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中国南海天然气水合物开采储层水合物相变与渗流机理: 综述与展望

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摘要:【研究目的】中国地质调查局先后于 2017 年、2020 年在南海北部神狐海域成功实施两轮水合物试采, 创造了产气时间最长、产气总量最大、日均产气量最高等多项世界纪录, 了解和掌握南海天然气水合物开采储层相变与渗流机理, 有助于进一步揭示该类型水合物分解机理、产出规律、增产机制等, 可为中国海域水合物资源规模高效开采提供理论基础。【研究方法】基于两轮试采实践, 笔者通过深入研究发现, 储层结构表征、水合物相变、多相渗流与增产、产能模拟与调控是制约水合物分解产气效率的重要因素。【研究结果】研究表明, 南海水合物相变具有分解温度低, 易在储层内形成二次水合物等特点, 是由渗流场–应力场–温度场–化学场共同作用的复杂系统; 多相渗流作用主要受控于未固结储层的物性特征、水合物相变、开采方式等多元因素影响, 具有较强的甲烷吸附性、绝对渗透率易突变、气相流动能力弱等特点; 围绕南海水合物长期、稳定、高效开采目标, 需要在初始储层改造基础上, 通过实施储层二次改造, 进一步优化提高储层渗流能力, 实现增产扩产目的。【结论】随着天然气水合物产业化进程不断向前推进, 还需要着力解决大规模长时间产气过程中温度压力微观变化及物质能源交换响应机制以及水合物高效分解、二次生成边界条件等难题。

关键词: 天然气水合物; 泥质粉砂储层; 水合物相变; 渗流机理; 海域天然气水合物勘查试采工程; 南海; 中国

创新点: 南海水合物相变是由渗流场–应力场–温度场–化学场共同作用的复杂系统; 南海泥质粉砂储层具有较强的甲烷吸附性、绝对渗透率易突变、气相流动能力弱等特点, 多相渗流机理复杂。

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Hydrate phase transition and seepage mechanism during natural gas hydrate production tests in the South China Sea: A review and prospect

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Abstract: This paper is the result of marine hydrates exploration engineering.

[Objective] The China Geological Survey successfully carried out two NGH production tests in the Shenhu area in the northern South China Sea (SCS) in 2017 and 2020, setting multiple world records, such as the longest gas production time, the highest total gas production, and the highest average daily gas production. Understanding and mastering the phase transition and seepage mechanism of natural gas hydrate reservoir exploitation in the SCS will help to further reveal the decomposition mechanism, production law, and production increase mechanism of this type of hydrate, and provide a theoretical basis for large-scale and efficient exploitation of hydrate resources in China sea. **[Methods]** As suggested by the in-depth research on the two production tests, key factors that restrict the gas production efficiency of hydrate dissociation include reservoir structure characterization, hydrate phase transition, multiphase seepage and permeability enhancement, and the simulation and regulation of production capacity, among which the hydrate phase transition and seepage mechanism are crucial. **[Results]** Study results reveal that the hydrate phase transition in the SCS is characterized by low dissociation temperature, is prone to produce secondary hydrates in the reservoirs, and is a complex process under the combined effects of the seepage, stress, temperature, and chemical fields. The multiphase seepage is controlled by multiple factors such as the physical properties of unconsolidated reservoirs, the hydrate phase transition, and exploitation methods and is characterized by strong methane adsorption, abrupt changes in absolute permeability, and the weak flow capacity of gas. To ensure the long-term, stable, and efficient NGHs exploitation in the SCS, it is necessary to further enhance the reservoir seepage capacity and increase gas production through secondary reservoir stimulation based on initial reservoir stimulation. **[Conclusions]** With the constant progress in the NGHs industrialization, great efforts should be made to tackle the difficulties, such as determining the micro-change in temperature and pressure, the response mechanisms of material-energy exchange, the methods for efficient NGH dissociation, and the boundary conditions for the formation of secondary hydrates in the large-scale, long-term gas production.

Key words: natural gas hydrate; clayey silt reservoir; hydrate phase transition; seepage mechanism; marine hydrates exploration engineering; South China Sea; China

Highlights: The hydrate phase transition in the SCS is a complex process under the combined effects of the seepage, stress, temperature, and chemical fields; The clayey silt reservoir in the SCS is characterized by strong methane adsorption, abrupt changes in absolute permeability, the weak flow capacity of gas, etc., and the multiphase seepage mechanism is complex.

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1 引 言

天然气水合物是指在一定温度、压力条件控制的稳定域内,由甲烷为主的烃类气体与水形成的类冰状结晶化合物,通常被称为“甲烷水合物”,简称水合物,90%以上赋存于陆架边缘海底沉积物中,不足10%分布在陆域永久冻土区岩石的裂隙、孔隙中。在标准温度压力条件下,1 m³的水合物可以释放出0.8 m³的水和约164 m³的天然气,燃烧后几乎不产生任何残渣,是一种资源量丰富且效能极高的清洁能源(Li et al., 2018)。据估算,全球水合物蕴藏的天然气资源总量约为2.1×10¹⁶ m³(Sloan et al., 2007)。为促进天然气水合物资源开发利用,加拿

大、美国针对陆域冻土区未成岩的砂砾质、砂质储层进行了3次垂直井试采,日本针对海域砂质储层开展了两轮3次垂直井试采(Moridis et al., 2005; Numasawa et al., 2008; Schoderbek et al., 2013; Hauge et al., 2014; Terao et al., 2014; Oyama et al., 2017),但因产气效率低或出砂等问题,均未能实现预期目标(表1)。中国南海天然气水合物储层类型主要为泥质粉砂型,该类储层在世界上分布最为广泛、资源量约占全球资源量的90%,但与砂砾质、砂质沉积物储层相比,孔隙度、渗透率极低,渗流能力差,开采难度极大。中国针对泥质粉砂储层水合物开采难题,通过开展理论与模拟实验,创新试采技术方法工艺,先后攻克了深海浅软地层垂直井

表 1 世界主要国家水合物试采情况

Table 1 NGH production tests in major countries

国家	区域	储层类型	年份	开采井型及方法	持续时间/d	累计产气量/m ³
中国	南海神狐海域	泥质粉砂沉积物	2017	垂直井, 降压法	60	30.9×10 ⁴
	南海神狐海域		2020	水平井, 降压法	42	149.86×10 ⁴
加拿大	麦肯齐三角洲	砂砾质沉积物	2002	垂直井, 热水循环法	5	516
	麦肯齐三角洲		2007—2008	垂直井, 降压法	6	1.3×10 ⁴
美国	阿拉斯加北坡	砂质沉积物	2012	垂直井, CO ₂ 置换法+降压法	30	2.4×10 ⁴
	日本南海海槽		2013	垂直井, 降压法	6	12×10 ⁴
日本	日本南海海槽	砂质沉积物	2017	垂直井, 降压法	12	3.5×10 ⁴
					24	20×10 ⁴

和水平井钻采技术,于2017年、2020年在南海神狐海域完成了探索性试采、试验性试采(图1)(Li et al., 2018; Ye et al., 2020)。

总的来看,虽然中国天然气水合物勘查开采工作起步较晚,但在国家的高度重视下,尤其近些年来取得了快速发展。通过开展大量的调查研究和技术攻关,在天然气水合物系统特征、成藏演化、运聚过程、试采技术工艺等方面形成了一批创新性认识(李小森等, 2008; 邹才能等, 2013; 吴能友等, 2017; Li et al., 2018; Shi et al., 2019; Ye et al., 2020; Qin et al., 2020a; 杨承志等, 2020; 苏丕波等, 2020; 张伟等, 2020; 钟广法等, 2020; 魏纳等, 2020; 宁伏龙等, 2020; 高德利, 2020; 吴能友等, 2020; 马公正等, 2020; 张伟等, 2020; 孙金声等, 2021)。在开采机理研究方面,以往主要集中于储层力学响应、物理性质变化、产能模拟预测、模拟器研制应用等方向的研究(李淑霞等, 2020; 韦昌富等, 2020; 蔡建超等, 2020; 卢海龙等, 2021; 吴能友等, 2021)。近年来,笔者基于南海神狐海域两轮试采实践,深入研究发现,储层结构表征、水合物相变、多相渗流与增渗、产能模拟与调控是制约水合物分解产气效率的重要因素,尤其水合物相变、渗流机理至为关键(秦绪文等, 2019a, 2019b; Lu et al., 2019; 陆程等, 2019, 2021; Qin et al., 2020b; 李守定等, 2020; Cai et al., 2020; Bian et al., 2020; Qi et al., 2021; Geng et al., 2021; Lu et al., 2021a, 2021b; Xu et al., 2021; Lei et al., 2022; Qi et al., 2022)。本文系统总结论述了近年来在南海天然气水合物开采储层水合物相变与渗流机理研究方面取得的主要进展,旨在揭示水合物分解机理、产出规律、增产机制等,为天然气水合物资源规模高效开采提供理论基础。

2 南海天然气水合物储层物性特征

2.1 矿物组成与孔隙特征

南海泥质粉砂储层含有大量石英、长石矿物,磨圆度较差;微生物化石较多,以有孔虫为主;黏土矿物以伊利石为主,主要充填于石英与长石之间。储层孔隙类型以生物化石孔、粒间孔、黏土晶间孔、溶蚀孔以及云母晶间孔等为主,且黏土孔以及生物化石孔在总孔隙中占比较大(图2)。通过对全岩与黏土矿物分析表明,不同样品的矿物组成及含量差异较大,有的样品以石英矿物为主,黏土矿物次之;有的样品以碳酸盐矿物为主,石英矿物含量较低;泥质粉砂储层中黏土矿物成分均以伊利石为主,含量超过75%(图3)。

储层平均孔隙半径分布范围较大,具有较大尺度的微生物化石孔和较小尺度的黏土孔;其中,中值孔隙半径较低,均小于1.5 μm;同时,存在大量亚微米级孔隙,主要以黏土矿物层间孔、粒内孔、粒间孔以及黏土颗粒团块间大孔为主(Lei et al., 2022),以碳酸盐为主的储层小于1 μm孔隙占比高达75%(图4,表2)。

总的来看,南海泥质粉砂储层黏土矿物含量高,开采中水合物分解产生的水会使黏土矿物发生膨胀,引起孔隙、喉道堵塞,因此会造成绝对渗透率、有效渗透率降低的风险。同时,亚微米级孔隙占比高,超低渗透特征明显,会造成水合物分解气和水在储层中的流动性降低,增加开采难度。

