引用格式：王程伟，苏玉亮，王文东，等.CO_2-C_2H_6吞吐提高致密油藏采收率实验研究[J].油气地质与采收率，2024，31（1）：111-118.
WANG Chengwei，SU Yuliang，WANG Wendong，et al.Experimental study on enhancing oil recovery of tight reservoirs through CO_2-C_2H_6 huff and puff[J].Petroleum Geology and Recovery Efficiency，2024，31（1）：111-118.

CO_2-C_2H_6吞吐提高致密油藏采收率实验研究

王程伟[1,2]，苏玉亮[1,2]，王文东[1,2]，李 蕾[1,2]，郝永卯[1,2]
（1.中国石油大学（华东）石油工程学院，山东 青岛 266580；2.非常规油气开发教育部重点实验室
中国石油大学（华东），山东 青岛 266580）

摘要：注CO_2已经成为致密油藏提高采收率的重要手段之一，相较于纯CO_2，部分烃类气体对原油的降黏及混相能力更强。为此，通过高温高压PVT实验研究了CO_2及复合气体（CO_2-C_2H_6）-原油的饱和压力及黏度的变化特征，并利用高温高压岩心吞吐实验揭示了不同气体介质、吞吐压力及吞吐轮次下原油动用程度。研究结果表明：复合气体中C_2H_6增强了气液两相混相能力，提高了CO_2降黏及溶解能力，原油流动性显著增加。复合气体中随着C_2H_6摩尔分数的增加，原油饱和压力由14.24 MPa增至18.02 MPa，提高了26.54%；原油黏度由23.68 mPa·s降至8.76 mPa·s。不同吞吐压力下复合气体（CO_2-C_2H_6）的采收率提高效果均强于纯CO_2的，且吞吐压力在最小混相压力附近采收率提高程度高于其他吞吐压力。复合气体（CO_2-C_2H_6）对孔隙半径为0.000 1～0.001 和0.01～1 μm孔隙中的原油动用程度强于纯CO_2的。

关键词：致密油藏；饱和压力；黏度；岩心实验；核磁共振技术
文章编号：1009-9603（2024）01-0111-08 DOI：10.13673/j.pgre.202305039
中图分类号：TE357 **文献标识码**：A

Experimental study on enhancing oil recovery of tight reservoirs through CO_2−C_2H_6 huff and puff

WANG Chengwei[1,2]，SU Yuliang[1,2]，WANG Wendong[1,2]，LI Lei[1,2]，HAO Yongmao[1,2]
（1.*School of Petroleum Engineering*，*China University of Petroleum*（*East China*），*Qingdao City*，*Shandong Province*，266580，*China*；2.*MOE Key Laboratory of Unconventional Oil & Gas Development*，*China University of Petroleum*（*East China*），*Qingdao City*，*Shandong Province*，266580，*China*）

Abstract：CO_2 injection has become one of the most important methods of enhanced oil recovery in tight reservoirs，but some hydrocarbon gases have more viscosity-reducing and miscibility on oil compared to pure CO_2. Therefore，this article studied the saturation pressure and viscosity changes of oil with CO_2 and composite gas（CO_2 and C_2H_6）by PVT experiments at high-temperature and high-pressure and revealed the percentage of producing oil with different gases，huff and puff pressures，and rounds by core huff and puff experiments at high-temperature and high-pressure. The results show that the C_2H_6 in the composite gas enhances the gas and liquid miscibility，improves the CO_2 viscosity reduction and dissolution ability，and significantly increases the fluidity of oil. With the increase of C_2H_6 mole fraction in the composite gas，the saturation pressure of oil increases by 26.54% from 14.24 MPa to 18.02 MPa，and the viscosity of crude oil decreases from 23.68 mPa·s to 8.76 mPa·s. Under different huff and puff pressures，the oil recoveries of composite gas（CO_2 and C_2H_6）are better than that of pure CO_2，and the increase of recovery near the minimum miscibility pressure is higher than under other huff and puff pressures. The percentage of producing oil by composite gases is higher

收稿日期：2023-05-14。
作者简介：王程伟（1995—），男，河南荥阳人，在读博士研究生，从事非常规油气藏开发研究。E-mail：wangchengwei_upc@163.com。
通信作者：苏玉亮（1970—），男，山东东营人，教授，博导。E-mail：suyuliang@upc.edu.cn。
基金项目："十四五"前瞻性基础性重大科技项目"致密油可动用性评价及提高采收率机理研究"（2021DJ2202），国家自然科学基金项目"页岩油CO_2吞吐多尺度流动模拟研究"（51974348）。

than that of pure CO_2 in the pores of 0.0001-0.001 μm and 0.01-1 μm.

Key words：tight reservoir；saturation pressure；viscosity；core experiment；nuclear magnetic resonance（NMR）

随着全球经济发展的日益加速以及工业技术的不断发展，油气消耗量逐渐增加，常规油气资源已无法完全满足全社会对能源的需求[1-4]。目前我国致密油藏资源丰富，分布范围广泛，可采储量已达40×10^8 t，主要分布在新疆油田、长庆油田等地，具有广阔的勘探开发前景[5-8]。与常规油藏相比，致密油藏储层分布大量纳米级孔隙，且孔隙结构复杂、毛细管阻力大、原油流动困难[9-11]。致密油藏若采用衰竭式开采，压力衰竭速度过快导致油藏开发周期短、采收率低、剩余油含量高，在弹性开采后应采取合理的增产措施[12-15]。同时致密油藏储层普遍水敏性较强，注水开采难度大且易对地层造成不可逆的伤害，因此注气开发逐渐受到关注[16-20]。

