引用格式：张志超，柏明星，杜思宇. CO_2驱油及埋存一体化技术应用研究进展[J]. 世界石油工业, 2025, 32(1): 100-107.
ZHANG Zhichao, BAI Mingxing, DU Siyu. Research progress of CO_2 displacement and storage integration technology[J]. World Petroleum Industry, 2025, 32(1): 100-107.

CO_2驱油及埋存一体化技术应用研究进展

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摘要：将二氧化碳（CO_2）注入到非常规油藏中不仅可提高采收率，同时能实现CO_2埋存，成为当前“双碳”愿景下的研究热点。在分析CO_2驱油提高采收率机理的基础上，对比分析了CO_2连续和间歇注气驱油提高油藏采收率的规律，总结了CO_2在油藏驱油及埋存一体化研究进展。CO_2驱油提高采收率机理主要是利用了CO_2在油藏孔隙内的传质、溶解及扩散作用。CO_2驱油过程中压力的增加能够促进CO_2与原油之间的传质，降低CO_2与油间界面张力，提高原油采收率。油藏中发育复杂裂缝能促进CO_2与原油间传质，降低渗流阻力，提高CO_2混相吞吐驱油效果。相比CO_2非混相驱油，混相驱油过程中CO_2与地层原油之间传质更加充分，同时能提高油藏大小孔内原油的动用程度。连续气驱存在过早突破的弊端，有效增油期短。CO_2间歇注气能够延缓生产井的CO_2突破时间，CO_2混相吞吐提高油藏采收率的效果更好。针对CO_2驱油过程中常出现的气窜、沥青质沉淀等问题，未来应该加强对CO_2驱油的流度控制和沥青质沉淀防治技术的研究。

关键词：CO_2驱油；驱油机理；采收率；CO_2油藏埋存
中图分类号：TE357.7　　**文献标识码：**A
文章编号：1006-0030(2025)01-0100-008　　**DOI:** 10.20114/j.issn.1006-0030.20240315002

Research progress of CO_2 displacement and storage integration technology

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Abstract: CO_2 injection into unconventional reservoirs can not only improve oil recovery but also achieve CO_2 storage, which has become a research hotspot under the "dual carbon" vision. Based on the analysis of the mechanism of CO_2 flooding to enhance oil recovery, the law of continuous and intermittent CO_2 gas flooding to improve oil recovery was compared, and the research progress of CO_2 integration in oil displacement and storage was summarized. The mechanism of enhanced oil recovery by CO_2 flooding is mainly based on the mass transfer, dissolution and diffusion of CO_2 in reservoir pores. The increase of pressure in the process of CO_2 flooding can promote the mass transfer between CO_2 and crude oil, reduce the interfacial tension between CO_2 and oil, and improve the oil recovery. The development of complex fractures in reservoir can promote mass transfer between CO_2 and crude oil, reduce seepage resistance, and improve the effect of CO_2 miscible huff and huff displacement. Compared with CO_2 immiscible flooding, mass transfer between CO_2 and formation crude oil is more complete during miscible flooding, which can improve the oil production degree in large pores. Continuous gas drive has the disadvantage of premature breakthrough and short effective oil increase period. Intermittent CO_2 gas injection can delay the CO_2 breakthrough time of production Wells, and the effect of CO_2 miscible huff and huff to improve oil recovery is better. In view of the problems such as gas channelling and asphaltene precipitation which often occur in the process of CO_2 flooding, it is necessary to strengthen the research on mobility control and asphaltene precipitation prevention technology in the future.

Keywords: CO_2 flooding; oil displacement mechanism; oil recovery; CO_2 reservoir sequestration

0　引言

当前中国正面临石油资源需求的不断加大和CO_2排放量逐年增加两大难题。2023年，中国对外石油资源依存度已经超过73%，而CO_2年排放量已经达到125.1×10^8 t，占世界总排放量的34%，位居