2.2 孔隙结构表征

与成岩储层相比,泥质粉砂储层具有松散、未固结的特点。利用计算机断层扫描和数字岩心技术能准确获取储层多孔介质三维结构的优势,对泥

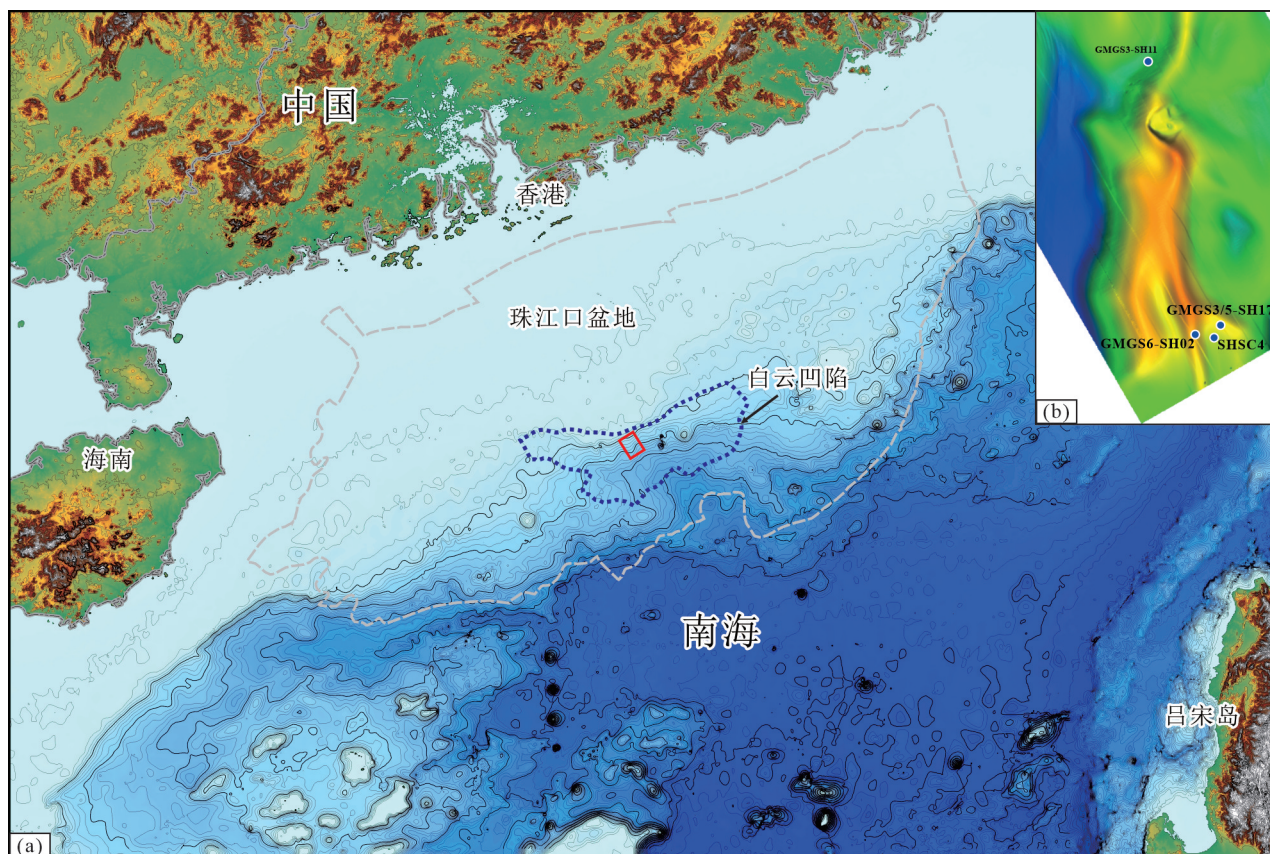


图1 研究区地质图

a—区域地质背景和研究区位置(用红色方块标出);b—GMGS5-SH17井的相对位置(Qin et al., 2020)

Fig.1 Geological map of the study area

a—Regional geological background and the location of the study area (marked with a red square); b—Relative location of Well GMGS5-SH17 (Qin et al., 2020)

质粉砂储层样品开展孔隙结构扫描,获得储层孔隙结构的空分布,并模拟得到样品的渗透率,表现出明显的高孔隙度、超低渗透率的特征(图5)。

针对泥质粉砂孔隙结构表征和孔隙度-渗透率相关性研究,我们首先通过传统欧式几何法分析发现,孔隙度与渗透率相关性较低,不能准确地表征南海泥质粉砂多孔介质孔隙结构的复杂性(图6a)。然后,利用分形几何理论具有量化复杂空间孔隙结构的优势(蔡建超等,2015),使用分形维数和进相值表征泥质粉砂储层复杂的微孔结构特征。与常规砂岩储层相比,泥质粉砂储层在孔隙度接近情况下,表现出较高的分形维数,进一步证实其孔隙空间较常规砂岩分布更加复杂(表3)。泥质粉砂储层样品进相值与渗透率呈现出较好的相关性(图6b)(Bian et al.,2020)。因此,针对南海泥质粉砂储层类型,可进一步利用分形几何理论建立泥质粉砂

储层渗透率拟合模型,深入分析南海水合物试采中储层渗透率变化规律。

3 天然气水合物相变

3.1 水合物分子动力学研究

近年来,水合物分子动力学研究不断发展,研究从气体混合物和简单的液体,到聚合物和纳米颗粒等复杂材料,揭示了水合物晶体成核与分解机理(Khurana et al.,2017; Kondori et al.,2017; Teixeira et al.,2018; Liu et al.,2019; Li et al.,2020)。通过对不同类型储层水合物分子动力学分析,笔者认为开展南海水合物成核与分解机理研究,需要进一步考虑储层固体表面结晶度、亲水性等要素影响,以建立更加切合实际的固体分子模型。同时,经过研究表明,果胶、壳聚糖、木薯粉和防冻蛋白等动力学抑制剂,可以有效延缓水合物成核过程或者降低水合

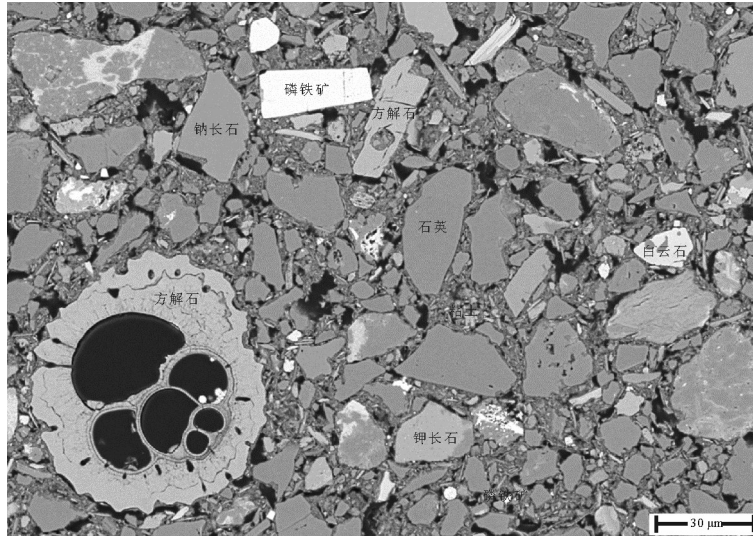


图2 水合物储层样品的典型矿物表面
Fig.2 Typical mineral surfaces of reservoir samples

物晶体生长,对于缓解开采中水合物二次形成、堵塞储层和生产井筒具有积极作用(图7)(Qi et al., 2021)。未来抑制剂的作用机理研究以及经济高效的动力学抑制剂材料优选将成为重要的研究方向。

3.2 水合物相平衡

有效掌握南海水合物的相平衡条件,准确获取相平衡曲线参数,是揭示储层内复杂相变与渗流规律、进行产能调控和制定降压策略的基础。以往针对南海水合物开展的相平衡研究,主要采用纯CH₄气代替水合物的甲烷气,或者用NaCl配制的溶液替代海水,或者人工配制的单一/混合介质替代沉积物

储层(Lu et al.,2002; Uchida et al.,2004; Sun et al., 2015; Zhang et al.,2016; Lü et al.,2018; Wang et al., 2019; Mu et al.,2019)。

笔者选用南海神狐试采区样品,根据原位孔隙水盐离子含量和气体组分特征,配置相平衡实验所需的气源和水源,采用梯度升温法和改进后的Chen-Guo模型,获取了含盐离子和多孔沉积物体系中的南海水合物相平衡条件(Geng et al.,2021)。与纯水-甲烷水合物体系相比,南海泥质粉砂沉积物中的相平衡曲线明显向左移动,分解温度明显更低,其机理源于泥质粉砂多孔介质亲水性及具有大

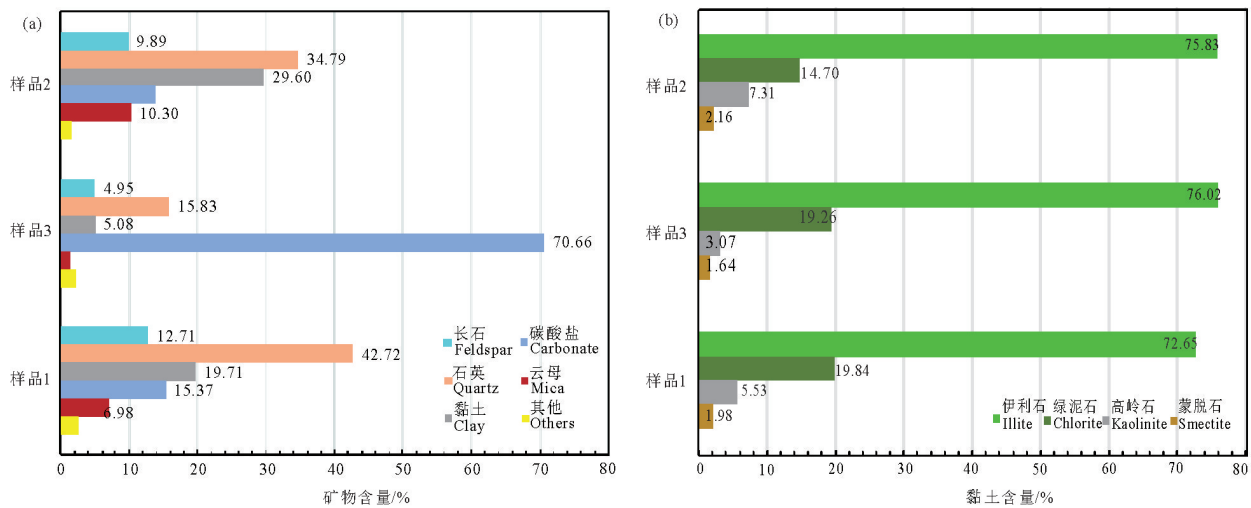


图3 南海神狐海域泥质粉砂储层矿物组分图(a)和黏土矿物含量图(b)
Fig.3 Comparison of mineral (a) and clay (b) contents of three samples in the Shenhu area of SCS