目前，用于致密油藏提高采收率的气体有CO_2，N_2、天然气、烟道气、空气等。其中，CO_2是目前研究最多、效果最为理想的气体，在油藏条件下更容易达到混相条件。近年中外注气提高采收率研究如表1所示。

表1 油藏注气驱油效率汇总

Table1 Summary of oil displacement efficiency under gas injection in reservoirs

研究人员	注入气体	压力/MPa	温度/℃	采收率/%
管奕婷等[21]	烃气	15.5	45	47.95
许清华[22]	烃气	49.1 ~ 53.08	110 ~ 128	68.08 ~ 86.48
李德祥等[23]	空气	23.8	110	55.4 ~ 61.3
PU等[24]	CO_2	4 ~ 26	75	21.2 ~ 40.9
刘鹏刚[25]	空气	40	102	18
HUANG等[26]	CO_2	15	80.15	大孔隙：40 ~ 80 小孔隙：50 ~ 80
ZHOU等[27]	CO_2	12.9	44	38.96
LI等[28]	CO_2	4 ~ 14	80	39.48 ~ 91.49

大量研究结果表明，致密油藏中注CO_2及N_2一定程度均能提高采收率，其中以CO_2效果最好。但是在致密油藏储层中，天然裂缝与人工裂缝发育交错，在注气过程中常出现窜流等问题，很大程度上限制气体波及范围及驱油效率。因此，开始探索复合气体、化学助剂辅助CO_2提高采收率机理[29-32]。GAJBHIYE通过实验手段明确CO_2/N_2混合气体对油气界面张力的变化特征，结果表明，CO_2摩尔分数的增加会降低油气两相界面张力，N_2摩尔分数的增加会增大油气两相界面张力，由此可知注入气体成分对注气提高采收率效果至关重要，在矿场实施阶段需重点考虑[33]。

发挥注入流体间的协同（混相压力、原油膨胀）驱油优势逐渐受到重视，然而由于多流体与原油、岩石间相互作用机理复杂，微观协同提高采收率机理仍不明确[34-36]。随着对不同注入介质-原油混相能力研究的不断深入，发现C_2H_6能够有效降低原油最小混相压力，且降低幅度高于纯CO_2[37]。同时油田开发过程中，大量烃类气体被开采，能够保证C_2H_6具有稳定气源。因此，笔者利用高温高压PVT、黏度实验装置，研究了CO_2及复合气体（CO_2-C_2H_6，文中的摩尔分数均为60%）-原油的饱和压力及黏度变化特征，并通过岩心吞吐实验揭示不同气体类型、吞吐压力及吞吐轮次下不同孔隙结构原油动用规律，为致密油藏注复合气体（CO_2-C_2H_6）提高采收率提供理论指导。

1 实验器材及流程

1.1 实验器材

实验用原油为地层原油和油田伴生气复配的模拟油，所用模拟油的流体特征与鄂尔多斯盆地的致密油相似。实验用岩心取自鄂尔多斯盆地现场致密砂岩岩心，岩心基础数据如表2所示。在开展物理模拟实验前，利用甲苯对岩心进行清洗，在150 ℃的烘箱中对岩心进行烘干。实验仪器包括：MacroMR12-110H-Ⅰ型核磁共振仪器、恒温箱、VindumVP-3K-C型驱替泵、手摇泵、增压泵、岩心夹持器等。

1.2 实验流程

1.2.1 岩心基础物性实验

选择实际地层岩心开展基础物性实验，首选通过气测渗透率、孔隙度测量仪确定致密砂岩岩心孔

表2　岩心基础数据
Table2　Basic core data

岩心编号	长度/cm	直径/cm	干重/g
1#	5.22	2.56	54.12
2#	5.26	2.56	52.02
3#	5.35	2.56	59.21
4#	5.22	2.56	55.02
5#	6.12	2.56	53.19
6#	5.42	2.56	54.36
7#	5.24	2.56	56.68

渗数据，其次通过铸体薄片及扫描电镜明确岩心孔隙结构及矿物特征。

1.2.2　高温高压PVT实验

按照地层原油气油比在高温高压PVT反应釜中配制原始活油样品，将高温高压PVT反应釜温度升至地层温度，打开反应釜内搅拌装置并稳定6 h。利用注入泵将高温高压PVT反应釜压力升至指定压力，并稳定6 h。以恒定速度退泵，降低高温高压PVT反应釜压力，记录退泵体积与压力（稳定2 h），高温高压PVT实验装置如图1所示。

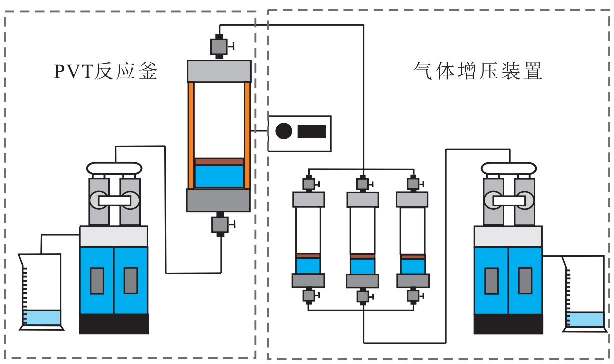


图1　高温高压PVT实验装置
Fig.1　High-temperature and high-pressure PVT experimental setup

1.2.3　高温高压黏度实验

按照地层原油气油比在高温高压PVT反应釜中配制原始活油样品，将活油样品导入螺旋管线中。利用水浴加热及升压装置，将螺旋管线温度及压力升至地层条件，并开启搅拌装置使油与气充分接触，最终通过高温高压黏度计算系统自动计算原油黏度。高温高压黏度实验装置如图2所示。

