油的双重驱替现象。特别值得注意的是,水驱平衡后,注入乳化降黏剂溶液,注入压力由水驱平衡时的0.37 MPa升至1.17 MPa,增加2.16倍,说明乳状液起到封堵作用,有效降低渗透率。随着注入倍数的增加,由于乳状液的调驱作用,注入压力呈波动式上升直至平衡。

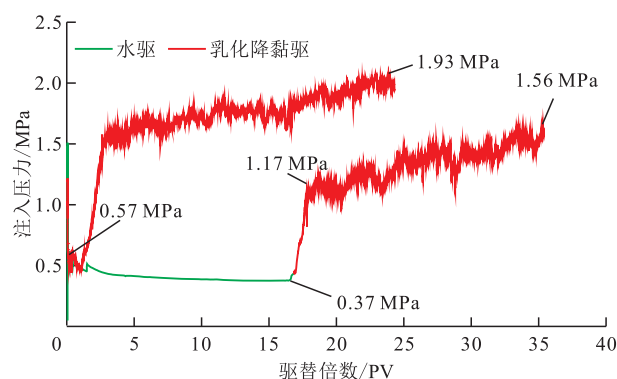


图8 不同驱替方式下注入压力的变化

Fig.8 Variations of injection pressures under different displacement modes

直接进行乳化降黏驱时,平衡注入压力(1.93 MPa)高于水驱后乳化降黏驱的平衡注入压力(1.56

MPa),说明直接乳化降黏驱的乳化程度更高,降低渗透率能力更强。

2.2.2 不同驱替方式驱油效率对比

水驱+乳化降黏驱和直接乳化降黏驱驱油效率如图9所示。水驱16.8 PV、综合含水率为98%时驱油效率为42.92%,后进行18.4 PV乳化降黏驱至综合含水率为98%时,驱油效率增至59.61%,增加了16.69%。直接进行25.2 PV乳化降黏驱驱油效率为77.85%,比水驱+乳化降黏驱提高18.24%。由图9可以看出,乳化降黏驱可快速提高驱油效率,对比25.2 PV的乳化降黏驱与水驱后18.4 PV乳化降黏驱的驱油效率提高幅度发现,直接进行乳化降黏驱能够更高效地提高驱油效率。

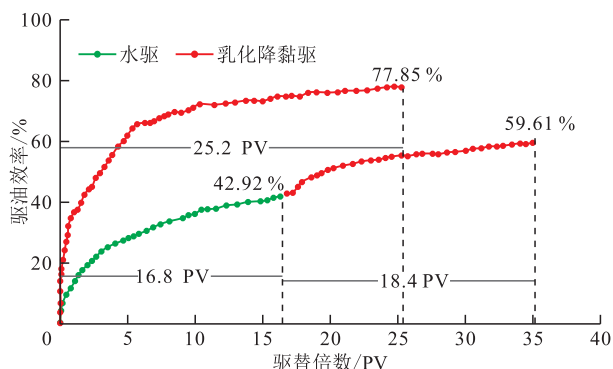


图9 不同驱替方式驱油效率变化

Fig.9 Displacement efficiency variations under different displacement modes

3 结论

普通稠油乳化降黏驱时,界面张力和剪切力共同作用下,使稠油原位乳化成水包油乳状液,乳化降黏驱是表面活性剂驱与乳状液驱的综合过程。普通稠油原位乳化形成的水包油乳状液在多孔介质中的捕集作用有卡封、架桥和吸附滞留3种封堵模式,造成局部流体频繁改道绕流,起到边调边驱的作用,扩大微观波及范围,提高驱油效率。多孔介质对乳状液的运移存在渗滤作用,不同大小的乳状液颗粒在不同孔喉位置的运移速度呈三快三慢的渗流特征,导致随着驱油过程的进行,乳状液在多孔介质中的时空分布具有规律性。不同驱替方式下,长岩心并联驱油实验对比分析表明,乳化降黏驱可以降低稠油启动压力,水驱后乳化降黏驱的驱油效率仍可提高16.69%,与直接乳化降黏驱的驱油效率(77.85%)相比,直接进行乳化降黏驱提高驱油效率更显著。

参考文献

[1] 盖平原,赵延茹,沈静,等.胜利油田稠油热采工艺现状及发展

方向[J].石油地质与工程,2008,22(6):49-51,10.

GAI Pingyuan, ZHAO Yanru, SHEN Jing, et al. Status quo and prospect of thermal recovery of dense oil in Shengli Oil Field [J]. Petroleum Geology and Engineering, 2008, 22(6): 49-51, 10.

[2] 杨勇.胜利油田稠油开发技术新进展及发展方向[J].油气地质与采收率,2021,28(6):1-11.