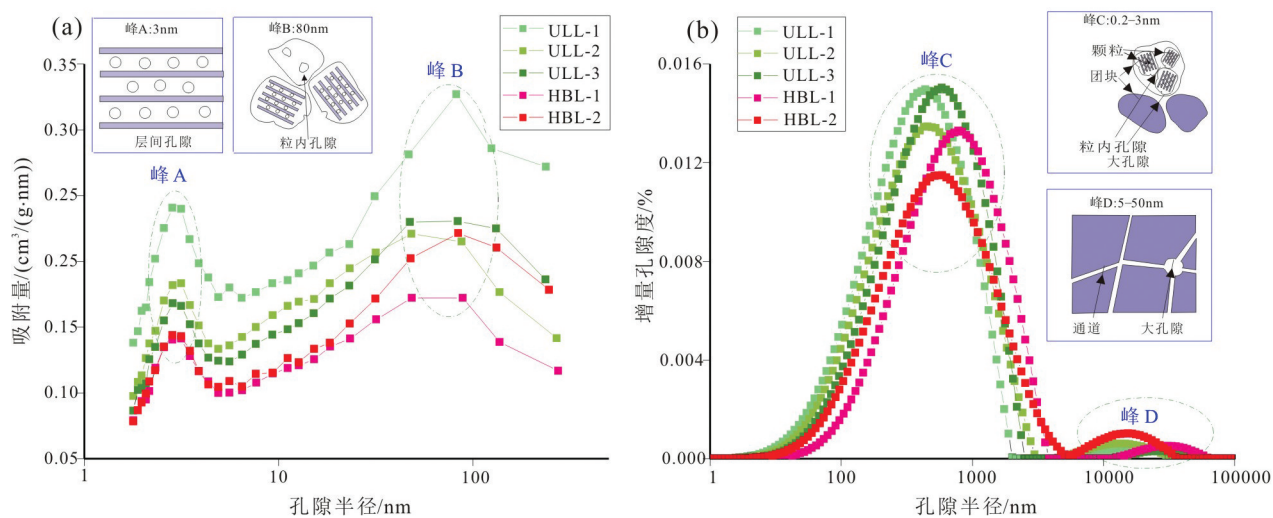


图4 基于(a) N₂吸附和(b) NMR的泥质粉砂储层孔径分布和孔隙类型(Li et al., 2022)
 Fig.4 Distribution of pore sizes and pore types based on (a) N₂-adsorption and (b) NMR (Li et al., 2022)

表2 不同样品孔隙半径参数对照
 Table 2 Comparison of pore radius parameters between samples

序号	孔隙度/%	平均孔隙半径/ μm	中值孔隙半径/ μm	亚微米孔隙率/%
1	16.78	1.543	1.341	38.9
2	24.14	4.1	1.23	45
3	20.77	2.86	0.6	75

量的亚微米级孔隙,对水分子的吸引以及小孔隙产生的毛细管力,导致水活度的降低;随盐度升高,相平衡线也逐渐向低温高压区域发生移动。改进后的Chen-Guo模型,具有较高精度的预测性能,沉积物体系的平均压力预测偏差仅为3.7%,大幅度提升了水合物试采产能模拟的准确程度(图8)。同时,南海泥质粉砂水合物分解焓明显增大,并随着盐度

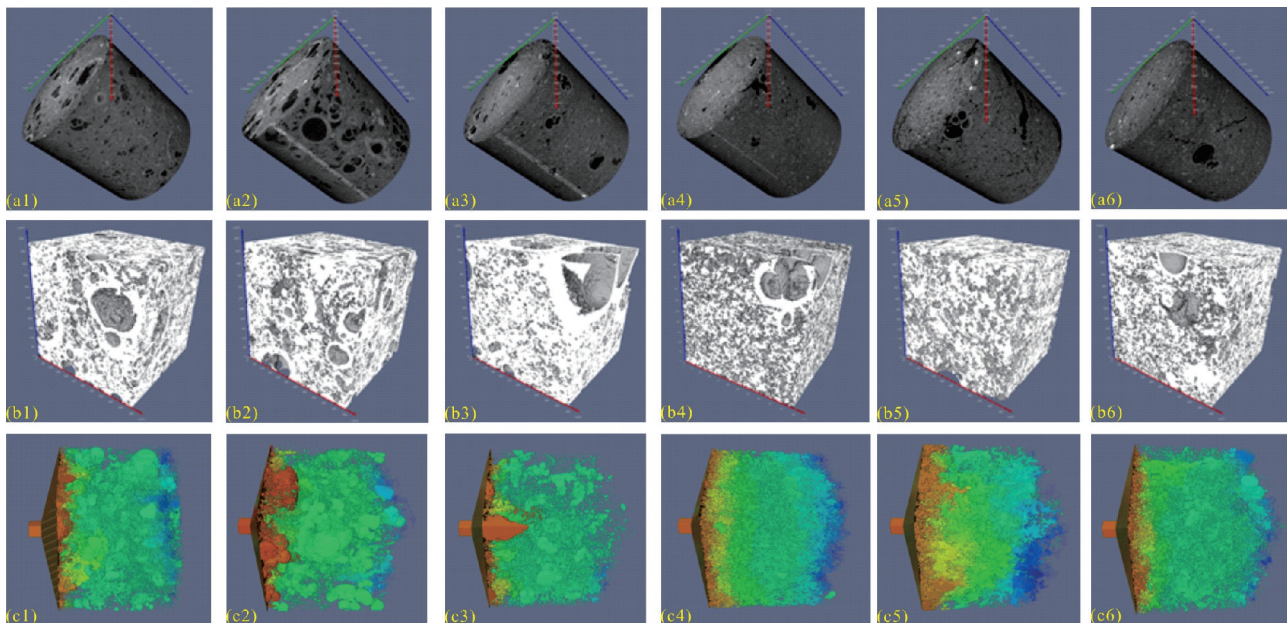


图5 六个水合物储层样品的原始灰度图(a)、二值化图(b)及压力场分布图(c)(Bian et al., 2020)
 Fig.5 Original grayscale images (a) and binarized images (b, 5123 pixels) and the pressure field (Pa) distributed along y direction in the permeability simulation of six hydrate samples (c) (Bian et al., 2020).

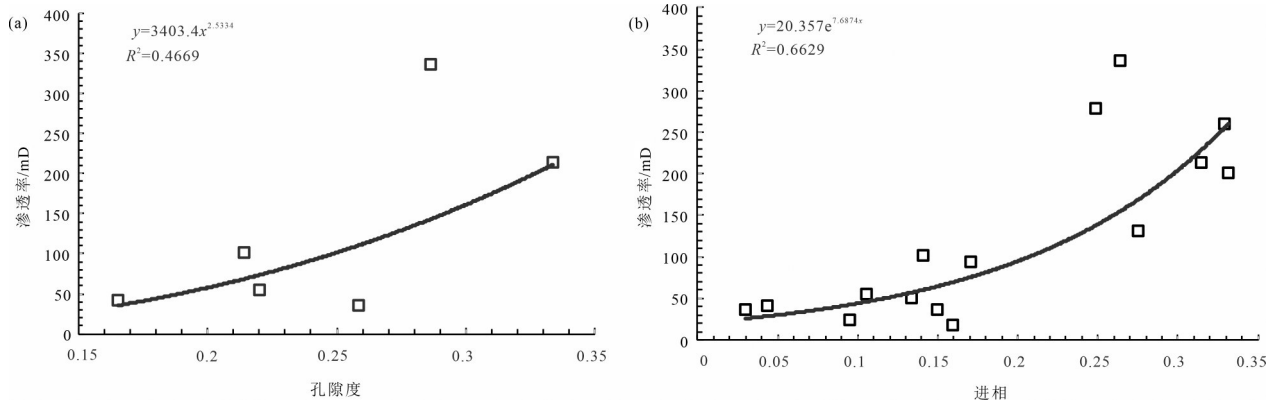


图6 水合物样品孔隙度和渗透率拟合示意图(a)以及样品在不同正方向上的进相与渗透率拟合曲线(b) (Bian et al., 2020)
 Fig. 6 Schematic diagram of porosity and permeability fitting of six hydrate samples (a); Fitted curve of succolarity and permeability for six hydrate samples along different positive directions (b) (Bian et al., 2020)

表3 六个水合物样品和两个砂岩岩心的三维分形维数计算(Bian et al., 2020)

Table 3 Calculated 3D fractal dimensions of six hydrate samples and two sandstone cores (Bian et al., 2020)

参数	1	2	3	4	5	6	砂岩 a	砂岩 b
分形维数	2.77	2.79	2.71	2.85	2.81	2.78	2.70	2.85

的不断减低水合物变得更加稳定,预示着该类型水合物降压分解会导致储层温度降低的程度明显提高,更容易在储层内形成二次水合物(图9)。

3.3 水合物相变对储层渗透率的影响

泥质粉砂多孔介质有着复杂的矿物组成及非

均质的孔隙结构,会对水合物相变过程产生复合影响,相变又会引起储层孔隙度、渗透率等物性变化,影响产气效率。以往水合物相变对储层渗透率影响的研究结果,主要是基于人工石英砂或玻璃珠等介质得到的,而针对南海真实储层的研究较为有限

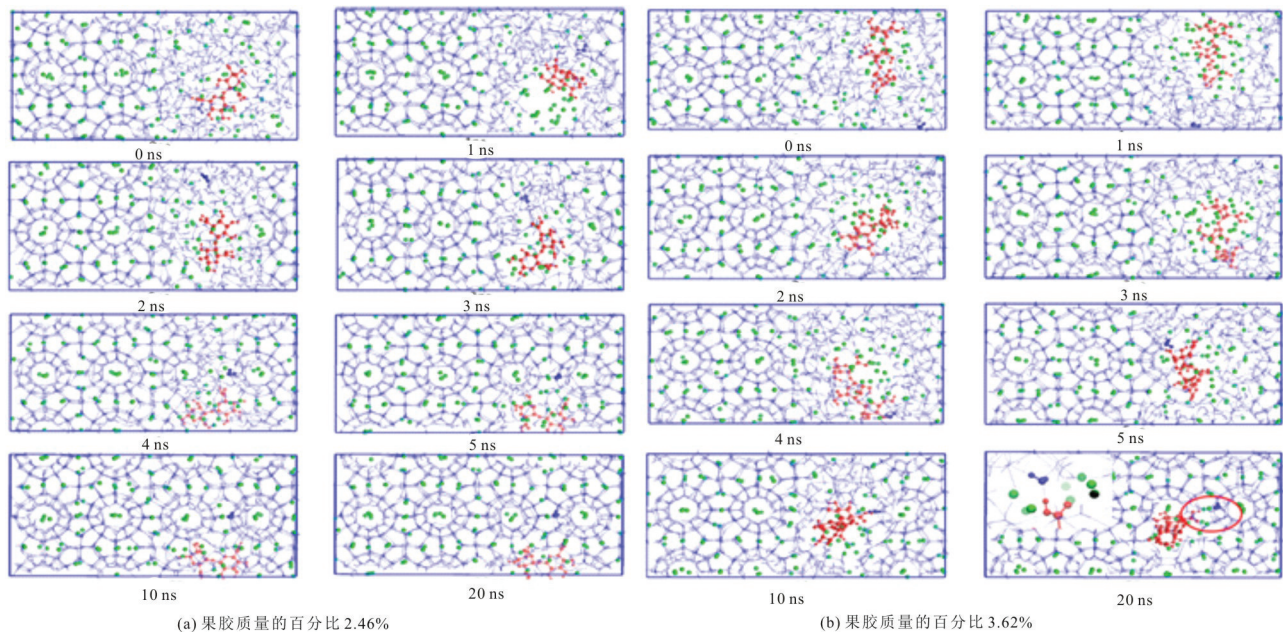


图7 果胶在0、1、2、3、4、5、10和20 ns的构型(其中蓝色代表水分子,蓝色虚线代表氢键,绿色代表甲烷,红色代表果胶) (Qi et al., 2021)