1.2.4　高温高压岩心吞吐实验

具体步骤包括：①将岩心抽真空饱和地层原油，并通过核磁共振测定原油孔隙分布。②按照摩尔分数比例（7∶3）配制复合气体（CO_2-C_2H_6）。③将岩心置于高温高压岩心吞吐实验装置（图3）中，利用气体增压装置将纯CO_2及复合气体增至不同压力

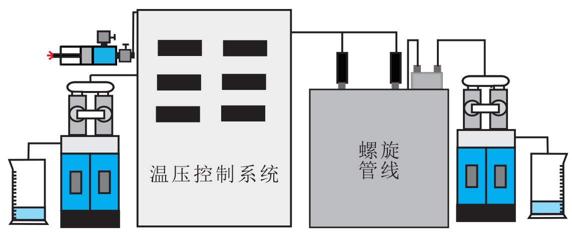


图2　高温高压黏度实验装置
Fig.2　High-temperature and high-pressure viscosity experimental setup

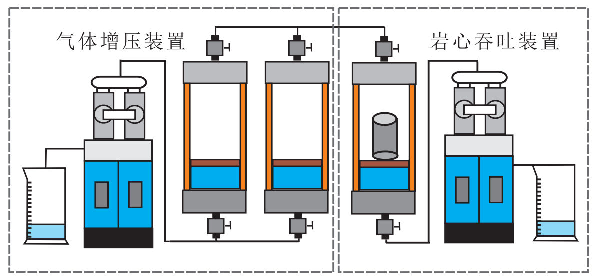


图3　高温高压岩心吞吐实验装置
Fig.3　High-temperature and high-pressure core huff and puff experimental setup

注入放有岩心的中间容器中，并稳定6 h。④稳定放压，通过称重法测定原油采收率，通过核磁共振明确剩余油动用特征。结合高压压汞与核磁共振技术[38-40]，可得到储层岩石的孔隙半径分布，而100%饱和流体的核磁共振 T_2 图谱可以评价孔隙半径分布。

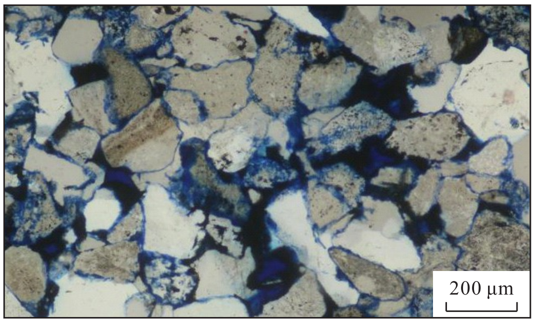
2　结果与讨论

2.1　岩心孔隙特征

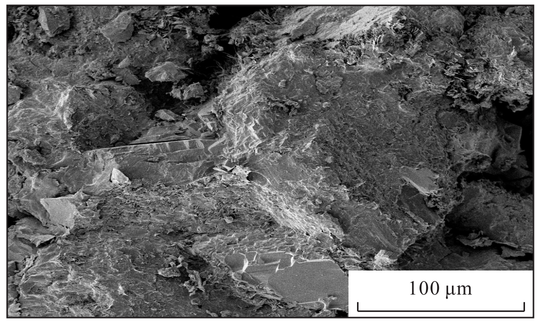
结合岩心铸体薄片及扫描电镜实验研究结果（图4），致密油藏储层岩石矿物主要由石英、斜长石、钾长石、云母、火成岩岩屑、变质岩岩屑和填隙物组成，偶见锆石、海绿石，黏土矿物颗粒微细，集中不均匀分布，粒径为0.06～0.30 mm，以细粒级为主；岩心孔隙发育中等，分布较均匀，连通性差，孔隙类型为粒间溶孔、粒间孔，少量粒内溶孔，粒间孔隙及微裂隙见自生石英、黏土矿物、伊利石、黄铁矿充填，见云母晶间微裂缝，孔隙半径为0.02～0.10 mm。

2.2　饱和压力变化特征

利用高温高压PVT实验装置，测定不同摩尔分数CO_2及复合气体（CO_2-C_2H_6）的混合原油饱和压力变化规律。由图5可知，随着CO_2摩尔分数的增加，原油饱和压力由14.03 MPa升至20.25 MPa。CO_2和60%含复合气体（CO_2-C_2H_6）的原油饱和压力分别为14.24和18.02 MPa，饱和压力上升26.54%，相同摩