收稿日期：2024-03-15　　**修回日期：**2024-10-02
基金项目：国家自然科学基金项目“枯竭油藏型储气库二氧化碳作垫层气机理及注采动态规律研究”（52174020）
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世界第1位[1]。中国的中高渗透老油田已经进入高含水开发后期。虽然一次、二次和三次提高采收率技术的应用取得了一定的提产成效，但原油供给仍严重不足。中国低渗透油藏的储量巨大，而应用常规驱油技术如水驱、聚合物及三元驱等对该类油藏的开发效果并不理想。因此，提高低渗透等非常规油藏的采收率是保障中国原油有效供给的一项重要措施。

CO_2用于低渗透油藏驱油能够提高油藏采收率早已经被证实[2–4]。此外，CO_2注入低渗透油藏驱油不仅能够提高油藏采收率，同时也能够实现CO_2地质埋存[5–6]，这对保障中国石油资源的有效供给和CO_2的净减排具有重要意义。

Zhao等[7]、Gamadi等[8]和Hawthorne等[9]认为CO_2能够提高低渗油藏采收率的主要原因是CO_2较好的扩散、溶解和传质作用。相较于水，CO_2在油藏孔隙中具有更强的流动性，因此能够进入更小的油藏孔隙中进行驱油，提高油藏采收率。CO_2在油藏中驱油按注入方式划分可分为连续注气驱油和间歇注气驱油；按照CO_2驱油过程中的相态变化又分为混相驱油和非混相驱油。当前普遍认为CO_2混相驱油比非混相驱油能够更好地提高油藏采收率和CO_2在油藏中的埋存。但CO_2驱油技术当前应用尚在探索阶段，对CO_2油藏驱油和埋存的一体化应用研究也刚刚起步。因此，本文根据CO_2驱油和埋存的技术发展现状，对当前CO_2驱油和埋存技术、机理和规律进行系统分析，旨在为中国应用CO_2开发低渗透等非常规石油资源和“双碳”目标的愿景实现提供一定的理论借鉴。

1 CO_2注入油藏提高采收率机理

CO_2能够提高油藏采收率主要取决于其自身性质和其注入油藏后对油藏和流体性质的改善。CO_2从注入井注入到油藏过程中随着温、压变化改变自身相态[10]（见图1），不同相态CO_2的物性变化如表1。当压力高于7.38 MPa、温度高于31.2 ℃，CO_2转变为超临界状态。超临界CO_2的密度接近液体，黏度接近于气体，其扩散系数相对较高。因此，CO_2注入低渗透等非常规油藏进行驱油时，其对油藏的补能速度较快。CO_2在地层原油中的溶解度较高，Gao等[11]、Davarpanah等[12]对CO_2与原油溶解、降黏相关性进行统计，发现CO_2在原油中的溶解度可达60.9 m^3/m^3，溶解CO_2后可使原油体积膨胀10%～40%、黏度降低30%～99%。温度越高，CO_2对原油的膨胀和降黏能力越好。压力越高，CO_2在地层油中的溶解度越高，CO_2与原油之间的传质作用越强烈。CO_2在地层原油中溶解的同时会在地层水溶解，一方面能够降低地层水的pH值，增加水相溶解地层岩石矿物的能力，增加水相密度，改善了油水流度比；另一方面，CO_2溶解于地层水能够降低油水界面张力。王欣[13]应用悬滴法和PVT实验研究发现随着CO_2溶解到原油和水中饱和压力的提高，油水之间的界面张力不断下降。当CO_2注入压力提升后，CO_2与地层原油之间的传质会变得更加剧烈（见图2）。随着实验压力逐渐增加，CO_2与地层原油间的相界面逐渐变得模糊；当实验压力接近或达到最小混相压力后，CO_2与地层油间相界面消失，变成混相状态。同时油相体积产生了较大的膨胀，这对提高油藏采收率是非常有利的。