Fig.7 Configurations of pectin at 0, 1, 2, 3, 4, 5, 10, and 20 ns. Blue represents water molecules, blue dotted lines represent hydrogen bonds, green represents methane, and red represents pectin (Qi et al., 2021)

(Liu et al.,2015; Kumar et al.,2015; Heeschen et al., 2016; Wang et al.,2017; Zhang et al.,2019; Song et al., 2020; Li et al.,2020; Qin et al.,2021)。

笔者选用神狐海域水合物分解后的泥质粉砂样品,利用低温-低场核磁共振驱替设备,开展了储层水合物相变与渗透率动态变化研究。与其他储层类型相同,南海泥质粉砂多孔介质内水合物的存在或消失会对储层孔隙结构起到改造作用,影响介质内可动流体的流动,从而引发其渗透率参数值在不同数量级之间发生动态变化。现阶段,基于单一生长模式或假设条件构建的不同渗透率模型,拟合结果差异性较大,均难以较好的显示出泥质粉砂水合物相变过程中水合物饱和度和复杂介质渗透率动态变化关系(图10)。可见,泥质粉砂水合物开采中储层渗透率的动态演化是由多机制、多因素共同控制的复杂过程。

3.4 二次水合物的主控因素

以往基于小尺度物理模拟实验或数值模拟表明,采用降压法开采天然气水合物,受水合物分解焓和焦耳-汤姆森效应共同作用,储层局部温度会降低至相平衡区域内,导致多孔介质内赋存的气、液两相流体可在低温高压环境下再次形成水合物或冰,堵塞渗流通道并降低储层渗透率,使得储层温度、压力场重新分布,进一步影响水合物分解,最终导致产气量降低。低温下二次水合物和冰的形成是降压开采必须要面对和解决的问题(Yu et al.,

2017; Yamamoto et al.,2017; Fan et al.,2017; Yu et al., 2018; Chen et al.,2018; Yang et al.,2021; Li et al., 2021)。为了进一步厘清真实开采环境下的二次水合物或冰形成的主控因素,笔者利用天然气水合物逆相变形成演化规律模拟装置(陆程等,2021),初步分析了从分解前缘至生产井筒这一特定区域内二次水合物的形成位置和形成规模,以及生产压差对二次水合物形成的影响。

研究表明,在相同生产压差条件下,初期水合物分解前缘距离井口较近时,受气体焦耳-汤姆森效应,近井储层温度降幅明显,越靠近井筒,温度下降幅度越大;随分解区不断增大,储层温度衰减程度大幅降低,井周温度可保持在冰点以上,储层压力分布基本保持稳定;同时,随分解前缘推进,气体节流膨胀效应减弱,水合物稳定区扩展速度显著放慢,二次水合物生成风险也将大幅降低(图11)。在分解范围相同条件下,与低压差相比,大压差会导致井周温度降低程度剧烈,在短时间内造成部分区域温度压力点左移至水合物稳定带,二次水合物生成速率高,导致产气速率有明显下降;小压差会引起低饱和度二次水合物生成,但对产气量无明显影响(图12)。由此可见,生产压差对二次水合物的形成具有重要的控制的作用。

4 天然气水合物分解区多相渗流机理

4.1 分解区甲烷气体等温吸附特征

从生产井筒至天然气水合物分解前缘之间的

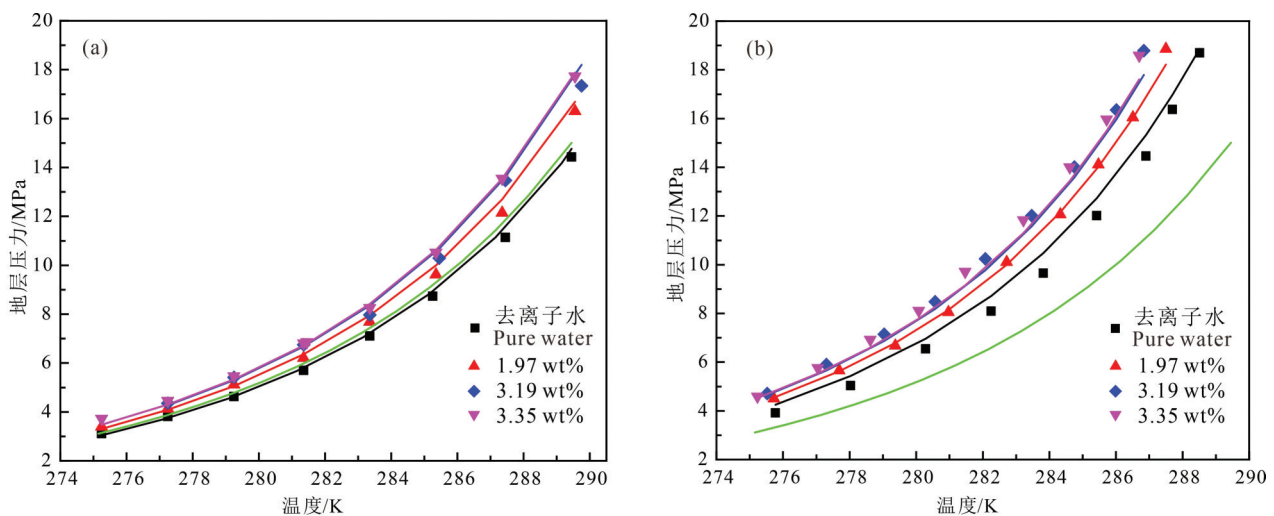


图8 水基体系不同盐度条件下天然气水合物分解条件(a)和不同盐度条件下沉积物基体系中水合物分解条件(b)(Geng et al., 2021)

Fig. 8 NGHs dissociation conditions in bulk water (a) and in sediments (b) with different salinities(Geng et al., 2021)

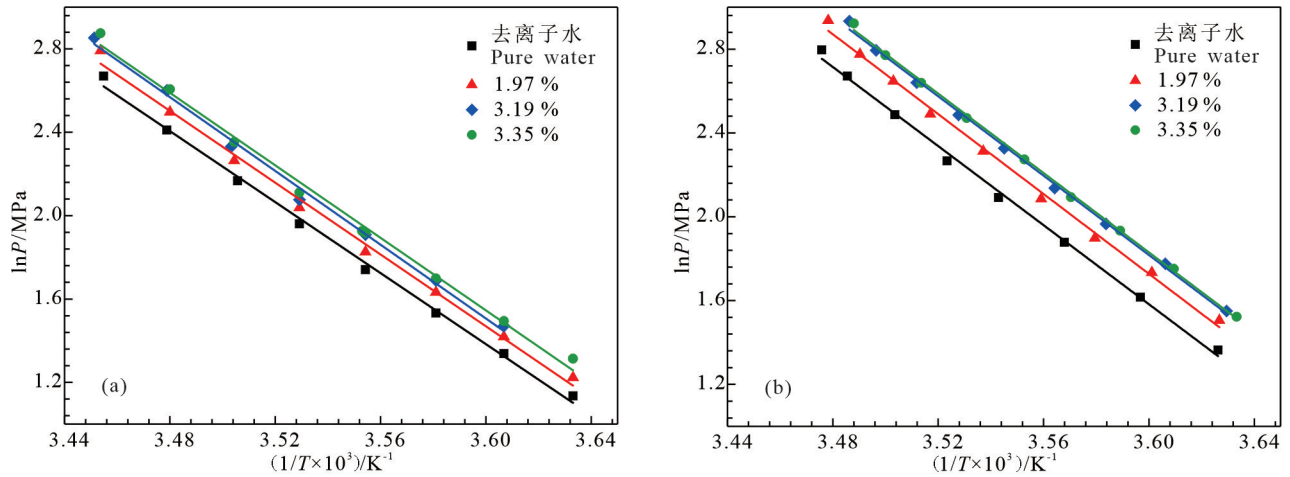


图9 甲烷水合物实验数据压力与温度图:a—水基体系;b—沉积物基体系,其中实线表明实验方法与数据的可靠性(Geng et al., 2021)

Fig. 9 The plots of reciprocal temperature ($1/T$) vs. the natural logarithm of dissociation pressure ($\ln P$) for experimental NGH in (a) the bulk water and (b) marine sediments. The solid lines indicate the reliability and accuracy of the experimental procedure and data points (Geng et al., 2021)