YANG Yong. New progress and next development directions of heavy oil development technologies in Shengli Oilfield [J]. Petroleum Geology and Recovery Efficiency, 2021, 28(6): 1-11.

[3] 赵琳,王增林,张星,等.稠油油藏自扩散降黏体系作用机理[J].大庆石油地质与开发,2021,40(1):110-116.

ZHAO Lin, WANG Zenglin, ZHANG Xing, et al. Mechanism of the self-diffusion viscosity reducing system in heavy oil reservoir [J]. Petroleum Geology & Oilfield Development in Daqing, 2021, 40(1): 110-116.

[4] 吴春洲,张伟,孙永涛,等.耐温防乳驱油体系辅助稠油热采研究与应用[J].断块油气田,2020,27(3):365-369.

WU Chunzhou, ZHANG Wei, SUN Yongtao, et al. Study and application of oil displacement system of temperature resistant and anti-emulsion surfactant to assist heavy oil thermal recovery [J]. Fault-Block Oil and Gas Field, 2020, 27(3): 365-369.

[5] ZHANG Hongling, LIU Huiqing, WANG Han, et al. Optimization design of profile control parameters for steam stimulation wells [J]. Acta Petrologica Sinica, 2007, 28(2): 105-108.

[6] SANTOS M D, NETO A D, MATA W. New antenna modelling using wavelets for heavy oil thermal recovering methods [J]. Journal of Petroleum Science and Engineering, 2011, 76(1/2): 63-75.

[7] 孙永涛,李兆敏,孙玉豹,等.稠油耐高温乳化降黏剂 AESO 的合成及其性能[J].大庆石油地质与开发,2021,40(3):103-108.

SUN Yongtao, LI Zhaomin, SUN Yubao, et al. Synthesis and properties of high-temperature emulsified viscosity reducer AESO for heavy oil [J]. Petroleum Geology & Oilfield Development in Daqing, 2021, 40(3): 103-108.

[8] 邓宏伟.超深层低渗透稠油 CO₂ 增溶降黏体系研发与应用[J].油气地质与采收率,2020,27(1):81-88.

DENG Hongwei. Development and application of CO₂ solubilizing and viscosity reducing system for ultra-deep and low-permeability heavy oil reservoirs [J]. Petroleum Geology and Recovery Efficiency, 2020, 27(1): 81-88.

[9] 李伟忠.金家油田低渗敏感稠油油藏适度出砂室内评价[J].断块油气田,2019,26(6):810-815.

LI Weizhong. Laboratory evaluation on reasonable sand production of low permeability sensitive heavy oil reservoir in Jinjia Oilfield [J]. Fault-Block Oil & Gas Field, 2019, 26(6): 810-815.

[10] 王一平.深层低渗稠油有效开发方式[J].承德石油高等专科学校学报,2016,18(1):8-11.

WANG Yiping. Effective method for development of deep heavy oil in low permeability reservoir [J]. Journal of Chengde Petroleum College, 2016, 18(1): 8-11.

[11] 刘祖鹏.边底水稠油油藏水溶性降黏剂吞吐技术研究[J].特种油气藏,2020,27(3):99-104.

