第19卷 第5期 油气地质与采收率 Vol.19, No.5
2012年9月 Petroleum Geology and Recovery Efficiency Sep. 2012

低渗透油藏二氧化碳混相驱超前注气实验研究
——以吉林油田黑79区块为例

娄 毅,杨胜来,章 星,余 跃,殷丹丹,李 敏,文 博
(中国石油大学(北京)石油工程教育部重点实验室,北京 102249)

摘要:为了进一步提高低渗透油藏采收率,进行了二氧化碳混相驱超前注气可行性实验研究。以吉林油田黑79区块为例,利用细管实验确定二氧化碳驱的最小混相压力,通过长岩心物理模拟实验研究低渗透油藏超前注气室内驱油效果,并与相同地层条件下水驱和同步注气的驱油效果进行了对比分析。结果表明,二氧化碳混相驱超前注气、同步注气和水驱的最终采收率分别为77.03%,73.09%和56.47%。二氧化碳混相驱超前注气最终采收率最高,原因是超前注气能够在开采前就使地层压力升高、地层能量增加,并且提前注入的气体与原油接触混相,可降低原油粘度、增加原油流度。

关键词:低渗透油藏 二氧化碳混相驱 超前注气 物理模拟 吉林油田
中图分类号:TE357.7 **文献标识码**:A **文章编号**:1009-9603(2012)05-0078-03

由于低渗透油藏储层的孔隙细小,水驱或者化学驱都容易造成注入流体伤害[1-2],若待开发的低渗透油藏有充足的二氧化碳气源且地层压力能够满足二氧化碳混相条件,则可以考虑二氧化碳混相驱注气开发。通常,现场使用二氧化碳注气方式为同步注气,对于超前注气的研究和应用甚少。超前注气定义为注入井在采油井投产之前进行提前注入二氧化碳气体对地层进行提压处理,使地层压力高于原始地层压力,能建立有效驱替系统注气方式。

吉林油田有着丰富的二氧化碳资源[3],若直接排放将污染环境、加剧温室效应,故将其用于油田驱油,可起到增产和减少环境污染的双重效果[4-6]。吉林油田黑79区块属于低渗透油藏,平均有效孔隙度为12.77%,平均渗透率为6.37×10^{-3} μm^2,油层温度为98 ℃,原始地层压力为24.5 MPa。通过细管实验研究该区块二氧化碳混相驱的最小混相压力,验证二氧化碳混相驱开发的可行性,并通过长岩心物理模拟实验,研究二氧化碳混相驱超前注气驱油效果,进而探索低渗透油藏超前注气开发相关规律。

1 实验设备与方法

1.1 实验设备与用品

实验设备主要包括:Ruska PVT-3000高压物性实验装置;CFS-100多功能综合驱替系统,控温为0~150 ℃,控温精度为±0.5 ℃,高温高压岩心夹持器长度为120 cm;回压阀,控压为0~40 MPa;精密压力表,压力为0~60 MPa,精度为±0.01 MPa;自主研发压力采集系统,采集压力为0~60 MPa,精度为±0.01 MPa。

细管实验是确定二氧化碳驱最小混相压力最准确的方法[7],实验选用长度为15.28 m的不锈钢蛇管,其内填充物为石英砂,渗透率为4 μm^2,孔隙度为31.05 %。

二氧化碳混相驱属多接触混相,所以采用长岩心物理模拟实验进行室内研究。长岩心实验所用岩心取自吉林油田黑79区块的天然岩心(表1),按照排列顺序对岩心进行编号,其顺序排列按照串联岩心渗透率的计算法则计算确定[8],以保证整个长岩心系统的渗透率最接近研究区块的地层渗透率。

实验采用纯度为99.9%的二氧化碳气为注入气,所用地层水根据吉林油田黑79区块地层水资料配制,其中Na^++K^+,Ca^{2+},Mg^{2+},Cl^-,SO_4^{2-},HCO_3^-的质量浓度分别为4 072.2,50.5,28.1,4 481.6,1 049.5和2 055.8 mg/L,总矿化度为11 737.7 mg/L,水型属于$NaHCO_3$型。实验用油为吉林黑79区块原油,在98 ℃时,脱气原油粘度为3.5 mPa·s,地层原油粘度为1.85 mPa·s,密度为0.761 5 g/cm³。