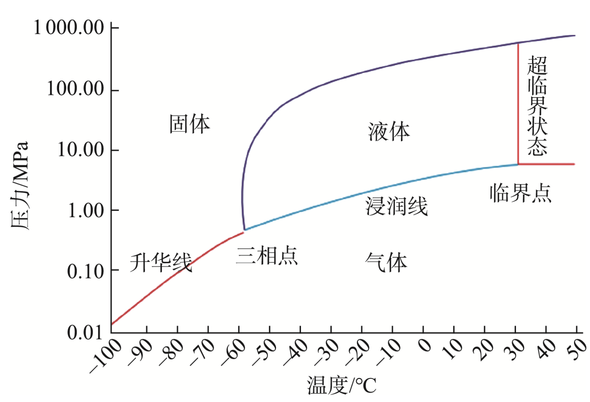

图1 CO_2的相态变化
Fig.1 Phase changes of CO_2

表1 不同相态CO_2性质
Tab.1 Properties of CO_2 in different phase states

CO_2相态	密度/（$kg·m^{-3}$）	黏度/（mPa·s）	扩散系数/（10^6 $m^2·s^{-1}$）
气态	0.6～2	0.01～0.3	10～40
液态	600～1 600	0.2～3	0.000 2～0.002
超临界	200～500	0.01～0.03	0.07

CO_2在油藏中驱油时会诱发CO_2-水-岩石相互作用，也能够改善储层物性，增强油气渗流和采出

能力[14]。Iglauer[15]、Zhang等[16]、Song等[17]和Gamadi等[8]基于CO_2-水-岩石相互作用实验证实：CO_2-水-岩石相互作用能够在油藏孔隙壁面上形成更多亲水性的石英和高岭石矿物，导致油藏孔隙亲水性增强。Rathnaweera等[18]通过1.5年的CO_2-咸水-砂岩反应实验发现长期CO_2-水-岩石反应不仅使岩石中的方解石、长石溶解，石英和高岭石也会发生溶解，导致岩心渗透率增加了10%以上。另一方面，在低渗透油藏实施CO_2压裂形成的裂缝比水力压裂形成的裂缝更加复杂，储层改造效果更好。Ishida等[19]分别应用相关函数和声波监测数据计算出当用超临界和液态CO_2进行花岗岩人工压裂时，裂缝的分形维数分别为2.4和2.15，表明低黏度的超临界造裂缝更为复杂。超临界CO_2压裂门槛值仅为水力压裂起裂压力的70%左右，为采用油基压裂液压裂的50%左右。

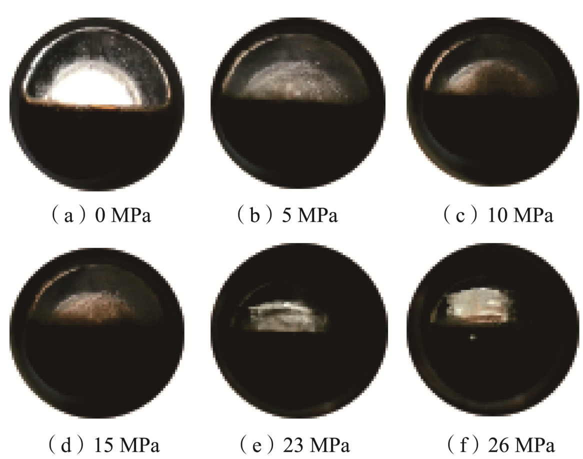

图2 不同压力下CO_2和油间传质和混相过程
Fig.2 Mass transfer and miscible process between CO_2 and oil under different pressures

2 CO_2驱油提高油藏采收率技术

2.1 CO_2连续注气驱油

CO_2连续注气驱油包括：非混相驱油、近混相驱油和混相驱油。混相驱油的效果要好于近混相驱油和非混相驱油。

2.1.1 CO_2非混相驱油

李阳[20]提出了CO_2混相能力（CO_2驱压与最小混相压力的比值）来评价CO_2驱油效果（见图3），发现随着CO_2混相能力的增加，细管的驱油效率不断提高。CO_2非混相驱油指驱压低于最小混相压力的CO_2驱油方式。陈欢庆[21]、李宾飞等[22]认为随着CO_2驱替压力的增加，CO_2向油和水中的溶解度增加，CO_2与油之间的传质增强，CO_2与油及油与水之间界面张力降低，油藏采收率得到提高。郎东江等[23]在35～60 ℃下进行CO_2驱油页岩核磁在线实验证实，CO_2驱油采收率会随着温度升高先升高后降低，存在最佳温度。温度的升高会产生2方面作用，一方面是CO_2在地层油中溶解度会下降，导致CO_2驱油效果变差；另一方面温度升高会促进CO_2与油间传质，这对增强CO_2驱油效果是有利的。因此，温度对CO_2驱油效果的影响主要取决于这2种作用的强弱。此外，油藏渗透率和裂缝发育对CO_2非混相驱油效果也存在一定影响，王香增[24]以延长油田现场实验分析证实，在1～16 mD的低渗透油藏，随着油藏渗透率的增加，见气前CO_2驱油的采出程度增幅变小，但最终采收率随着渗透率增加先增加后减小。中高渗油藏CO_2非混相驱油时气窜严重，不适合应用该技术。CO_2连续驱油过程中会在油藏内诱发CO_2-水-油-岩石相互作用，导致油藏的性质和油水的性质改变。陈欢庆[21]认为CO_2注入到油藏中会使油藏岩石更加亲水，随着接触时间的延长，岩石的亲水性越好。油藏岩石亲水性的改善会降低CO_2或水驱油时的黏附功，提高驱油效率。