a—铸体薄片实验结果



b—扫描电镜实验结果

图4　岩心孔隙特征

Fig.4　Core pore characteristics

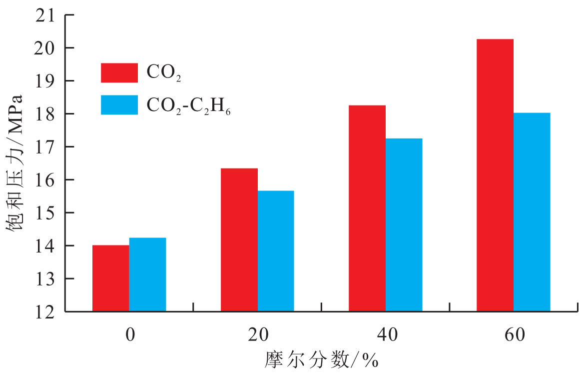


图5　原油注气时饱和压力变化

Fig.5　Saturation pressures of oil during gas injection

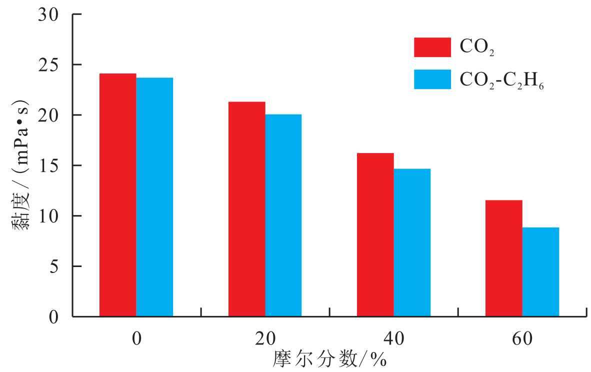


图6　原油注气时黏度变化

Fig.6　Viscosity of oil during gas injection

尔分数下，注入复合气体后的原油饱和压力均低于纯CO_2的(降低0.7～2.23 MPa)。

对比纯CO_2与复合气体(CO_2-C_2H_6)饱和压力变化规律可知，当纯CO_2注入到原油中时，CO_2溶解于原油中，CO_2分子与原油中的烃类分子相互作用，增加原油分子间吸引力，同时改变原油组分的相对含量，进而导致原油饱和压力的增加，且随着注入气体摩尔分数的上升，饱和压力逐渐增大。相同摩尔分数条件下，复合气体(CO_2-C_2H_6)的饱和压力低于纯CO_2的。由此可知，C_2H_6气体能够增加CO_2在原油中的溶解能力，增强CO_2分子在原油分子间的相互作用能力，提高油气混相能力，从而强化储层原油动用程度。

2.3　黏度变化特征

利用高温高压黏度实验装置，测定不同摩尔分数CO_2及复合气体(CO_2-C_2H_6)的混合原油黏度变化规律。由图6可知，随着CO_2摩尔分数的增加，原始油样的黏度由24.06 mPa•s降至11.55 mPa•s，黏度下降52%。CO_2和复合气体(CO_2-C_2H_6)的原油黏度分别为23.68和8.76 mPa•s，黏度下降63%。相同摩尔分数下，注入复合气体后的原油黏度均低于纯CO_2的(降低1.02～2.79 mPa•s)。

对比CO_2与复合气体(CO_2-C_2H_6)黏度变化规律可知，当CO_2注入原油中时，CO_2溶解于原油中，能够使原油间的分子力部分转化为气-液分子间的引力，以降低原油间的内摩擦力从而起到降黏效果。随着气体摩尔分数的增加，溶解于原油中的CO_2逐渐增多，进而导致原油黏度不断降低。相同摩尔分数条件下，复合气体(CO_2-C_2H_6)的黏度均低于纯CO_2的。由此可知，C_2H_6气体增强了CO_2对原油的降黏能力，增加了原油的流动性，从而提高原油采收率。

2.4　岩心吞吐提高采收率变化特征

由图7可知，随着吞吐轮次的增加，采收率逐步增大。岩心赋存原油主要在第1,2轮次被大面积动用，第3,4轮次原油动用程度较低。随着吞吐压力的上升，CO_2-原油混相程度增强，原油黏度降低，使岩心原油采收率逐渐升高。由原油最小混相压力研究结果可知，CO_2-原油最小混相压力约为16 MPa。由CO_2吞吐实验研究结果可知，当吞吐压力高于16 MPa时，吞吐采出程度明显增加。

由图8可知，岩心赋存原油主要在第1,2轮次被大面积动用，第3,4轮次原油动用程度较低。由原油最小混相压力研究结果可知，复合气体(CO_2-C_2H_6)-原油最小混相压力约为14 MPa，当吞吐压力高于14 MPa时，采收率明显增加。

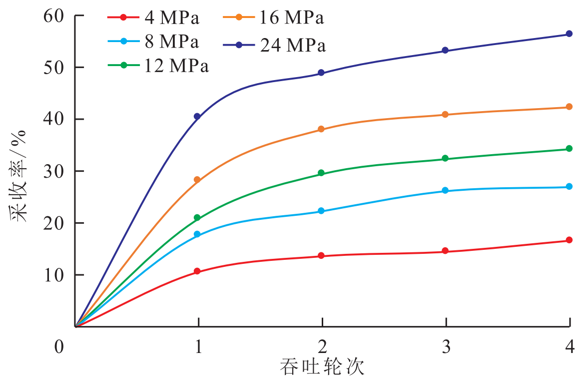


图7　岩心CO_2吞吐实验结果

Fig.7　Results of core experiments under CO_2 huff and puff

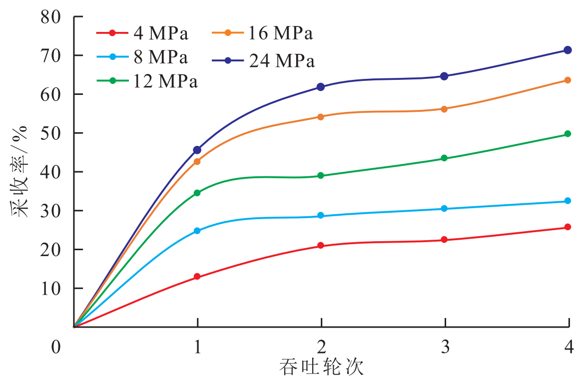


图8　岩心CO_2-C_2H_6吞吐实验结果

Fig.8　Results of core experiments under CO_2-C_2H_6 huff and puff

CO_2及复合气体(CO_2-C_2H_6)在不同吞吐压力(分别为4,8,12,16和24 MPa)下经4轮吞吐后采收率如图9所示。对比岩心CO_2与复合气体吞吐实验结果可知,由于C_2H_6能够增强CO_2在原油中的溶解度,减小原油分子的内摩擦阻力,从而增强CO_2对原油的降黏能力,进而提高岩心原油动用程度,使相同吞吐条件(压力、轮次)下复合气体提高原油采收率程度高于CO_2(复合气体为71.43%;CO_2为56.38%),且压力在最小混相压力附近时采收率提高程度最大。