收稿日期:2012-07-31。
作者简介:娄毅,男,在读硕士研究生,从事油气田开发理论与技术研究。联系电话:13716248097,E-mail:louyi8765@yahoo.com.cn。
基金项目:国家重点基础研究发展规划(973)项目"二氧化碳减排、储存和资源化利用的基础研究"(2011CB707300)。

表1　长岩心物理模拟实验所用岩心参数

岩心编号	直径/cm	长度/cm	孔隙度,%	气测渗透率/10^{-3} μm^2
H-1	2.5	8.422	11.43	6.1
H-2	2.5	8.104	12.06	5.63
H-3	2.5	8.066	13.77	6.95
H-4	2.5	7.64	18.29	4.6
H-5	2.5	7.87	13.32	7.8
H-6	2.5	5.984	23.58	4.51
H-7	2.5	6.386	19.06	8.72
H-8	2.5	8.05	12.47	4.01
H-9	2.5	7.32	17.23	8.746
H-10	2.5	8.212	17.35	5.83
H-11	2.5	8.368	15.78	7.92
H-12	2.5	6.61	14.95	9.33

1.2　实验方法

细管实验　利用Ruska PVT-3000配制油样；细管饱和原油；参考SY/T 6573—2003 最低混相压力细管实验测定方法[9]进行注二氧化碳驱替，记录采收率；逐步提高压力重复驱替过程，直到采收率—驱替压力曲线上出现拐点。

长岩心物理模拟实验　测定岩心的直径和长度，参考SY/T 5336—1996岩心常规分析方法[10]进行岩心清洗、饱和地层水、抽真空及测定干重等处理；采用氮气测定岩心孔隙度和渗透率；按照表1中岩心排列顺序将岩心装入清洗过的长岩心夹持器内，并测试驱替系统死体积及水驱渗透率；将设备升温至地层温度（98 ℃）后恒温12 h，饱和地层油；24 h后利用长岩心驱替分别进行二氧化碳超前注气、同步注气驱油和水驱油实验，回压为24.5 MPa，记录各个实验的注入压力、产出气液量及采出程度。其中，超前注气的室内长岩心实验是在关闭长岩心后端产出口的情况下，注入二氧化碳气体，使得整个长岩心驱替系统开始提升压力，直至系统压力高于原始地层压力2 MPa，24 h后开启长岩心后端出口，继续注入二氧化碳并产出油。

2　实验结果及分析

2.1　细管实验

不同区块的原油由于其组分不同，因而具有不同的二氧化碳驱最小混相压力，只有在油藏压力高于最小混相压力时油藏才能实现混相驱[11]。利用细管实验测定不同驱替压力下的原油采收率，通过分析二者的关系（图1）可确定黑79区块二氧化碳驱的最小混相压力为22.8 MPa。故在黑79区块原始地层压力为24.5 MPa的条件下，可以达到二氧化碳混相的条件。

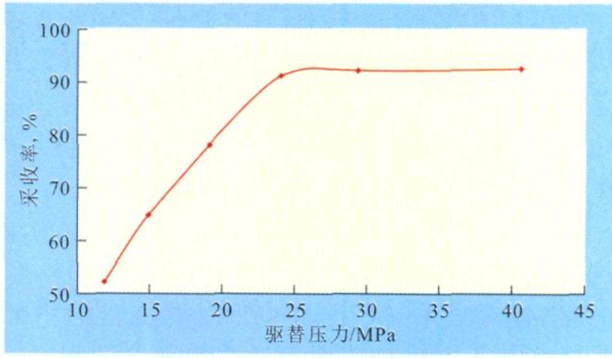

图1　细管实验原油采收率与驱替压力的关系

2.2　长岩心物理模拟实验

按照室内长岩心物理模拟二氧化碳混相驱超前注气驱油、同步注气驱油以及水驱油的实验方法，测试这3种注入方式下的驱替系统注入压力和驱油效率，得到驱替系统注入压力与注入孔隙体积倍数的关系（图2）以及采收率与注入孔隙体积倍数的关系（图3）。