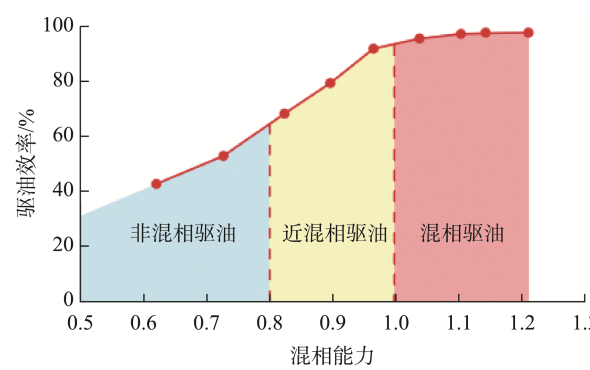

图3 CO_2与油间的混相能力与细管中油采收率间关系
Fig.3 The relationship between the miscibility of CO_2 with oil and the oil recovery in thin pipes

2.1.2 CO_2近混相驱油

当前一些油藏的温压条件很难满足CO_2与地层油之间的混相驱油条件。此外，综合考虑设备

的安全性，一些学者提出进行CO_2近混相注入驱油技术。陈浩等[25]、张贤松等[26]通过细管实验结合模拟分析，认为近混相驱油发生在一个接近最小混相压力的压力区间。在该压力区间内，CO_2驱油采收率在85%～95%之间，对应的CO_2与原油之间的界面在0.01～0.05 mN/m，能够取得较好的驱油效果。近混相驱油时CO_2纯度下限为64%。陈浩等[27]通过细管实验分析了C_2～C_6组分加入CO_2中对近混相驱油的影响，发现轻质组分的加入能够降低达到近混相时需要的CO_2纯度。在CO_2纯度不变时，能够降低近混相区间压力。张谦伟等[28]通过CO_2驱替细管实验证实近混相驱油能够取得一定的低渗透油藏采收率。

2.1.3　CO_2混相驱油

相比CO_2近混相驱油和非混相驱油，CO_2混相驱油对低渗透油藏的驱油效果最好，能够同时提高CO_2在油藏大孔和小孔内的驱油效率。龙晃等[3]认为CO_2混相驱油能够提高油藏采收率主要是由于混相过程中降低了CO_2与原油之间的界面张力，促进了CO_2与油间传质和扩散作用。Cai等[29]、李蕾等[30]通过低渗透和超低渗透粉砂岩的CO_2非混相和混相驱油实验证实，CO_2驱替后油藏岩心采收率分别从32.6%提高至69.4%和53.4%至72.9%。黄兴等[31]通过CO_2混相驱油和非混相驱油的核磁共振T_2谱在岩心测试实验证实，CO_2混相驱油相比非混相驱油降低了岩心小孔的产油孔隙下限，提高了岩心小孔隙内油的动用程度，但混相驱油过程会促使油藏内原油中沥青质的沉淀量增多，影响驱油效果。

2.2　CO_2间歇注气驱油

CO_2间歇注气驱油方式包括CO_2吞吐驱油、CO_2周期注气及CO_2水气交替（CO_2-WAG）驱油技术。相比CO_2连续注气驱油，间歇性CO_2注入过程能够有效降低CO_2过早在生产井突破产生的不利影响，提高波及体积，特别是对于复杂裂缝发育的油藏。Li等[32]、王欢等[33]通过不同的CO_2注入方式下的驱油实验发现，CO_2周期注气比CO_2-WAG的驱油效果更好，而连续注气驱油的效果最差。