岩心吞吐核磁共振实验研究结果如图10和图11所示。由Ⅰ类储层典型岩心在不同吞吐压力下吞吐至剩余油状态时的核磁共振T_2图谱可知,Ⅰ类储层孔喉集中分布在0.000 1～0.001,0.01～1 μm,随着吞吐压力的逐渐升高,不同孔喉原油均得到有效动用。由图10可知,吞吐压力小于8 MPa时,CO_2主要动用0.01～1 μm孔喉中赋存的原油,0.000 1～0.001 μm内赋存的原油动用程度较小。随着吞吐压力的逐渐增加,0.000 1～0.001 μm内赋存的原油逐渐动用,且当吞吐压力在CO_2-原油最小混相压力附近时该孔喉原油动用程度较高。相较于CO_2,复合气体(CO_2-C_2H_6)对原油的降黏程度更高,且加入C_2H_6能够更大程度降低原油最小混相压力,因此复合气体对0.000 1～0.001,0.01～1 μm孔喉中的原油动用程度均强于CO_2的(图11)。

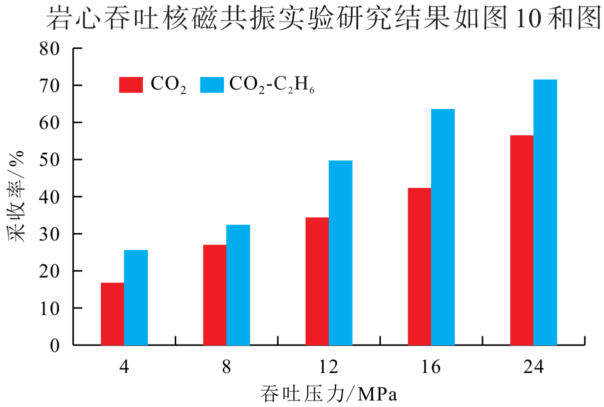


图9　不同吞吐压力下吞吐提高采收率变化特征

Fig.9　Oil recoveries under different gas huff and puff

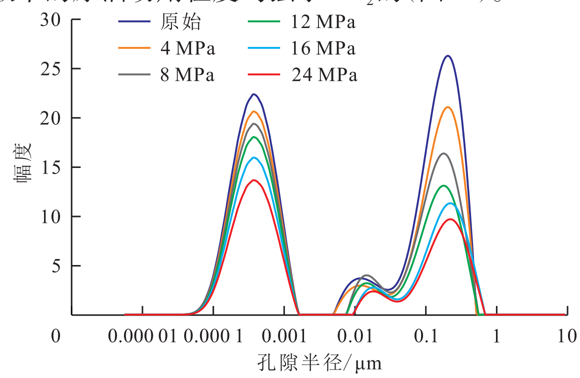


图10　CO_2吞吐核磁共振T_2图谱

Fig.10　NMR T_2 spectrum under CO_2 huff and puff

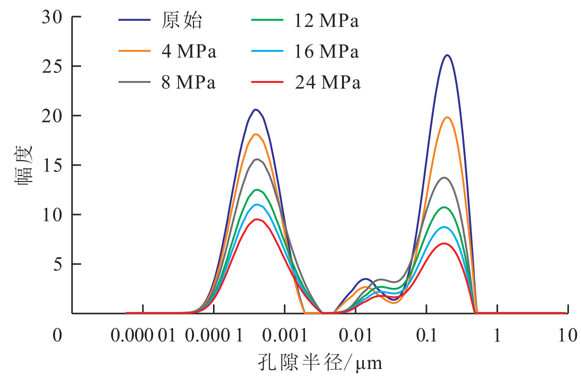


图11　CO_2-C_2H_6吞吐核磁共振T_2图谱

Fig.11　NMR T_2 spectrum under CO_2-C_2H_6 huff and puff

不同孔喉中CO_2及复合气体(CO_2-C_2H_6)吞吐提高原油采收率效果(图12)表明,0.01～1 μm孔喉原油采收率提高程度均高于0.000 1～0.001 μm(0.01～1 μm:8%～46%;0.000 1～0.001 μm:20%～68%),且岩心已知孔喉处复合气体吞吐提高采收率程度均高于CO_2的(相较于CO_2约提高5%～10%)。

对比CO_2及复合气体在不同孔喉处的原油采收率可知,致密砂岩储层不同孔喉的原油均可通过CO_2或复合气体吞吐技术实现有效动用,且随着吞

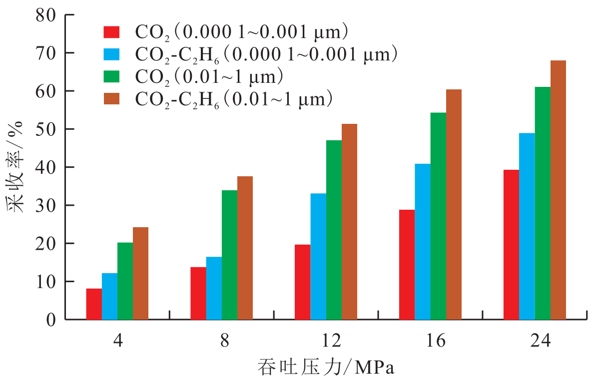


图12 不同孔喉吞吐提高采收率变化特征

Fig.12 Oil recoveries of different pores under huff and puff

吐压力的不断上升,气体大量溶解于原油中,降低原油分子间的内摩擦力,从而降低原油黏度,提高原油流动能力。同时CO_2及复合气体均能够与原油实现混相,大幅度降低油气界面张力,从而提高原油动用程度。相比于CO_2吞吐,C_2H_6气体能够提高复合气体与原油间的溶解、降黏及混相程度,将CO_2吞吐无法动用的剩余油携带出储层,且当吞吐压力接近最小混相压力时,原油采收率变化程度最高。