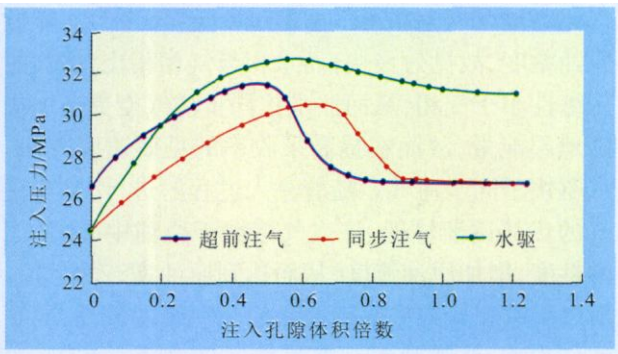

图2　3种注入方式下注入压力与注入孔隙体积倍数的关系

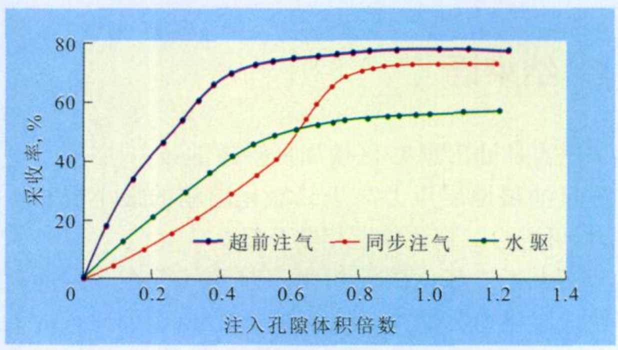

图3　3种注入方式下采收率与注入孔隙体积倍数的关系

由图2可见，超前注气在突破前达到的最高注入压力为30.72 MPa，气体突破之后压力开始急剧下降，0.7倍孔隙体积之后注入压力基本稳定在26.66

MPa；同步注气在突破前达到的最高注入压力为30.21 MPa，气体突破之后压力开始急剧下降，0.9倍孔隙体积之后注入压力基本稳定在26.63 MPa；水驱在突破前达到的最高注入压力为32.52 MPa，见水之后压力开始缓慢下降，1倍孔隙体积之后注入压力基本稳定在30.92 MPa。产生该现象的原因为二氧化碳在原油中混相，使原油体积膨胀，降低原油粘度，增加原油的流度，从而降低了生产压差。

由图3可见，二氧化碳混相驱超前注气、同步注气、水驱的最终采收率分别为77.03%，73.09%和56.47%。单就采收率上升的时间方面，超前注气的采收率快速上升以最短时间达到峰值，对于提高采收率的效果最明显。水驱前期采收率上升也很快，见效比同步注气早。而总体趋势来说，无论是超前注气还是同步注气驱油，其最终采收率都大于水驱的最终采收率。超前注气和同步注气在气体突破之前采收率上升幅度很大，是提高采收率的关键阶段，在气体突破之后产出的油很少。产生这些现象的原因是：对于超前注气来说，在开采前就提升了地层的压力，增加了地层的能量，而且提前注入的气体与原油接触混相，可充分降低界面张力，降低原油粘度，故见效最快；而水相与气相相比，水相的压缩性小于气相，从而注水比同步注气能更快地提高地层能量，故而在提高采收率的见效速度方面，水驱快于同步注气。随着注入过程的进行，同步注气的优势逐渐显现，注入气溶解于原油中，降低原油粘度，增加原油流度，从而达到原油增产的目的，所以反映在最终采收率上是超前注气的最高，同步注气次之，注水最低。在气体突破之后，由于气窜严重，导致超前注气与同步注气一样，在后期的采收率上升幅度甚微。

3 结束语

吉林油田黑79区块属低渗透油藏，具备充足气源且油藏地层压力高于二氧化碳驱的最小混相压力，可进行二氧化碳混相驱开发。

由于二氧化碳混相驱超前注气可在开采前就使地层压力升高并使地层能量增加，提前注入的气体与原油接触混相，从而降低原油粘度，增加原油流度，使得黑79区块采用二氧化碳混相驱超前注气驱油效果最好，最终采收率为77.03%，比同步注气和水驱的最终采收率高3.94%和20.56%，并且在提高采收率的见效速度方面也优于其他2种注入方式。因此，对于低渗透油藏，采用二氧化碳混相驱超前注气开发的驱油效果优于同步注气和水驱。