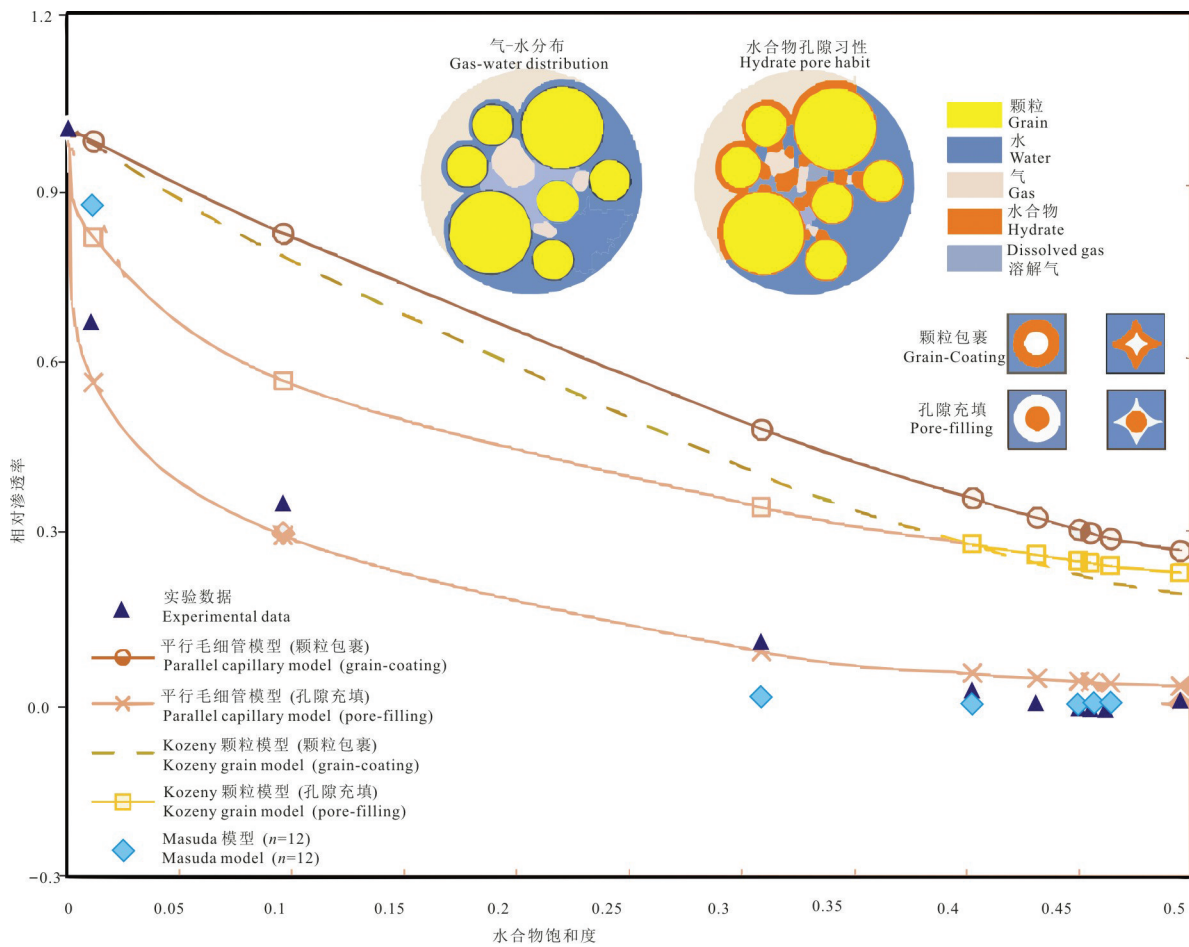


图10 不同模型计算的水合物饱和度与渗透率/初始渗透率的关系图

Fig.10 Relationships between hydrate saturation and permeability/initial permeability calculated using various models

区域是水合物分解气、水等多相流体发生渗流的主要场所。针对南海天然气水合物储层黏土矿物含量高、微纳米级孔隙占比高等特点,笔者开展了水合物分解区的甲烷等温吸附特征实验。结果表明,在干燥条件下,当泥质粉砂储层温度小于页岩时,可达到与页岩相当的吸附量(图 13a);其吸附量与伊利石接近,略小于高岭石与绿泥石,远小于蒙脱石(图 13b);在相同温度下,吸附曲线整体呈现随压力增加而上升的趋势,当压力达到一定值时,部分吸附曲线开始出现增速变缓或下降(图 13c)。在含水条件下,当压力小于 2 MPa 时,含水率对甲烷吸附几乎无影响;当压力介于 2~10 MPa 时,含水率降低了甲烷吸附量;当压力大于 10 MPa 时,含水率增加了甲烷吸附量(图 13d)。基于实验数据,笔者发现修正后的 Langmuir 模型能够较好地反映较低压力条件下的等温吸附现象,而利用 DR

方程可以表征中高压条件下的等温吸附现象(图 14)(Qi et al.,2022)。

南海泥质粉砂储层具有甲烷吸附特性的首次发现以及其吸附特性对分解区内的气水两相渗流行为产生的重要影响,这对于深入开展开采机理研究、建立产能模拟数学解耦方法、选择储层改造方式具有重要的指导作用。

4.2 分解区储层微观孔隙结构与渗透率变化

南海水合物试采实践发现,使用不同降压方式开采,生产井筒周围压降速度激增,流体在井周运移会导致细粒沉积物颗粒在孔隙变窄处发生堆集、堵塞,导致绝对渗透性大幅降低。笔者利用计算机断层扫描和数字岩心技术,通过 CT 技术测量海域泥质粉砂储层结构变化的装置(秦绪文等,2019),首次开展了不同驱替压力下泥质粉砂多孔介质流

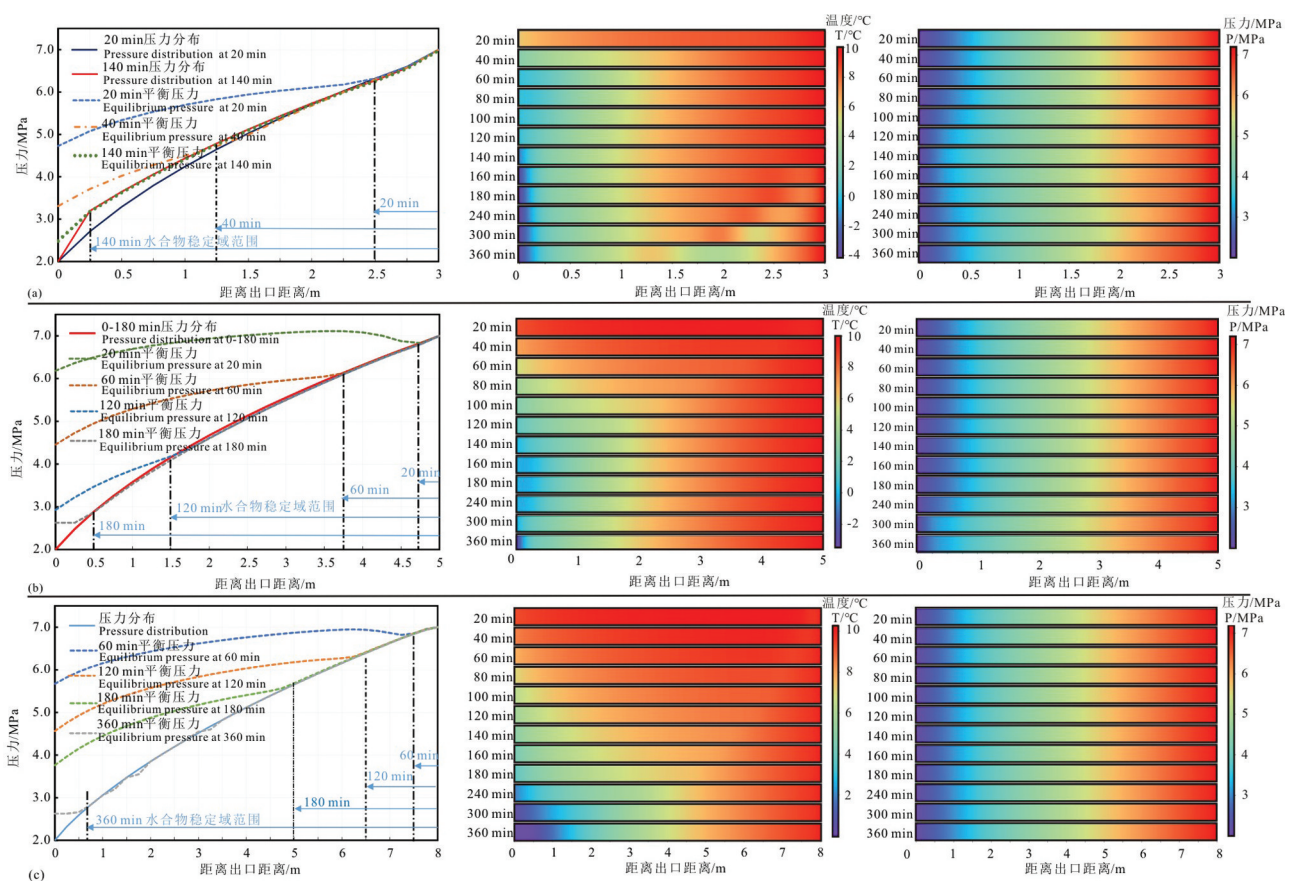


图 11 地层压力、水合物平衡压力随时间分布以及分解区储层温度和压力的分布(a—距离出口 3 m, b—距离出口 5 m, c—距离出口 8 m)

Fig.11 Distribution of reservoir pressure and equilibrium pressure of hydrates over time when the dissociation front is (a) 3 m, (b) 5 m, (c) 8 m away from the production well, as well as distribution of reservoir temperature and pressure in the hydrate dissociation zone

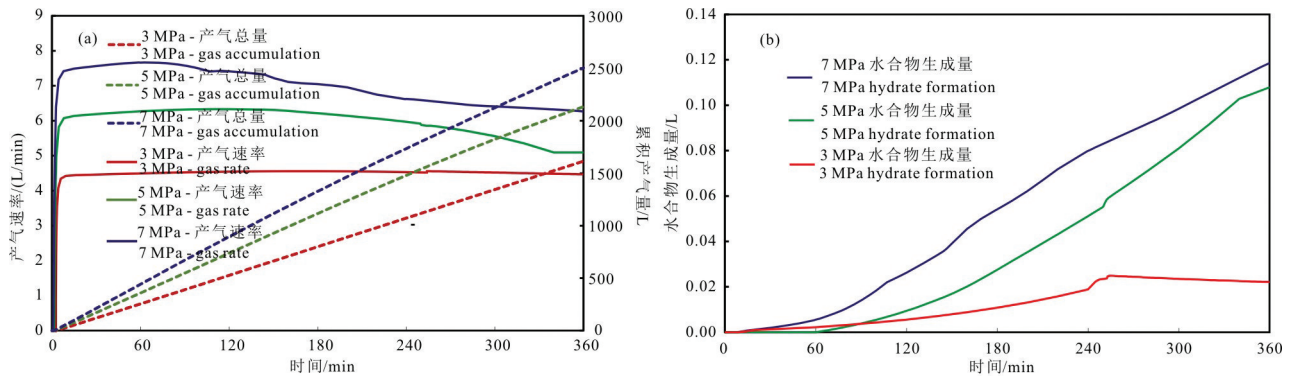


图12 不同压差下天然气(a)和二次水合物生成(b)的产量曲线图

Fig. 12 Production curves of gas production rate (a) and secondary hydrate formation (b) under different pressure differences

速敏感性研究,获得了泥质粉砂储层孔隙、喉道结构发生形变的临界压力,揭示了绝对渗透率降低的主控因素。

研究发现,泥质粉砂多孔介质渗透率会随驱替压力的增高而降低,3 MPa/m的压力梯度是该类储层孔隙结构、渗透率发生急剧变化的临界点;压力梯度小于3 MPa/m时,结构虽会发生蠕变,但孔隙结构与渗透特性均会保持相对稳定;大于3 MPa/m后,孔隙结构被迅速破坏,导致渗透率降低且过程不可逆(图15a、b)。其渗透率降低的本质原因是受外力影响,随驱替压力增加,孔隙空间发生变形,导致可供流体渗流的孔隙与喉道整体分布变窄,小孔喉数量增多,大孔喉数量减少,孔喉平均、中值半径变小,最大孔喉半径减少(图15c、d)(Lu et al.,2019; Cai et al.,2020)。