2.2.1　CO_2非混相吞吐

Wan等[34]分析美国巴肯页岩油藏CO_2吞吐情况发现，与水驱相比CO_2非混相吞吐驱油提高油藏采收率22.5%。张佳亮等[35]对吉木萨尔泸草沟组页岩进行了渗吸和CO_2吞吐过程中的核磁共振测试，发现CO_2吞吐相比渗吸能够动用更大的孔隙区间，非混相吞吐能够提高采收率2%～10%。

CO_2吞吐提高油藏采收率主要与油藏温度、压力、吞吐轮次、焖井时间及原油自身性质相关，而油藏的渗透率对CO_2吞吐采收率影响较小[36–38]。随着地层压力下降和油藏温度的降低，CO_2在油相中的溶解度增加，改善地层油的性质效果更好，有利于油藏采收率的提高。Alfarge等[37]、Li等[39]发现CO_2非混相吞吐提高油藏采收率的效果主要是在前3个周期，之后对油藏采收率的提高效果会逐渐变差。张志超等[40]、Alavian[41]发现油藏中裂缝越复杂，CO_2与基质内原油之间的传质和CO_2向基质的扩散效果越好，CO_2吞吐驱油效果越好。同时，增加闷井时间能够促进油气传质，更好地改善油的性质，提高油藏采收率。但闷井时间过长会促使原油中沥青质的沉淀量增大，堵塞油藏孔隙，影响CO_2驱油效果。

2.2.2　CO_2混相吞吐

李斌会等[42]基于CO_2混相吞吐页岩过程中的核磁共振测试分析，发现CO_2混相吞吐能够降低油藏孔隙的动用下限至20 nm，可以提高油藏小孔隙内原油的动用程度。Wang等[43]基于CO_2混相焖井周期注气与混相驱油对比实验，发现混相焖井过程中强化了CO_2与油相间传质，促进了CO_2进入更小油藏孔隙中驱油并能抑制CO_2过早在岩心中突破，与CO_2混相驱油相比能够提高采收率11%以上，同时发现CO_2混相周期注气虽然能提高油藏采收率，但会导致岩心中形成更多的沥青质沉淀。因此，在进行CO_2混相吞吐驱油时，要综合平衡CO_2门井导致的沥青质沉淀影响和CO_2对地层原油性质改善的影响。

师调调等[44]对比了CO_2混相和非混相吞吐对页岩不同孔径内原油采出程度的影响，发现CO_2混相吞吐能够动用更小的纳米级孔隙中的原油，与非混相吞吐相比能够提高采收率8.44%。Wan等[34]发现CO_2混相吞吐开采页岩油时能够提高油藏采收率17.5%。Li等[39]发现与非混相吞吐相比，CO_2混相吞吐能够提高页岩油采收率10%，焖井时间可缩短5 h。CO_2混相吞吐过程中，CO_2能够更好地与油之间发生传质，为储层的蓄能效果更好，开采过程中有更充足的驱油动力。