二氧化碳混相驱超前注气在气体突破之后，由于气窜严重，产出油量变小，采收率上升幅度甚小。若结合水气交替注入的方式，可以产生气相渗透率滞后效应，并形成较大的滞留气饱和度，降低气相渗透率，在一定程度上减少气窜的影响，使得气相和液相交替驱扫不同的含油孔道，进一步提高驱油效率。故在现场应用二氧化碳混相驱时，可以考虑超前注气与水气交替注入综合应用的复合注气方式。

参考文献：

[1] 杜朝锋，武平仓，邵创国，等.长庆油田特低渗透油藏二氧化碳驱提高采收率室内评价[J].油气地质与采收率，2010，17(4)：63-64.

[2] 娄毅，杨胜来，王玉霞，等.NH_4Cl和$NaNO_2$化学生热体系对储层损害的研究[J].油田化学，2011，28(3)：292-295.

[3] 杜立辉，孟昭昭，刘敏慧.吉林油田CO_2注入工艺技术[J].油气田地面工程，2011，30(7)：33-35.

[4] 李武广，杨胜来，娄毅.CO_2地质埋存目标区优选体系与评价方法研究[J].天然气地球科学，2011，22(4)：747-752.

[5] 王友启，赵峰华，刘柏林，等.炼油厂排放二氧化碳用于驱油埋存的可行性评价[J].油气地质与采收率，2010，17(2)：70-73.

[6] 赵勇，李敏，万丛礼，等.沾化凹陷孤西地区二氧化碳特征及成因[J].油气地质与采收率，2011，18(2)：38-40.

[7] 郝永卯，陈月明，于会利.CO2驱最小混相压力的测定与预测[J].油气地质与采收率，2005，12(6)：64-66.

[8] 杨胜来，魏俊之. 油层物理学[M].北京：石油工业出版社，2004：149-152.

[9] 刘宁，郑希谭，陈钢，等. SY/T 6537—2003 最低混相压力细管实验测定方法[S].北京：石油工业出版社，2003.

[10] 任义宽，高连云，王文录. SY/T 5336—1996 岩心常规分析方法[S].北京：石油工业出版社，1996.

[11] 郭龙.渤南油田义34块特低渗透油藏二氧化碳混相驱实验[J].油气地质与采收率，2011，18(1)：37-40.

编辑 刘北羿

oxygen in the end gas and acid value, viscosity and group composition of the oil with additives in the high temperature autoclave. The heavy oil was from the producing well 951217 in the Block J230 of Xinjiang Oilfield. It is found that the acid value of the oxidized oil is 8.37 mg/g and its viscosity is 3 787 mPa · s but oxygen volume fraction decreases to 4.75 vol% after 72 h with 0.10 wt% catalyst of FeL and air injected at 1.2 MPa and 200 ℃. Furthermore, the viscosity of emulsion is 42 mPa · s at 50 ℃ after mixing 70 g oxidized oil, 30 g water and 0.07 g caustic additives R1. Good results can be achieved through decreasing the volume fraction of oxygen with catalyst and reducing the viscosity of heavy oil with caustic additives during the process of cyclic steam with air.

Key words: steam stimulation; air; low-temperature oxidation; catalysis; viscosity reduction

Luo Qiang, Research Institute of Experiment and Detection of Xinjiang Oilfield Company, PetroChina, Karamay, Xinjiang, 834000, China

Zhang Enlei, Gu Daihong, He Shunli et al. Experiment study on effect of impurities on CO_2 drive. *PGRE*, 2012, 19(5): 75-77.