4.3 分解区泥质粉砂气-水两相渗流能力

气-水两相相对渗透率曲线可以有效反映水合物分解过程中,产出气、产出水两相共存条件下储层内某一相流体的渗流动态特征。笔者利用地质储层径向流模拟系统(陆程等,2019),首次开展了不同覆压下水合物分解区泥质粉砂储层气-水两相渗流能力演化规律研究,获得气-水两相相对渗透率曲线,初步厘清了生产井周复杂的多相多场渗流能力动态变化。

研究表明,泥质粉砂黏土矿物含量较高,两相渗流时气体很难进入到细小的喉道中进行有效驱替,随含气饱和度不断升高,气水干扰严重,影响气相流动性,最大有效气相相对渗透率值没有突破0.1,反映出该类天然气水合物在发生分解后的气、水两相流体通过水合物分解区被产出的难度较大。同时,与砂岩等

不同类型储层相比,泥质粉砂储层两相相对渗透率曲线表现为等渗点发生右偏移且位置更靠下,共渗区更窄,最大气相相对渗透率更小,预示在此类储层中气相的流动能力更弱。因此,为了进一步提高产气规模,需要对储层进行有效改造(图16)。针对在较大生产压差导致储层结构发生蠕变变形、绝对渗透率发生连续变化等复杂条件下,开展多相渗流规律研究还有待进一步深入。

5 储层渗流能力优化与水合物产能调控

5.1 储层渗流能力优化与温度场改造

储层渗流能力是影响水合物长期、稳定、高效开采的关键核心因素。在水合物开采过程中,泥质粉砂型水合物分解后,生产井控范围内原有储层改造区人工注入的支撑剂有效性会受到影响,难以长时间保持近井周高导流能力特性。由于储层改造区闭合、失效的风险增加,初次改造后的增渗效果会随着水合物开采出现递减的趋势。同时,改造区内温度也会随着水合物不断开采而降低,导致二次水合物或冰生成,并逐步占据沉积物孔隙,堵塞喉道,使产气量降低的风险进一步提升。可见,与初始储层改造相比,储层二次改造对水合物长时间开采,持续提升增渗效果更为重要。以往储层渗流能力研究主要集中于初始储层改造优化(Chaouachi et al.,2015;曹钦亚等,2017;Too et al.,2018;陈强等,2020;罗天雨等,2020;姚远欣等,2020;杨柳等,2020),尚未开展过储层二次改造对增渗扩产影响的机理研究。

在储层二次改造适宜性评价和裂缝扩展机理

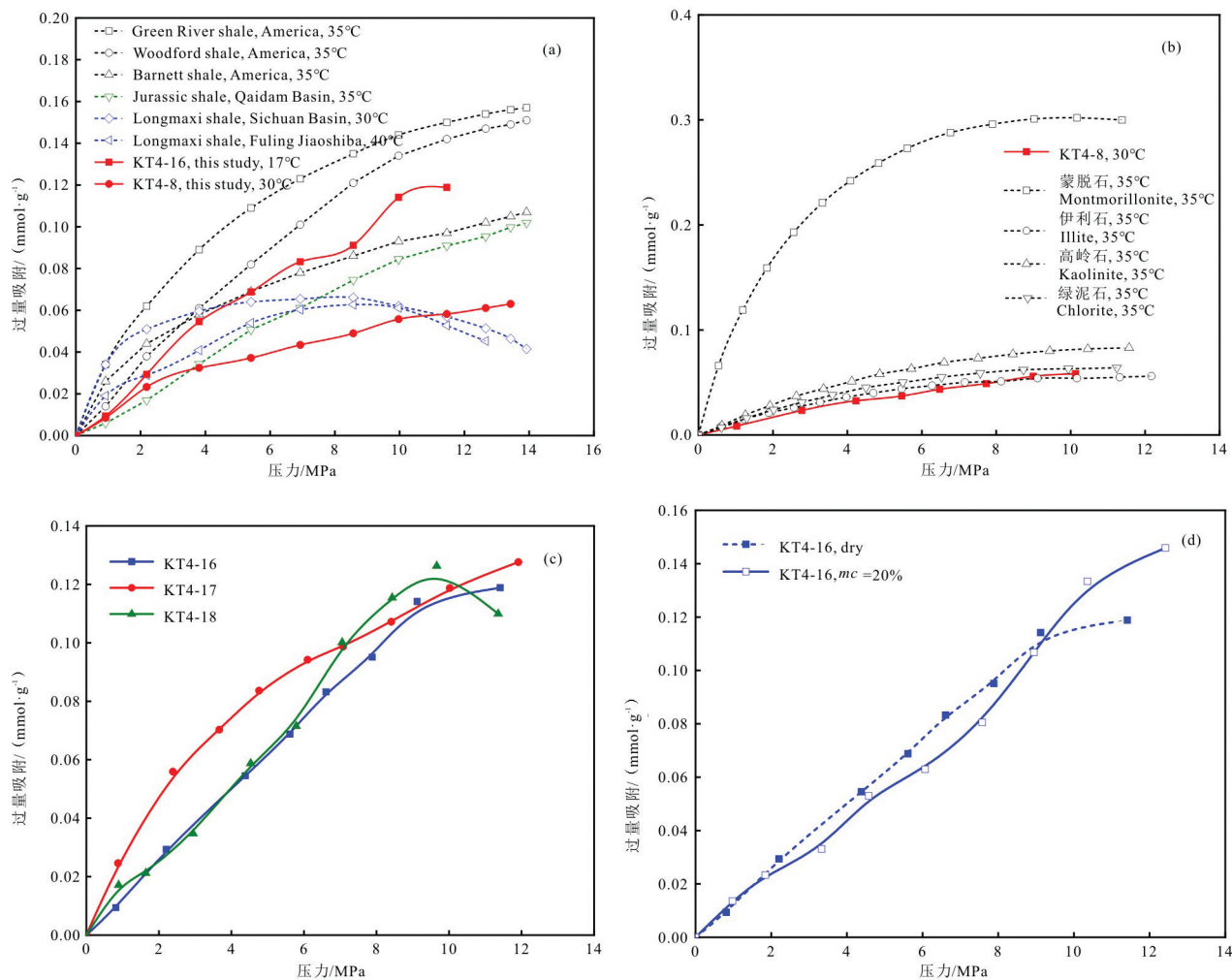


图13 泥质粉砂甲烷吸附特性图

a—不同压力下泥质粉砂和页岩的吸附性能对比;b—不同压力条件下黏土矿物和泥质粉砂吸附能力的比较;c—干态条件下泥质粉砂样品对甲烷的等温吸附曲线;d—在干态和湿态下黏土质粉砂吸附等温曲线比较(Qi et al., 2022)

Fig.13 Methane adsorption characteristics of clayey silt

a—Comparison of the methane adsorption capacities of shale, clayey silts, and coal under different pressures; b—Comparison of the adsorption capacities of clay minerals and clayey silts under different pressure; c—Methane isothermal adsorption curves of clayey silt samples under dry condition; d—Comparison of isothermal adsorption curves of clayey silts under dry and moist conditions (Qi et al., 2022)

研究方面,笔者利用自主研发的泥质粉砂油气层的压裂实验装置(秦绪文等,2019),针对南海水合物储层样品,通过开展水力压裂、CT成像等实验发现,水合物分解区细粒沉积物具有较强的水力成缝能力,具备实施储层二次改造的条件。泥质粉砂储层内存在的黏土矿物遇水膨胀后,极大增强了储层的塑性,致使地层中消耗更多能量用来扩展裂缝。地层围压越高,泥质粉砂塑性变形程度越高,越易形成相对简单的水平裂缝和细小的裂缝带,且裂缝宽度不断增大;随泵注压力的不断提高,在井眼周围易产生大量微裂缝(图17)。在水合物“温度场改

造—调控”机理研究方面,创新提出原位补热降压充填开采法,探索将氧化钙注入水合物层与降压分解水反应产生热量,补充分解导致地层热损失的新思路,并提出了该方法的开采方案、关键技术与工艺步骤。通过数值模拟研究,这种新的开采工艺与水平井压裂相结合后增产效果显著提升,裂缝渗透率和氧化钙注入量是制约该方法能否显著提高采收率的关键参数(李守定等,2020)。在下一步研究中,还需要进一步厘清储层改造支撑强化机理,明确渗流能力主动调控方法,并开展“大型物理模拟实验”验证以及工程可行性评估。

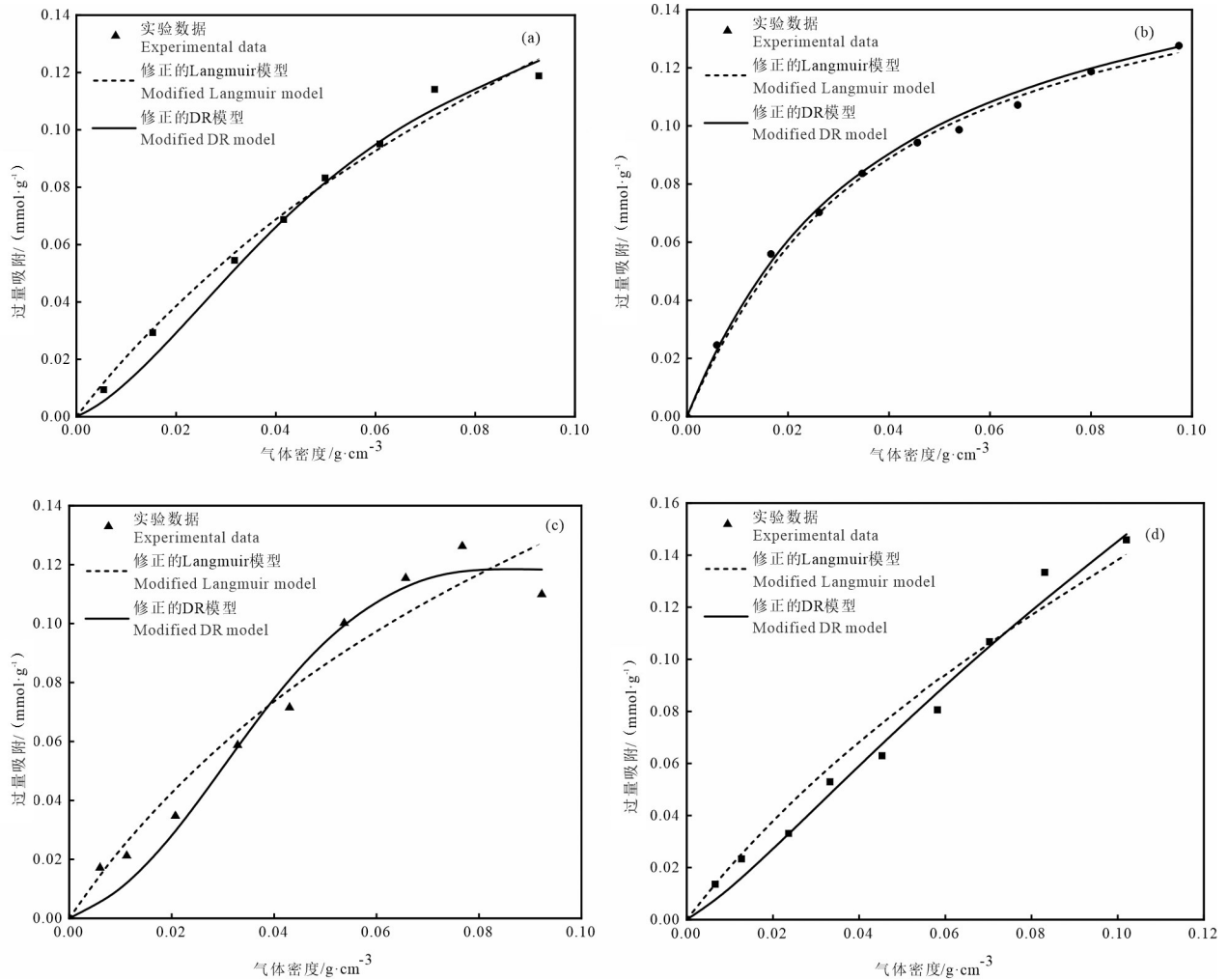


图 14 改进的 Langmuir 和 DR 模型拟合不同实验样品结果图

(a—KT4-16; b—KT4-17; c—KT4-18; d—KT4-16)(Qi et al., 2022)

