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CO_2地质封存泄漏研究进展

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摘　要：CO_2地质封存（GCS）是一项将CO_2注入并且永久封存于地下含水层或废弃油气储层等地质体内的CO_2减排技术。由于场地地质条件和人类开发活动导致的不确定性，注入储层的CO_2可通过泄漏废弃井、断层或裂缝以及盖层的“薄弱带”等途径发生泄漏。基于对国内外文献的广泛调研，综述了GCS泄漏及封存安全的研究进展。CO_2沿钻井泄漏一般是因为化学或力学作用导致CO_2沿钻井环空水泥、井筒桥塞或围岩破碎带发生泄漏。CO_2注入储层可能导致盖层破裂，激活原本闭合的断层或断层面滑动。CO_2沿断层/裂缝泄漏主要受有效渗透率、裂缝开度等因素影响。盖层泄漏的方式可归纳为渗透泄漏、扩散泄漏和沿裂隙泄漏3种。CO_2透过盖层的扩散泄漏对于大时空尺度CO_2地质封存泄漏评估不应忽视。CO_2泄漏通常会导致受影响的含水层内地下水的pH值减小、盐度升高、离子增多等地球化学响应，甚至存在自由态CO_2。含水层内流体压力和地球化学特征可用于有效监测封存CO_2、咸水与其他流体的泄漏。GCS泄漏研究目前还十分有限，我国尤其缺乏泄漏的定量研究。

关　键　词：CO_2捕集和封存(CCS)；CO_2地质封存(GCS)；泄漏；封存安全；咸水层
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Progress in leakage study of geological CO_2 storage

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Abstract: Geological CO_2 storage(GCS) is a technology for carbon emission-cut, by injecting anthropogenic CO_2 for long-term storage into underground aquifers or depleted hydrocarbon reservoirs. Because of the uncertainties induced by geological site condition and human activities, injecting CO_2 into the reservoir may lead to leakage through abandoned wells, faults, fractures, and the "weak zones" in the caprock. A comprehensive review on GCS-associated leakage and safety issues was made, based on an extensive investigation of both domestic and international literature. Leakage from a wellbore may occur through the annulus cement, well plugs or the fracture zone of the contact rocks, due to chemical corrosion and/or mechanical failure. Injecting massive amount of CO_2 into reservoirs may induce fractures in the seal, activation of potential faults and their slip. Leakage of CO_2 along faults/fractures is mainly affected by factors such as the effective permeability and fracture aperture. Leakage through the caprock can be seepage, diffusive or one that occurs through fissures. The diffusive leakage through the caprock should not be neglected when assessing leakage for large-scale GCS projects. Leakage of CO_2/brine into the overlying aquifer causes its variation in geochemistry such as a lower pH, higher salinity, more ions, or even the presence of free CO_2. Monitoring of pressure and sampling in the overlying aquifer can be effective to identify CO_2 leakage from the underlying reservoir. Research on GCS-associated leakage is very limited, with a particular lack of quantitative studies in China.

Keywords: CO_2 capture and storage(CCS); geological CO_2 storage(GCS); leakage; safety of storage; saline aquifer

1　引　言

CO_2捕集和封存（CCS）是一项将化石燃料发电厂等企业产生的CO_2捕集起来，运输并注入筛选的地质体内，以实现与大气隔离的永久CO_2封存技术。CO_2地质封存（GCS）是CCS中技术成熟度最

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高、最具有直接减排效果的技术，现阶段确定的主要地质封存储层有废弃油气田、煤层和深部咸水层三类。由于深部咸水层的水一般不能作为饮用水，且分布广泛、总体储存容量大，利用深部咸水层进行GCS被认为最具潜力[1]。国际上已开展了不同规模的GCS项目，如挪威的Sleipner项目[2]和Snohvit项目[3]、加拿大的Weyburn项目[4]、阿尔及利亚的Salah项目[5]以及德国的Ketzin项目[6]等。2011年5月至2015年4月中国的神华集团在鄂尔多斯盆地陈家村场地成功实施的30万吨CO_2咸水层封存（以下称“神华CCS项目”）是我国首个纯公益且全流程示范的煤基CO_2咸水层封存项目[7–9]。