- LIU Zupeng. Water-soluble viscosity reducer stimulation in the heavy-oil reservoir with bottom-edge aquifer [J]. *Special Oil & Gas Reservoirs*, 2020, 27(3): 99-104.
- [12] 孙焕泉, 王海涛, 吴光焕, 等. 稠油油藏注CO₂提高采收率影响因素研究[J]. *石油实验地质*, 2020, 42(6): 1 009-1 013, 1 023.
- SUN Huanquan, WANG Haitao, WU Guanghuan, et al. CO₂ EOR factors in heavy oil reservoirs [J]. *Petroleum Geology & Experiment*, 2020, 42(6): 1 009-1 013, 1 023.
- [13] ADAMS D M. Experiences with water flooding Lloydminster heavy-oil reservoirs [J]. *Journal of Petroleum Technology*, 1982, 34(8): 1 643-1 650.
- [14] MAI A, BRYAN J, GOODARZI N, et al. Insight into non-thermal recovery of heavy oil [J]. *Journal of Canadian Petroleum Technology*, 2009, 48(3): 27-35.
- [15] MILLER K A. Improving the state of the art of western Canadian heavy oil water flood technology [J]. *Journal of Canadian Petroleum Technology*, 2006, 45(4): 7-11.
- [16] MAI A, KANTZAS A. Heavy oil waterflooding: effects of flow rate and oil viscosity [J]. *Journal of Canadian Petroleum Technology*, 2009, 48(3): 42-51.
- [17] ROCHA DE FARIAS M L, CARVALHO M S, SOUZA A, et al. A comparative study of emulsion flooding and other IOR methods for heavy oil fields [C]. Mexico City: SPE Latin American and Caribbean Petroleum Engineering Conference, 2012: 1-8.
- [18] LIU Qiang, DONG Mingzhe, MA Shanzhou. Alkaline/surfactant flood potential in western Canadian heavy oil reservoirs [C]. Tulsa: SPE/DOE Symposium on Improved Oil Recovery, 2006: 1-10.
- [19] 孙盈盈. 油水在多孔介质中的乳化及其对驱油效率的影响 [D]. 北京: 中国石油大学(北京), 2008.
- SUN Yingying. Oil-water emulsify in porous media and its impact on oil displacement efficiency [D]. Beijing: China University of Petroleum(Beijing), 2008.
- [20] FU Xuebing, LANE R H, MAMORA D D. Water-in-oil emulsions: flow in porous media and EOR potential [C]. Calgary: SPE Canadian Unconventional Resources Conference, 2012: 1-12.
- [21] KUMAR R, DAO E, MOHANTY K K. Heavy oil recovery by in-situ emulsion formation [J]. *SPE Journal*, 2012, 17(2): 326-334.
- [22] CHEN Lifeng, ZHANG Guicai, GE Jijiang, et al. Research of the heavy oil displacement mechanism by using alkaline/surfactant flooding system [J]. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 2013, 434(19): 63-71.
- [23] ZEIDANI K, POLIKAR M, HUANG H, et al. Heavy oil-in-water emulsion as a novel sealant in the near well bore region [C]. Calgary: Canadian International Petroleum Conference, 2007: 1-13.
- [24] GUILLEN V R, ROMERO M I, CARVALHO M S, et al. Capillary-driven mobility control in macro emulsion flow in porous media [J]. *International Journal of Multiphas Flow*, 2012, 43: 62-65.
- [25] DING Boxin, DONG Mingzhe, YU Long. A model of emulsion plugging ability in sandpacks: yield pressure drop and consistency parameter [J]. *Chemical Engineering Science*, 2020, 211: 115248.
- [26] NING Jian, WEI Bing, MAO Runxue, et al. Pore-level observations of an alkali-induced mild O/W emulsion flooding for economic enhanced oil recovery [J]. *Energy & Fuel*, 2018, 32(10): 10 595-10 604.
- [27] XU Ke, ZHU Peixi, COLON T, et al. A microfluidic investigation of the synergistic effect of nanoparticles and surfactants in macro-emulsion-based enhanced oil recovery [J]. *SPE Journal*, 2017, 22(2): 459-469.
- [28] XU Ke, LIANG Tianbo, ZHU Peixi, et al. A 2.5-D glass micro-model for investigation of multi-phase flow in porous media [J]. *Lab on A Chip*, 2017, 17(4): 640-646.
- [29] DING Boxin, SHI Longyang, DONG Mingzhe. Conformance control in heterogeneous two-dimensional sandpacks by injection of oil-in-water emulsion: theory and experiments [J]. *Fuel*, 2020, 273: 117751.
- [30] DING Boxin, SANG Qian, NIE Zhiqian, et al. An improved study of emulsion flooding for conformance control in a heterogeneous 2D model with lean zones [J]. *SPE Journal*, 2021, 26(5): 1-15.
- [31] YU Long, DONG Mingzhe, DING Boxin, et al. Experimental study on the effect of interfacial tension on the conformance control of oil-in-water emulsions in heterogeneous oil sands reservoirs [J]. *Chemical Engineering Science*, 2018, 189: 165-178.
- [32] NI Yidan, DING Boxin, DONG Mingzhe, et al. Conformance control for SAGD using Oil-in-water emulsions in heterogeneous oil sands reservoir [C]. Beijing: International Petroleum Technology Conference, 2019: 1-21.
- [33] DEVEREUX O F. Emulsion flow in porous solids: I. A flow model [J]. *The Chemical Engineering Journal*, 1974, 7(2): 121-128.
- [34] SOO H, RADKE C J. A filtration model for the flow of dilute, stable emulsion in porous media-I. Theory [J]. *Chemical Engineering Science*, 1986, 41(2): 263-272.
- [35] YU Long, DING Boxin, DONG Mingzhe, et al. Plugging ability of oil-in-water emulsions in porous media: experimental and modeling study [J]. *Industrial & Engineering Chemistry Research*, 2018, 57(43): 14 795-14 808.
- [36] DING Boxin, DONG Mingzhe. Optimization of plugging high mobility zones in oil sands by injection of oil-in-water emulsion: experimental and modeling study [J]. *Fuel*, 2019, 257: 116024.