Fig. 14 Simulation results of samples (a) KT4-16 (dry condition), (b) KT4-17 (dry condition), (c) KT4-18 (dry condition), and (d) KT4-16 (moist condition) using the modified Langmuir and DR models (Qi et al., 2022)

5.2 水合物开采产能模拟与调控

数值模拟是预测水合物开采动态,识别开采敏感因素的重要手段,是进行天然气水合物产能调控的重要平台,模拟器则是开展数值模拟必备的工具。目前模拟器主要以 TOUGH + Hydrate、TOUGH-Fx/Hydrate、MH21-HYDRES、FEHM、GPRS-HYDRATE、CMG STARS 等为主(卢海龙等, 2021)。笔者结合南海天然气水合物矿藏特点,研发了水合物引擎平台(Hydrate Smart V1.0)(秦绪文, 2019)以及储层物性数据综合管理平台(GH Properties V1.0)(秦绪文, 2021)、水合物生产测试现场数据分析平台(Hydrate Captain V1.0)(陆程, 2020)。与国外同类型模拟器相比,Hydrate Smart

模拟器不仅具有网格定义、构造模型、属性模型、岩性分区、网格筛选等一系列基质模型构建功能,还具备模型定义、物性参数、井段模型、生产控制、水合物特征、平衡初始化、模拟计算等功能,并能通过应用一维曲线、二维平面、二维剖面与三维视图等手段对模拟结果进行综合研判(图 18)。利用自主研发的水合物数值模拟器,对第一轮垂直井试采开展了模拟研究表明,当水合物试采时间到 60 天时,水合物层的分解半径约为 5 m,水合物分解气量占累积产气量的 85%;若持续采用垂直井降压开采,压降漏斗传导将受到限制,水合物层分解产气速率会降低;在试采 60 d 内,储层的温压条件不会造成高饱和度的二次水合物大量形成,但是长期开

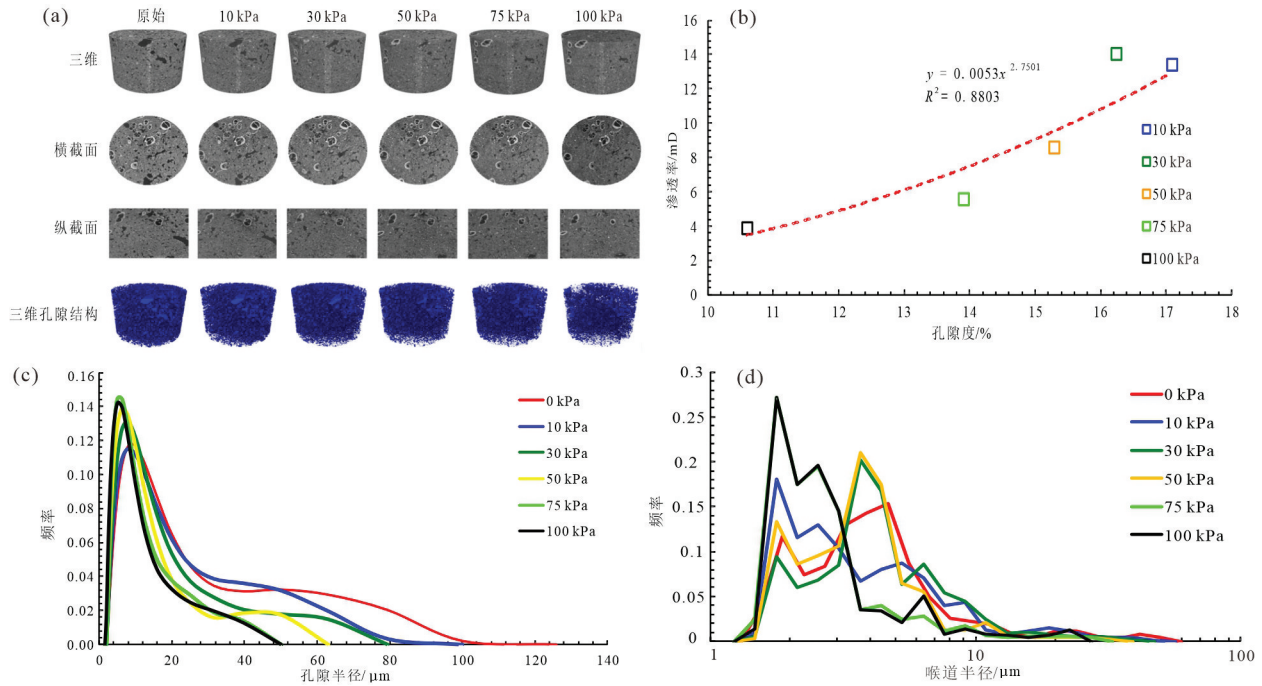


图 15 泥质粉砂储层微观孔隙结构与压力变化关系图

a—泥质粉砂样品在不同压力下的三维、横断面、纵断面和孔隙重建CT图像;b—不同驱替压力下样品孔隙度与渗透率关系图;c—不同压力下泥质粉砂样品的孔径分布数据;d—不同驱替压力下样品的喉道尺寸分布(Lu et al., 2019; Cai et al., 2020)

Fig.15 Relationship between microscopic pore structure and pressure change of clayey silt reservoir

The three-dimensional, cross-sectional, and longitudinal sections and pore reconstruction CT images of the fourth experimental sample under different pressures. a—The pixel resolution of the sample was about 3 μm; b—Porosity versus permeability for the fourth set experiments; c—Pore size distribution of the clayey-silt sample under different axial stresses; d—Throat size distribution of the clayey-silt sample under different axial stresses (Lu et al., 2019; Cai et al., 2020)

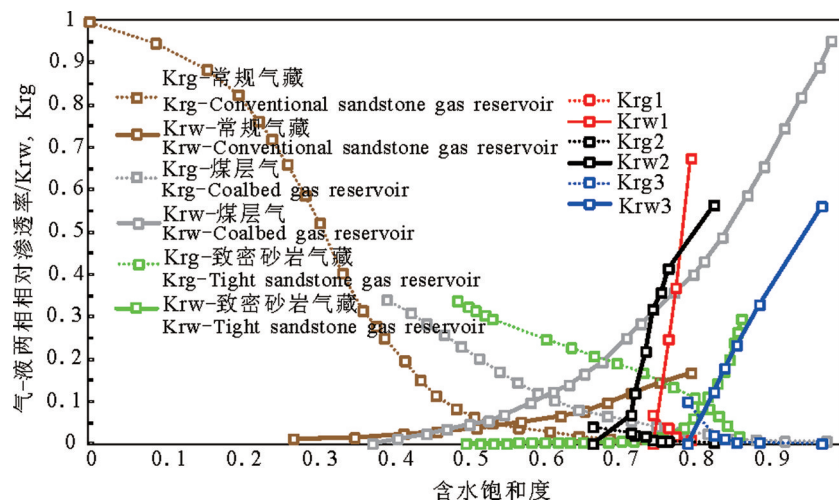


图 16 泥质粉砂与常规砂岩煤层气、致密砂岩气-水两相相对渗透率曲线对比图(Lu et al., 2021)

Fig. 16 Relative permeability curves of other gas reservoirs (Lu et al., 2021)