3 结论

随着注入气体摩尔分数的上升,饱和压力逐渐增大。相同摩尔分数条件下,复合气体(CO_2-C_2H_6)的饱和压力低于纯CO_2的。C_2H_6气体能够增加CO_2在原油中的溶解能力,从而强化储层原油动用程度。随着气体摩尔分数的增加,溶解于原油中的CO_2逐渐增多,进而导致原油黏度不断降低。相同摩尔分数条件下,注入复合气体(CO_2-C_2H_6)的原油黏度均低于纯CO_2的。C_2H_6气体增强了CO_2对原油的降黏能力,增加了原油的流动性,从而提高原油采收率。

岩心赋存原油主要在第1,2轮次被大面积动用,且吞吐压力在油气最小混相压力附近,原油采收率明显增加。C_2H_6能够增强CO_2在原油中的溶解度,减小原油分子的内摩擦阻力,从而增强CO_2对原油的降黏能力,进而提高岩心原油动用程度。在不同吞吐压力下,复合气体(CO_2-C_2H_6)的采收率提高效果均高于纯CO_2的(复合气体的为71.43%;纯CO_2的为56.38%),且吞吐压力在最小混相压力附近采收率提高程度高于其他吞吐压力。致密油藏储层孔喉集中分布在0.000 1~0.001和0.01~1 μm中,随着吞吐压力的逐渐升高,不同孔喉原油均得到有效动用。相较于纯CO_2,复合气体(CO_2-C_2H_6)吞吐对0.000 1~0.001和0.01~1 μm孔喉中的原油动用程度更强,能够将纯CO_2吞吐无法动用的剩余油携带出储层,是未来致密油藏高效开发的一种有效技术。

参考文献

[1] 张映红,路保平,陈作,等.中国陆相致密油开采技术发展策略思考[J].石油钻探技术,2015,43(1):1-6.
ZHANG Yinghong, LU Baoping, CHEN Zuo, et al. Technical strategy thinking for developing continental tight oil in China [J]. Petroleum Drilling Techniques, 2015, 43(1): 1-6.

[2] 徐祖新,姜文亚,刘海涛.常规与非常规油气关系研究现状与发展趋势[J].油气地质与采收率,2016,23(3):14-19.
XU Zuxin, JIANG Wenya, LIU Haitao. Research status and development tendency of the relationship between conventional and unconventional oil and gas [J]. Petroleum Geology and Recovery Efficiency, 2016, 23(3): 14-19.

[3] 康毅力,田键,罗平亚,等.致密油藏提高采收率技术瓶颈与发展策略[J].石油学报,2020,41(4):467-477.
KANG Yili, TIAN Jian, LUO Pingya, et al. Technical bottlenecks and development strategies of enhancing recovery for tight oil reservoirs [J]. Acta Petrolei Sinica, 2020, 41(4): 467-477.

[4] 李国欣,雷征东,董伟宏,等.中国石油非常规油气开发进展、挑战与展望[J].中国石油勘探,2022,27(1):1-11.
LI Guoxin, LEI Zhengdong, DONG Weihong, et al. Progress, challenges and prospects of unconventional oil and gas development of CNPC [J]. China Petroleum Exploration, 2022, 27(1): 1-11.

[5] 郭鸣黎,陈艳,郑振恒,等.致密油藏可采储量概率快速评估方法——以红河油田长8油藏为例[J].石油实验地质,2021,43(1):154-160.
GUO Mingli, CHEN Yan, ZHENG Zhenheng, et al. Rapid evaluation of probable recoverable reserves in tight reservoirs: a case study of Chang 8 reservoir (eighth member of Yanchang Formation) in Honghe oil field [J]. Petroleum Geology & Experiment, 2021, 43(1): 154-160.

[6] 田伟,刘慧卿,何顺利,等.吉木萨尔凹陷芦草沟组致密油储层岩石微观孔隙结构表征[J].油气地质与采收率,2019,26(4):24-32.
TIAN Wei, LIU Huiqin, HE Shunli, et al. Characterization of microscopic pore structure of tight oil reservoirs in Lucaogou Formation, Jimusaer Sag [J]. Petroleum Geology and Recovery Efficiency, 2019, 26(4): 24-32.

[7] 杨正明,骆雨田,何英,等.致密砂岩油藏流体赋存特征及有效动用研究[J].西南石油大学学报:自然科学版,2015,37(3):85-92.
YANG Zhengming, LUO Yutian, HE Ying, et al. Study on occurrence feature of fluid and effective development in tight sandstone oil reservoir [J]. Journal of Southwest Petroleum University: Science & Technology Edition, 2015, 37(3): 85-92.

[8] 曹喆,柳广弟,柳庄小雪,等.致密油地质研究现状及展望[J].

天然气地球科学,2014,25(10):1 499-1 508.
CAO Zhe, LIU Guangdi, LIU-ZHUANG Xiaoxue, et al. Research status on tight oil and its prospects [J]. Natural Gas Geoscience, 2014, 25(10): 1 499-1 508.

[9] 马世忠,张宇鹏.应用压汞实验方法研究致密储层孔隙结构——以准噶尔盆地吉木萨尔凹陷芦草沟组为例[J].油气地质与采收率,2017,24(1):26-33.
MA Shizhong, ZHANG Yupeng. Study on the pore structure of tight reservoir by using method of mercury injection-A case study of the Lucaogou Formation in Jimsar sag, Junggar Basin [J]. Petroleum Geology and Recovery Efficiency, 2017, 24 (1): 26-33.