随着GCS项目在世界各地的广泛开展，其技术的安全性和泄漏风险越来越引起关注[10]。2011年1月11日，加拿大萨斯喀彻温省的一对夫妇召开新闻发布会声称Weyburn GCS项目封存地下的CO_2已经泄漏到自家的农场，引起公众媒体和科学界对GCS安全性的高度关注[11]。由于场地地质条件和人类开发活动导致的不确定性，注入储层的CO_2一般可通过 3 种途径发生泄漏，即泄漏井、断层或裂缝以及盖层的“薄弱带”(局部高渗带）[12–15]。GCS项目的安全评估必须全面调查场地可能存在的泄漏途径，分析CO_2沿这些潜在泄漏途径发生逃逸的机制，评估泄漏发生的概率（风险)，预测泄漏发生的可能后果，最后提出避免或阻止泄漏发生的措施。尤其是大规模GCS项目，CO_2羽体及污染物在储层中的扩散范围可能很大，这种情况下CO_2通过上述3种途径发生泄漏的机会更大。

2 CO_2沿钻井泄漏

CO_2沿钻井迁移常常是GCS场地的主要泄漏途径[15–16]，是由于许多适合GCS的地层往往位于油气开发相对集中的区域，场地附近可能存在大量废弃油气井（泄漏风险相对较高)，即使不位于油气开发区域，对于大规模GCS项目或低渗场地，也可能需要咸水抽汲井或降压井，区内的各种钻井可能贯穿盖层而成为GCS项目泄漏的通道。

CO_2沿钻井泄漏一般是因为化学或力学作用导致CO_2沿钻井环空水泥、井筒桥塞或围岩破碎带发生泄漏[13, 17–18]。化学作用是由于当地下水中CO_2含量超过2%时对套管和环空水泥具有弱腐蚀性，CO_2含量大于6%时则具有强腐蚀性。力学作用一般因为CO_2注入引起温度降低或注入压力过大，导致套管收缩或水泥环开裂、密封性丧失而致[19–20]。CO_2沿废弃井泄漏有诸多文献[21–23]采用解析法/半解析法进行了定量研究，通过解析或半解析模型预测CO_2羽体的扩散范围，计算CO_2到达泄漏井的时间和沿废弃井泄漏的速率，估计泄漏CO_2羽体在上覆含水层中的扩散范围。由于解析法或半解析法无法考虑CO_2在泄漏井中因迅速膨胀导致的温度变化等复杂过程，应用受限。为此，GCS的泄漏很多借助数值模拟进行研究诸如加拿大阿尔伯塔的天然气泄漏场地、德国Altmark天然气田EGR项目的CO_2沿废弃井泄漏模拟等[24]。数值解和解析解都表明，CO_2泄漏存在一个最大泄漏速率，到达最大泄漏速率后泄漏速率减小。对于场地地质条件和废弃井数据导致的泄漏不确定性，目前主要运用蒙特卡罗方法，将泄漏井的有效渗透率、泄漏点埋深等作为模型不确定性，对大量随机实现模型进行运算，以分析泄漏发生的概率和可能的最大泄漏速率，在这方面的研究有Kopp等[25–27]。

3 CO_2沿断层/裂缝泄漏

向深部咸水层大规模注入CO_2会导致地层压力过高和应力状态发生改变，可能使盖层产生裂缝，激活原本闭合的断层或断层面滑动。CO_2沿断层/裂缝泄漏的研究主要关注泄漏的动态过程和机理[28–34]、泄漏的影响因素[35]、泄漏风险和后果[36]。研究的方法可概括为解析法、半解析法[37–39]和数值模拟法[13, 40–42]。CO_2泄漏的影响因素研究通常采用模型敏感性分析实现。现有研究表明，CO_2沿断层/裂缝泄漏主要受有效渗透率、裂缝开度、岩层非均质性、CO_2注入深度等因素影响，其中渗透率通常是影响CO_2和咸水泄漏速率的最敏感因素[41, 43–47]。