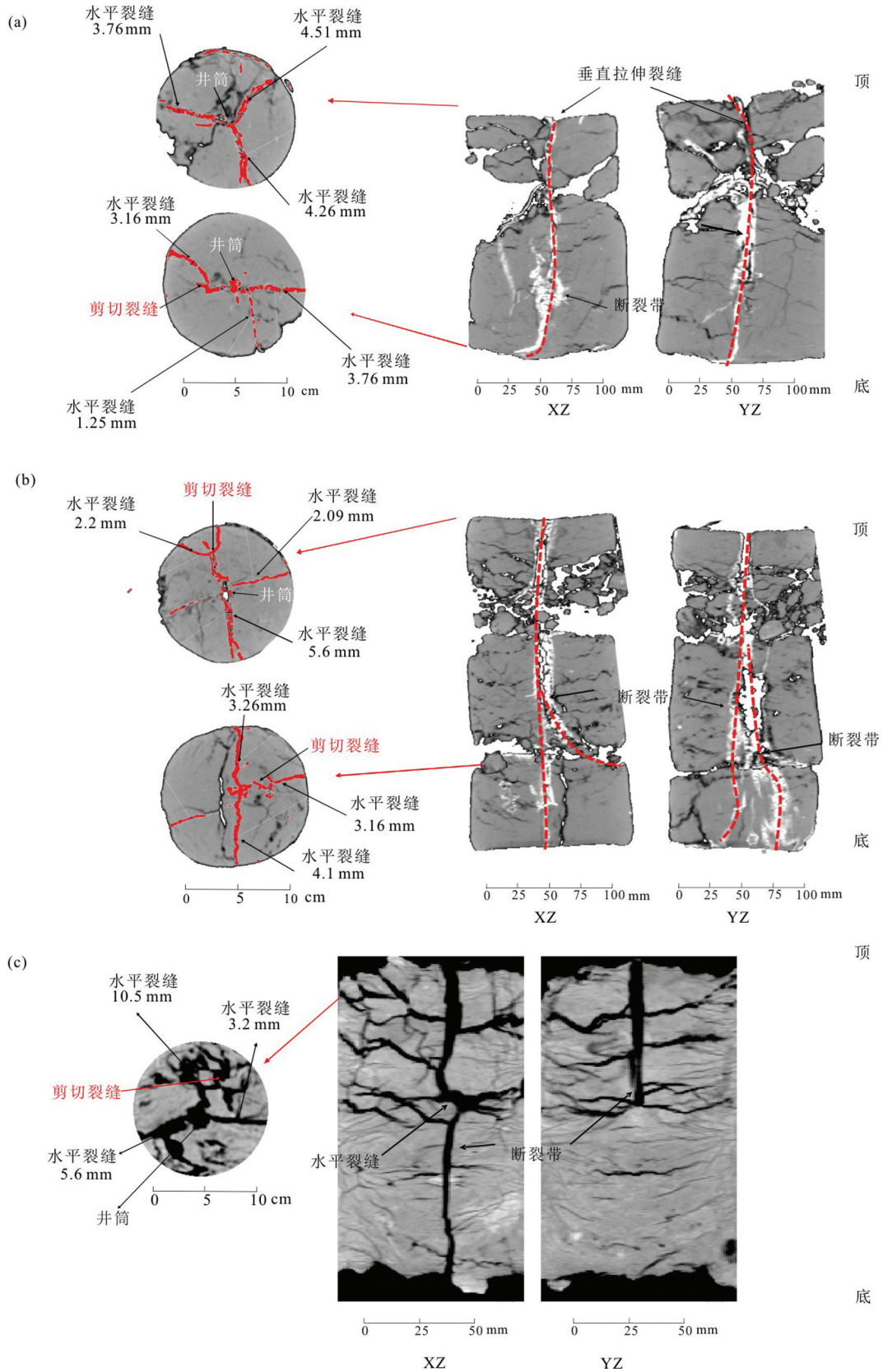


图 17 水合物分解区泥质粉砂储层水力压裂断裂特征 CT 扫描图(Lu et al., 2021)
 Fig. 17 Fracture characteristics of samples 1-3 after hydraulic fracturing by CT (Lu et al., 2021)

采会导致水合物分解前缘位置形成大范围二次水合物,这为创新提出利用水平井试采工艺实施第二轮试采提供了重要的理论支撑(图 19)。

降压策略是水合物试采中指导生产制度编制,进行产能调控的重要依据。通过对南海泥质粉砂储层结构表征、水合物相变、两相渗流、储层渗流能力以及第一次试采生产动态特征等方面综合研究,针对水平井开采,提出了“小幅度缓慢降低井底流压,防止冰与二次水合物生成,长期保持储层有效渗流能力,逐级稳步提高生产压差扩大产量”的“小降长稳”的降压策略,并在第二轮试采实施过程中得到了应用和验证。

6 结论和展望

中国南海天然气水合物资源勘探开发潜力巨大。南海北部神狐海域两轮天然气水合物试采实践表明,天然气水合物开采机理研究至关重要,储层结构表征、水合物相变、多相渗流与增渗、产能模拟与调控是制约水合物分解产气效率的重要因素,尤其水合物相变、渗流机理至为关键。研究结果表明,南

海水合物相变具有分解温度低,易在储层内形成二次水合物等特点,是由渗流场-应力场-温度场-化学场共同作用的复杂系统。多相渗流作用主要受控于未固结储层的物性特征、水合物相变、开采方式等多元因素影响,具有较强的甲烷吸附性、绝对渗透率易突变、气相流动能力弱等特点。因此,针对南海水合物长期、稳定、高效开采,需要在初始储层改造基础上,通过实施储层的二次改造,进一步优化提高储层渗流能力,实现增渗扩产目的。

随着天然气水合物产业化进程的不断推进,从南海天然气水合物开采基础理论角度来看,仍需要着力解决大规模、长时间产气过程中温度压力微观变化及物质能量交换响应机制以及水合物高效分解、二次生成边界条件等难题,重点开展以下4个方面的研究:

- (1)在储层物性研究方面:研究对象需要从以往关注水合物分解区的泥质粉砂多孔介质,重点转向分解前缘区域的含水合物沉积物。依托静态微观可视化技术,厘清该区域内不同状态下的水合物微观分布对孔隙度、渗透率等基础物性参数的影

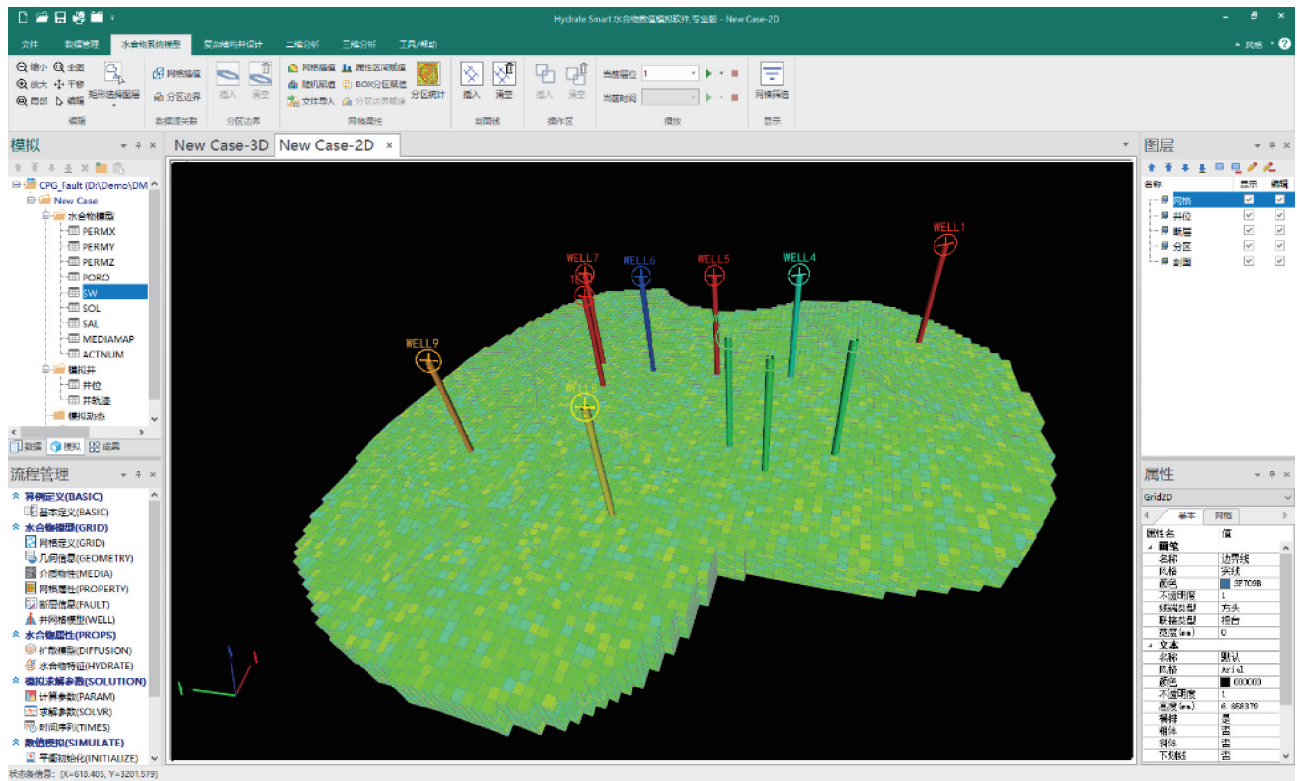


图 18 Hydrate Smart 平台界面(Sun et al., 2021)
Fig. 18 Interface of Hydrate Smart platform (Sun et al., 2021)

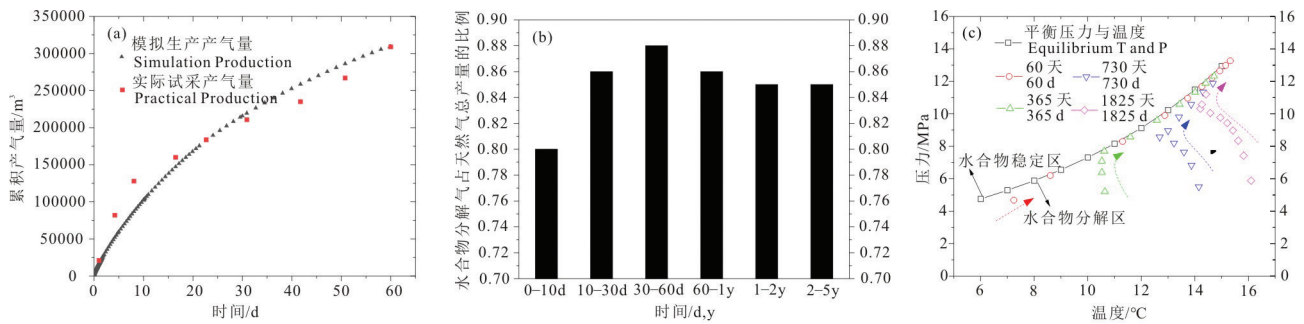


图19 首轮水合物试采生产动态特征与地层温压变化关系图

a—海域首轮水合物试采产气量预测与实际产气量采气对比图;b—天然气水合物分解气在不同开采时段占总产气量比例关系图;c—水合物开采不同阶段含水合物层温度、孔隙压力条件与水合物平衡条件的对比关系图(Qin et al., 2020)

Fig.19 Relationship between the production dynamic characteristics and the variation of formation temperature and pressure of the first offshore NGHs production test

a—Comparison between simulated and practical gas production during the first offshore NGHs production test;b—The proportion of gas from NGHs dissociation to total gas production in different stages of hydrate exploitation;c—Comparative relationship between the temperature and pore pressure conditions of hydrate-bearing layers and the hydrate equilibrium condition in different stages of hydrate exploitation (Qin et al., 2020)

响,建立开采过程中水合物分解前缘变化对储层能量补给作用机制。

(2)在水合物相变研究方面:需要加强含水合物泥质粉砂沉积物的生成与分解动力学、二次水合物结晶动力学和抑制机理研究。改进现有分子动力学模拟的水分子力场模型、固体分子模型,建立更加贴近南海沉积物实际条件的动力学模型;基于岩心尺度,进一步完善实验模拟装置,建立连续相变过程中不同水合物赋存状态下含水合物沉积物的物性参数表征方法,构建其动态演化的数学模型。

(3)在多相渗流与增渗研究方面:基于岩心尺度,需要重点针对生产井筒至分解前缘之间泥质粉砂分解区内,获取含水合物相变储层相对渗透率和毛细管压力的动态变化参数,厘清多相渗流规律及主控因素,建立从岩心到矿场尺度的相渗模型。同时,需要进一步开展水合物储层二次改造、增渗扩产研究,厘清未固结储层改造支撑强化、储层“温度场改造”机理,研制与之配套的新型材料和工艺,掌握不同相变控制方式下的储层渗流能力变化特征,评价不同增产方法的开采效果。

(4)在产能调控研究方面:需要不断迭代更新水合物相变、渗流以及各种复杂效应耦合的数值计算模型,提高产能模拟的准确度,厘清制约水合物产气效率的主控因素,并形成针对不同试采场景的产能调控机制。

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