[10] 闫健,秦大鹏,王平平,等.鄂尔多斯盆地致密砂岩储层可动流体赋存特征及其影响因素[J].油气地质与采收率,2020,27(6):47-56.
YAN Jian, QIN Dapeng, WANG Pingping, et al. Occurrence characteristics and main controlling factors of movable fluid in tight sandstone reservoirs in Ordos Basin [J]. Petroleum Geology and Recovery Efficiency, 2020, 27(6): 47-56.

[11] 惠威,薛宇泽,白晓路,等.致密砂岩储层微观孔隙结构对可动流体赋存特征的影响[J].特种油气藏,2020,27(2):87-92.
HUI Wei, XUE Yuze, BAI Xiaolu, et al. Influence of micropore structure on the movable fluid occurrence in tight sandstone reservoir [J]. Special Oil & Gas Reservoirs, 2020, 27(2): 87-92.

[12] 李忠兴,屈雪峰,刘万涛,等.鄂尔多斯盆地长7段致密油合理开发方式探讨[J].石油勘探与开发,2015,42(2):217-221.
LI Zhongxing, QU Xuefeng, LIU Wantao, et al. Development modes of Triassic Yanchang Formation Chang 7 Member tight oil in Ordos Basin, NW China [J]. Petroleum Exploration and Development, 2015, 42(2): 217-221.

[13] 徐黎明,阎逸群,曹仁义,等.致密油准自然能量开发及产能影响因素研究[J].石化技术,2016,23(1):114-116.
XU Liming, YAN Yiqun, CAO Renyi, et al. A study on division of development stages and productivity-influencing factors for tight oil developed by pseudo-natural energy [J]. Petrochemical Industry Technology, 2016, 23(1): 114-116.

[14] 许洋,杨胜来,张占东,等.致密储层衰竭开采规律研究[J].辽宁石油化工大学学报,2017,37(2):37-41,53.
XU Yang, YANG Shenglai, ZHANG Zhandong, et al. Study on ming failure law of tight reservoir [J]. Journal of Liaoning Shihua University, 2017, 37(2): 37-41, 53.

[15] 向勇,侯力,杜猛,等.中国CCUS-EOR技术研究进展及发展前景[J].油气地质与采收率,2023,30(2):1-17.
XIANG Yong, HOU Li, DU Meng, et al. Research progress and development prospect of CCUS-EOR technologies in China [J]. Petroleum Geology and Recovery Efficiency, 2023, 30 (2): 1-17.

[16] 蒲春生,康少飞,蒲景阳,等.中国致密油藏水平井注水吞吐技术进展与发展趋势[J].石油学报,2023,44(1):188-206.
PU Chunsheng, KANG Shaofei, PU Jingyang, et al. Progress and development trend of water huff-n-puff technology for horizontal wells in tight oil reservoirs in China [J]. Acta Petrolei Sinica, 2023, 44(1): 188-206.

[17] 吉敏.不同驱替模式下致密油水平井注水开发经济效益评价——以J油田M区为例[J].石油地质与工程,2020,34(4):69-73.
JI Min. Economic benefit evaluation of waterflooding development of tight oil horizontal wells under different displacement modes by taking M area in J oilfield as an example [J]. Petroleum Geology and Engineering, 2020, 34(4): 69-73.

[18] 樊建明,王冲,屈雪峰,等.鄂尔多斯盆地致密油水平井注水吞吐开发实践——以延长组长7油层组为例[J].石油学报,2019,40(6):706-715.
FAN Jianming, WANG Chong, QU Xuefeng, et al. Development and practice of water flooding huff-puff in tight oil horizontal well, Ordos Basin: a case study of Yanchang Formation Chang 7 oil layer [J]. Acta Petrolei Sinica, 2019, 40(6): 706-715.

[19] 苏玉亮,陈征,唐梅荣,等.致密储层不同驱替方式下超临界CO_2蓄能返排效果实验研究[J].油气地质与采收率,2020,27(5):79-85.
SU Yuliang, CHEN Zheng, TANG Meirong, et al. Experimental study of supercritical CO_2 storage and flowback under different displacement methods in tight reservoirs [J]. Petroleum Geology and Recovery Efficiency, 2020, 27(5): 79-85.

[20] 王香增,杨红,王伟,等.低渗透致密油藏CO_2驱油与封存技术及实践[J].油气地质与采收率,2023,30(2):27-35.
WANG Xiangzeng, YANG Hong, WANG Wei, et al. Technology and practice of CO_2 flooding and storage in low-permeability tight reservoirs [J]. Petroleum Geology and Recovery Efficiency, 2023, 30(2): 27-35.

[21] 管奕婷,郭平,汪周华,等.英东油田注气驱室内实验研究[J].重庆科技学院学报:自然科学版,2014,16(4):46-50.
GUAN Yiting, GUO Ping, WANG Zhouhua, et al. Laboratory experimental study of gas injection in Yingdong Oilfield [J]. Journal of Chongqing University of Science and Technology: Natural Sciences Edition, 2014, 16(4): 46-50.

[22] 许清华.东河塘油藏烃气混相驱机理及混相特征研究[D].成都:西南石油大学,2017.
XU Qinghua. The mechanism and characteristic study of the gas miscible flooding in Donghetang oil reservoir [D]. Chengdu: Southwest Petroleum University, 2017.

[23] 李德祥,张亮,崔国栋,等.新疆油田低渗透区块空气驱实验研究[J].科学技术与工程,2015,15(9):180-184.
LI Dexiang, ZHANG Liang, CUI Guodong, et al. Experimental study of air injection for IOR in low permeability reservoir of Xinjiang Oilfield [J]. Science Technology and Engineering, 2015, 15(9): 180-184.