4 CO_2透过盖层泄漏

GCS的有效性和可持续性关键取决于上覆盖层的密封完整性，与盖层的岩性（主要是泥质含量)、韧性、盖层厚度、连续性及分布面积有关[15]。盖层泄漏的方式可归纳为渗透泄漏、扩散泄漏和沿裂隙泄漏[13, 15, 48] 3种。由于盖层通常以泥质含量高、沉积厚度大为特点，一般研究中均假设盖层不可渗透。故此泄漏的研究也多假设泄漏集中发生在被研究的断层或泄漏井处。然而，在两种情况下CO_2透过盖层本身的泄漏不应忽略：(1) 盖层渗透率相对较高，意味着盖层也许发育离散裂隙或小裂缝，此时CO_2很可能透过盖层既发生渗透泄漏也发生扩散泄漏，前者发生在裂缝网络中，而后者发生在盖层基质中[49–50]。(2）盖层比较完整且渗透率低，但储层压力高且消散慢，问题涉及尺度大。有研究表明，尽

管盖层渗透率极低，但储层咸水在高压条件下仍然会以十分缓慢的“扩散”方式向上覆或下伏含水层泄漏。扩散泄漏的速率通常非常小，然而对于跨越数千年时间尺度和数十公里空间尺度的GCS项目，这部分泄漏仍占有显著量级[51]。Birkholzer等[52]证实了扩散泄漏可能会导致封存地质体内大量CO_2损失。

5　CO_2泄漏危害

CO_2/咸水泄漏的最直接后果是进入上覆含水层，导致GCS场地地下水污染。关于这方面研究，国内外已有大量文献进行报道[53–61]，采用的研究方法多为室内试验或试验与数值模拟相结合，总体来看，目前基于实际GCS场地的这方面研究还较欠缺，主要来自Sleipner和德国Ketzin等场地的有限报道[62–63]。国内学者主要利用TOUGHREACT或PHREEQC软件对神华CCS场地和江汉盆地等CCS备选场地进行了泄漏假设模拟和影响因素分析[64–65]，研究结论可大致归纳为：CO_2泄漏通常会导致上覆含水层地下水pH值减小、盐度升高、矿物溶解、迁移和再沉淀、吸附/解吸、离子增多、微量元素释放（重金属迁移）、含水层氧化还原环境发生改变等地球化学响应；可能导致浅部地层及地表环境的剧烈变化，影响浅层及地表的生态系统。

此外，如果场地盖层较少或完整性差而泄露位置又较浅，CO_2可能继续上升至土壤层甚至逸散至地表大气中。土壤中CO_2浓度升高会改变土壤中微生物的生物量含量（通常呈现出先促进后抑制的规律）、植物叶片光合作用、蒸腾作用，植株根系、土壤呼吸、土壤化学性质及肥力等[66–68]。

6　泄漏监测

泄漏监测是分析管理GCS风险的基础，对其进行理论研究有助于监测井布置方案设计。目前世界上几个大型封存项目的监测均采用三维或四维地震监测CO_2羽体[69]。然而，羽体监测的缺点是并不具有事先预见性，从泄漏防范角度而言意义有限。由于CO_2注入引起的储层压力扰动范围比CO_2羽体扩散范围大很多，监测上覆地层流体压力和地球化学特征被证明是泄漏监测的有效手段[70]。由于储层咸水受注入CO_2驱替，首先沿泄漏通道向上覆含水层泄漏，因此监测上覆含水层压力的变化可以预先获得CO_2泄漏的信号[71]。

通过监测压力变化侦测CO_2或储层咸水泄漏有诸多解析解研究[39, 70, 72–76]，研究的基本思路是采用解析法建立流体压力变化和泄漏速率的相关关系，从而定量评估储层流体的可能泄漏特征。这些方法并不能有效地监测盖层扩散泄漏，除非盖层的渗透率非常高[49]。另一些学者则采用数值模拟手段对GCS项目的CO_2泄漏监测进行研究，分析影响泄漏和压力变化的敏感因素。Park等[77]对Sleipner场地的研究显示，对上覆地层的压力监测可至少提前60 d预测CO_2泄漏的发生。此外，国内一些学者对GCS安全性监测也进行了定性的理论总结和方法探索[15, 78–79]。