Abstract: Carbon dioxide flooding is a promising tertiary oil recovery technology in respect both to technical and, if operating costs are properly controlled, to economic benefit. Moreover, the injection of this greenhouse gas also has environmental merits. Flue gas from power plants and natural CO_2 gas is the main available source of the CO_2, however, CO_2 sources are rarely pure. Purifying the flue gas will increase operating costs significantly. Therefore, understanding the roles of impurities in fluid phase behavior and miscibility characteristics is necessary for designing a cost-effective CO_2 enhanced oil recovery process. This paper studies the effect of the different impurities in the CO_2 stream on the phase behavior and the MMP. With the effect of impurities on the CO_2 MMP, it is shown that the presence of intermediate hydrocarbon gas solvents in the CO_2 gas stream can reduce the CO_2 MMP, whereas, the N_2 and CH_4 tend to have the opposite effect. EOS simulation is demonstrated to be an effective toll to analyzing the miscibility of oil-gas systems. Core flood tests are conducted to investigate the oil recovery behavior resulting from CO_2 injection. The ultimate oil recoveries of the tests show that the miscibility and near-miscibility have the same mechanism. The presence of intermediate hydrocarbon gas solvents in the CO_2 gas stream can enhance the ultimate recovery, whereas, the N_2 and CH_4 tend to have the opposite effect.

Key words: CO_2 drive; minimum miscibility pressure; impurities; slim tube test; displacement experiment

Zhang Enlei, MOE Key Laboratory of Petroleum Engineering, China University of Petroleum (Beijing), Beijing City, 102249, China

Lou Yi, Yang Shenglai, Zhang Xing et al. Experimental research on CO_2 miscible flooding by advanced gas injection in low permeability reservoir-case of H79 block, Jilin oilfield. *PGRE*, 2012, 19(5): 78-80.

Abstract: In order to enhance the oil recovery in low permeability reservoir by CO_2 miscible flooding through advanced gas injection, its feasibility is tested in laboratory. The minimum miscible pressure is determined by micro-tubes tests; the laboratory result of CO_2 miscible flooding by advanced gas injection with long core physical simulation device is researched and the result is compared with that of synchronous gas injection and water flooding. The ultimate recovery of CO_2 miscible flooding by advanced gas injection is 77.03%, synchronous gas injection is 73.09% and water flooding is 56.47%. Results show that, since the advanced gas injection can increase the formation pressure and energy, the oil's viscosity is reduced and its mobility is increased because gas injected in advance is contacted with oil, recovery of advanced gas flooding is higher than that of synchronous gas injection and water flooding.

Key words: low permeability reservoir; CO_2 miscible flooding; advanced gas injection; physical simulation; Jilin oilfield

Lou Yi, MOE Key Laboratory of Petroleum Engineering, China University of Petroleum (Beijing), Beijing City, 102249, China

Zhang Jiyao, Gao Ruimin, Yu Huagui et al. Preliminary study about oxygen consumption of injecting air into low-temperature and low-pressure reservoir. *PGRE*, 2012, 19(5): 81-83.

Abstract: The Ganguyi blocks is the main production area of Yanchang oilfield, the main developing oil layer is Chang 6 reservoir with low pressure, low permeability and low temperature characteristics. Since 2007, the air-foam enhance oil recovery technology is used, and it achieved good results. An instrument is used to simulate the oxygen consumption of injecting air into a reservoir with 30 ℃ and 6 MPa, and the oxygen content diminishes with index, it will drop under the explosion limit after 80 days, and it can run out if the time is long enough, the law is verified in field test based on a low-temperature and low-pressure reservoir. So, the air-foam enhance oil recovery technology can be used in the low-temperature and low-pressure reservoir.

Key words: low-temperature and low-pressure reservoir; air injection; oxygen consumption; Yanchang oilfield; Ganguyi blocks

Zhang Jiyao, Shannxi Yanchang Petroleum (Group) Co., Ltd, Xi'an Ctiy, Shannxi Province, 710075, China

Wang Duanping, Yang Yong, Niu Shuanwen et al. Layer block classification evaluation and adjustment of complicated fault block oil reservoir. *PGRE*, 2012, 19(5): 84-87.

Abstract: In order to improve the water flooding recovery factor of the fault block oil reservoir and adapt to the needs of the development, this paper considers the static geological features and dynamic development features, then, it proposes layer block classification method of comprehensive evaluation for complicated fault block oil reservoir. A single sand body is the classification object in the vertical, moreover, the cutting of fault block and the change of lithological boundary are considered in the plane. In other words, using "layer block" for the basic elements of the reservoir classification, this paper classifies and evaluates precisely the fault block oil reservoir, and proposes combination of different layers block developed and adjustment program. The practice shows that this method is the base for carrying out potential assessment and adopting the accurate adjustment policies, it has the guiding signifi-