[24] PU W, WEI B, JIN F, et al. Experimental investigation of CO_2 huff-n-puff process for enhancing oil recovery in tight reservoirs [J]. Chemical Engineering Research and Design, 2016, 111: 269-276.

[25] 刘鹏刚.轻质油藏注空气氧化机理及驱油实验研究[D].成都:西南石油大学,2018.
LIU Penggang. Experimental study on oil oxidation mechanism

and displacement efficiency during air injection process in light oil reservoir [D]. Chengdu: Southwest Petroleum University, 2018.

[26] HUANG Xing, LI Ang, LI Xiang, et al. Influence of typical core minerals on tight oil recovery during CO_2 flooding using the nuclear magnetic resonance technique [J]. Energy & Fuels, 2019, 33(8): 7 147-7 154.

[27] ZHOU Xiang, YUAN Qingwang, ZHANG Yizhong, et al. Performance evaluation of CO_2 flooding process in tight oil reservoir via experimental and numerical simulation studies [J]. Fuel, 2019, 236: 730-746.

[28] LI Xiang, XUE Junjie, WANG Yanqing, et al. Experimental study of oil recovery from pore of different sizes in tight sandstone reservoirs during CO_2 flooding [J]. Journal of Petroleum Science and Engineering, 2022, 208: 109740.

[29] LIU Yueliang, RUI Zhenghua, YANG Tao, et al. Using propanol as an additive to CO_2 for improving CO_2 utilization and storage in oil reservoirs [J]. Applied Energy, 2022, 311: 118640.

[30] 夏金娜. 致密油藏泡沫辅助空气驱技术研究[D]. 青岛:中国石油大学(华东),2013.
XIA Jinna. Study on technique of foam-assisted air flooding for compact reservoir [D]. Qingdao: China University of Petroleum (East China), 2013.

[31] 郭德明,潘毅,孙扬,等. 低渗稠油油藏降黏剂-CO_2复合驱提高采收率机理研究[J]. 油气藏评价与开发,2022,12(5):794-802.
GUO Deming, PAN Yi, SUN Yang, et al. EOR mechanism of viscosity reducer-CO_2 combined flooding in heavy oil reservoir with low permeability [J]. Petroleum Reservoir Evaluation and Development, 2022, 12(5): 794-802.

[32] 钱川川,骆飞飞,蒋志斌,等. 注空气提高低渗透油藏采收率实验及低温氧化反应特征[J]. 大庆石油地质与开发,2022,41(1):97-103.
QIAN Chuanchuan, LUO Feifei, JIANG Zhibin, et al. EOR experiment of air injection and low-temperature oxidation reaction characteristics in low-permeability reservoirs [J]. Petroleum Geology & Oilfield Development in Daqing, 2022, 41 (1): 97-103.

[33] GAJBHIYE R. Effect of CO_2/N_2 mixture composition on interfacial tension of crude oil [J]. ACS Omega, 2020, 5 (43): 27 944-27 952.

[34] ZHANG Shiyang, SHE Yuehui, GU Yongan. Evaluation of polymers as direct thickeners for CO_2 enhanced oil recovery [J]. Journal of Chemical & Engineering Data, 2011, 56(4): 1 069-1 079.

[35] 毕佳琪. 低渗特低渗油层富气-氮气复合驱研究[D]. 大庆:东北石油大学,2020.
BI Jiaqi. Research on rich gas nitrogen composite flooding in low permeability and extra low permeability reservoir [D]. Daqing: Journal of Northeast Petroleum University, 2020.

[36] 陈涛平,毕佳琪,孙文. 混相和非混相富气-N_2复合驱试验研究[J]. 长江大学学报:自然科学版,2021,18(4):57-65.
CHEN Taoping, BI Jiaqi, SUN Wen. The experimental study on miscible and immiscible rich gas-N_2 compound flooding [J]. Journal of Yangtze University: Natural Science Edition, 2021, 18(4): 57-65.

[37] HAWTHORNE S B, MILLER D J, GRABANSKI C B, et al. Measured crude oil MMPs with pure and mixed CO_2, methane, and ethane, and their relevance to enhanced oil recovery from middle Bakken and Bakken shales [C]. Calgary: SPE Unconventional Resources Conference, 2017.

[38] 黄兴,李响,张益,等. 页岩油储集层二氧化碳吞吐纳米孔隙原油微观动用特征[J]. 石油勘探与开发,2022,49(3):557-564.
HUANG Xing, LI Xiang, ZHANG Yi, et al. Microscopic production characteristics of crude oil in nano-pores of shale oil reservoirs during CO_2 huff and puff [J]. Petroleum Exploration and Development, 2022, 49(3): 557-564.

[39] 肖佃师,卢双舫,陆正元,等. 联合核磁共振和恒速压汞方法测定致密砂岩孔喉结构[J]. 石油勘探与开发,2016,43(6):961-970.
XIAO Dianshi, LU Shuangfang, LU Zhengyuan, et al. Combining nuclear magnetic resonance and rate-controlled porosimetry to probe the pore-throat structure of tight sandstones [J]. Petroleum Exploration and Development, 2016, 43(6): 961-970.

[40] 李楚雄,申宝剑,卢龙飞,等. 松辽盆地沙河子组页岩孔隙结构表征——基于低场核磁共振技术[J]. 油气藏评价与开发,2022,12(3):468-476.
LI Chuxiong, SHEN Baojian, LU Longfei, et al. Pore structure characterization of Shahezi Formation shale in Songliao Basin: Based on low-field nuclear magnetic resonance technology [J]. Petroleum Reservoir Evaluation and Development, 2022, 12 (3): 468-476.

编辑 单体珍