7　现有研究不足之处

目前有关GCS封存安全和泄漏风险研究存在以下几方面的问题：

（1）我国现有CCS研究主要集中在选址方法[80–81]、注入封存模拟[82–85]、环境影响监测[15, 86–87]、水岩化学反应[88–89]等方面，关于GCS封存安全和泄漏风险方面的定量研究十分有限，多数停留在介绍、综述国外研究成果和理论，缺少这一课题的专门定量研究。

（2）考虑大量废弃井泄漏的GCS数值模拟研究十分有限。对于能源开发历史较长的油气盆地，区内往往分布着成百上千、甚至上万个钻孔，这些钻孔如缺乏有效监管，其泄漏风险并不可知。对于这类情况的泄漏诊断和风险评估，解析法固然是一种途径，这对于数值模拟而言计算负荷上仍存在较大挑战。然而，解析解不可避免地存在缺点，即必须进行一系列理想化假设（如储层均质假设），因此对于地质条件复杂的场地，解析法未必能够达到理想效果。基于精细地质模型与并行优化算法的高性能数值模拟是解决该问题的重要途径。

（3）现有CO_2地质封存的泄漏研究普遍假设或简化断层、裂缝或泄漏井的条件[75, 90]。实际中这些井、裂缝或断层的情况复杂的多。对断层、裂缝等精细刻画的GCS储层模型目前少有报道。

（4）考虑盖层扩散泄漏的长期风险评估有待更多研究。现有泄漏研究绝大部分只考虑CO_2/咸水沿钻井或断层等泄漏通道发生“集中”泄漏，然而对于时空尺度都很大的GCS项目，透过盖层的长期“扩散”泄漏仍需考虑。

（5）全面考虑多种封存机制的GCS安全和风险评估仍需深入。CO_2在储层中的封存通过4种机制得以实现，即构造封存、毛细封存（残余气封存）、溶解封存和矿物封存[91]。只有少数学者[92–93]从封存机制角度评价CO_2泄漏的潜在风险，这些研究也往往只考虑一种或两种封存机制。

（6）基于实际深部咸水层GCS工程的泄漏影响研究有限。有关CO_2泄漏对上覆地层的地球化学影响，相当一部分研究是基于室内或场地浅层含水层的注气试验，基于实际场地的CO_2泄漏过程以及泄漏对深部含水层的影响研究较少。

（7）全面考虑多过程耦合的GCS风险研究有待发展。现有GCS力学研究大量关注GCS的多相流体渗流、反应溶质渗流、流固（水力–力学）耦合过程，而对渗流–热力–化学–力学多过程耦合效应对GCS过程及密封性的影响关注非常有限。

（8）GCS泄漏的风险预测与管理研究还十分有限。GCS安全不仅依赖注入前对封存场地的全面调查和注入开始后的储层管理，还依赖于泄漏预测及泄漏发生后完备的风险管理措施。无论CO_2泄漏前的储层干预还是泄漏后的修复研究均十分有限。

8 结 语

CO_2泄漏关系到GCS项目的设计和维护，也对当地的健康、安全和环境都可能构成威胁。CO_2一旦泄漏，要对其进行干预必然会增加CCS运营商和有关单位的成本。我国深部咸水层有巨大的CO_2封存潜力，然而，我国目前在GCS领域研究基础仍相对薄弱，加之我国地质条件复杂、地表生态环境脆弱和人口经济条件复杂，GCS项目的风险可能高于其它国家，导致我国GCS项目的大规模实施面临困难和挑战。当前急需针对我国GCS示范或备选场地的特征，尽快开展相应的科学研究和技术储备，总结和发展出一套全面论证GCS项目安全性的理论体系、评估方法和风险管理体系。特别是2015年刚结束注入的神华CCS项目，其封井后的后续监测和风险评估仍十分重要，是确保CO_2被长期安全有效地封存于地下的有效措施。

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