3 CO_2驱油及埋存一体化技术应用研究现状

3.1 CO_2驱油及埋存一体化措施

CO_2驱油及埋存一体化（CCS-EOR）是指将CO_2注入非常规油藏进行混相或非混相驱油，优化参数提高油藏采收率的同时，实现CO_2在油藏中的埋存率最大化，从而取得经济和环境双重效益[45]。CO_2和原油的密度差异、黏度差异及油藏含水率对CO_2驱油和埋存有重要的影响，导致CO_2在驱油过程中常发生气体突破、黏性指进、重力超覆等作用，影响油藏的采收率和气体埋存效果[46–47]。对于CO_2在油藏中驱油和埋存规律的研究，王欢等[33]应用数值模拟方法分析了低渗透油藏CO_2-WAG和连续注气驱油提高采收率及CO_2埋存效果，发现水气交替驱提高油藏采收率和埋存效果比连续注气效果好很多，水气交替可多提高油藏采收率15%以上，可实现30.88% PV（Pore Volume）的CO_2地下埋存量。Assef等[48]分析了CO_2循环注气驱油过程中的渗流行为，认为CO_2循环注气驱油过程中存在渗流方向转变，产生了相渗滞后效应，导致CO_2在油藏中的埋存量增加。高冉等[49–51]则提出了CO_2驱油及埋存一体化因子f来优化在油藏连续注CO_2驱油和埋存，认为CO_2驱油初期，应该对驱油项赋予较大的权重因子，注重驱油效果；当生产井气窜后，应该对CO_2埋存项赋予较大的权重因子。姚约东等[52]应用数值模拟的方法，研究了CO_2混相驱油效果和埋存效率，发现CO_2混相驱油和埋存效果要好于非混相驱油，混相驱油时油藏采收率能达到29.2%，CO_2储存系数能达到7.76左右。此外，CO_2在油藏内驱油时，CO_2-水-油-岩石间反应会改变岩石性质，对驱油效果和埋存效率会产生影响。Cui等[53]通过CO_2与新疆砂岩油田岩心的水岩反应实验，发现CO_2注入岩心中后能够改善低油藏岩石的渗透率，从而提高了CO_2在油藏的驱油和埋存效率。

3.2 CO_2驱油及埋存一体化矿场应用

目前全球较大规模的CCS项目共28个，年封存CO_2能力为3 816×10^4 t，其中22个为封存与驱油项目，年CO_2封存能力[54–55]为2 926×10^4 t。已知的最早且效果显著的CO_2油藏驱油和埋存的项目是加拿大的Weyburn断陷油田项目。该油田由于地层能量下降，产量从1964年的45 000 bbl*/d下降到1980年的15 000 bbl/d。为提高油藏采收率，从2000年开始在该油藏进行CO_2-EOR项目，实现日注气5 000 t/d，使原油产量上升至25 000 bbl/d，并保持了较长时间的原油稳产效果[56–57]。到2017年该油田已经累计向油藏中注入了2 700×10^4 t的CO_2 [57]。

2020年双碳目标的提出为中国进行CO_2在油藏中的驱油和埋存（CCUS-EOR）发展提供了重大机遇。目前中国石油天然气集团有限公司已经建成了大庆低渗透、吉林特低渗透、长庆超低渗透和新疆砾岩4大CO_2驱油与埋存先导性示范区[5]。吉林油田累计注入CO_2共452×10^4 t，CO_2混相驱油过程中地层能量有效恢复，采出井含水普遍下降，驱油效果较好。实践中发现CO_2混相驱油对高含水低渗透油藏的驱油效果也较明显。以吉林油田综合含水率为91.6%的低渗透黑79小井距区块2012年注CO_2混相驱油效果分析，到2021年已经累计向油藏中注入CO_2量32.7×10^4 t（1.05倍油藏孔隙体积），阶段提高原油采收率23%以上，单井增产5倍以上[5]。大庆油田树101特低渗透区块进行CO_2非混相驱油提高油藏采收率10%以上，实现20×10^4 t的CO_2油藏地下埋存。

4 结论及认识

（1）CO_2驱油提高油藏采收率的机理主要是CO_2与原油之间的传质、溶解和向油藏中扩散。在注CO_2驱油过程中，压力的增加能够促进CO_2与原油之间的传质，降低CO_2与油间界面张力，提高原油采收率。油藏中发育复杂裂缝能促进CO_2与油间传质，降低渗流阻力，提高CO_2混相吞吐驱油效果。

（2）CO_2驱替方式和参数与油藏的匹配性对提高CO_2在油藏中驱油和埋存一体化效果有重要的影响。连续CO_2混相驱油能够达到较高的油藏采收率，但CO_2在油藏中的埋存效果不如CO_2间歇注气效果好。

（3）CO_2驱油过程中常出现的气窜、沥青质沉淀等问题，会影响CO_2驱油和埋存效果。因此，对CO_2驱油的流度控制和沥青质沉淀防治技术的研究

* 非法定计量单位，1 bbl=0.137 t，下同

将是未来需要攻关的重点。此外，对于CO_2驱油及埋存参数的协同优化研究对提升CO_2油藏驱油和埋存效果也具有重要的意义。

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