井工厂井网部署与压裂模式发展现状与展望

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摘要：随着我国油气对外依存度逐渐加剧，致密油气、页岩油气等非常规油气能源成为了我国能源发展的重点方向。井工厂压裂技术因其可以改造低渗透性地层、大幅降低施工成本、缩短施工周期、提高设备利用率、节约用地而被广泛应用于非常规油气开发之中。本文在论述井工厂压裂技术发展现状的基础上，介绍了丛式水平井的井筒走向、水平段长度、井筒间距等井网部署特点，统计分析了水平井分段分簇的裂缝长度、簇间距和射孔簇数等关键技术参数特点；介绍了丛式水平井井工厂压裂常用的压裂方式，包括双井同步压裂、双井拉链式压裂和多井组合压裂等，对比分析了各种压裂方式的利弊。建议有针对性的发展立体井网井间裂缝干扰预测、井丛压裂孔簇设计等理论，为我国非常规油气储层井工厂压裂技术发展指明了方向。

关键词：水力压裂；井工厂压裂；丛式水平井；分段分簇；井网部署；井丛压裂；立体井网；非常规油气
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Development status and prospect of well pattern deployment and fracturing mode in well factory

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Abstract: With the increasing dependence on foreign oil and gas, unconventional oil and gas energy such as tight oil and gas and shale oil and gas have become the focus of China's energy development. Well factory fracturing technology is widely used in unconventional oil and gas development because it can reconstruct low-permeability formations, significantly reduce construction costs, shorten construction time, improve equipment and land utilization. Based on the discussion of the development status of well factory fracturing technology, this paper introduces the well pattern deployment characteristics of cluster horizontal wells, such as wellbore direction, length of horizontal sections, wellbore spacing and further statistically analyzes the key technical parameters of horizontal wells in segmented clusters, such as fracture length, cluster spacing and perforating cluster number. Moreover, the fracturing methods commonly used in cluster horizontal well factory fracturing are also introduced, including dual-wells simultaneous fracturing, dual-well zipper fracturing and multi-well combination fracturing, and the advantages and disadvantages of the common fracturing methods are analyzed by contrast. It is suggested that the theories such as prediction of interwell fracture interference and well cluster fracturing perforation cluster design should be developed. The research points out the direction for the development of well fracturing technologies for unconventional oil and gas reservoir in China.

Key words: hydraulic fracturing; well factory fracturing; cluster horizontal well; segment clustering; well pattern deployment; cluster fracturing; three-dimensional well pattern; unconventional oil and gas

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0 引言

致密油气、页岩油气储层通常具有低孔低渗特点，水平钻井和水力压裂技术是开发此类储层的两大核心技术。随着水力压裂技术在非常规油气储层的大规模应用，当位于一个区块的多口井需要压裂时，每口井分别进行压裂设备搬迁、安装和压裂液配备，不但会延长工期也会增加生产成本。加拿大能源公司最先提出了井工厂水力压裂技术，并被用于北美页岩气开发，目前已经形成了一套较为成熟的开发模式[1-2]。

中国也广泛地采用井工厂压裂技术，长宁地区龙马溪组页岩气采用拉链式压裂改造模式，完成2个水平井组7口井的压裂实践，较单独压裂作业效率提高1倍[3]。川南地区五峰组—龙马溪组页岩气地区受地形限制，采用整体化的工厂压裂技术，使得钻井、压裂作业效率提高50%以上，设备安装时间减少70%，6口井的平台建设周期降至约1年[4]。焦石坝页岩气田，采用小型丛式井工厂压裂技术，在40多个平台200余口井完成4000余段压裂，平均单井无阻流量为38.5×10^4 m^3/d，相比单井施工周期缩短30%～40%[5]。东辛油田盐227块致密砂砾岩油藏累计实施Y227、L567等8个井工厂整体压裂，在实现高效开发的前提下累计节约投资4.3亿元[6]。

与传统的单井压裂作业相比，井工厂压裂技术优化了施工模式和顺序，一方面其提高了设备利用率，减少了搬迁与安装时间；另一方面，方便回收和处理井下压裂液[7]，既能充分利用水资源，又降低了环境污染风险。

近些年，井工厂压裂技术得到了较大的发展，包括：丛式水平井井网布置、段簇优化设计、多级压裂、同步压裂、拉链压裂、多井组合压裂等。笔者对井工厂压裂技术的特点和现状进行了分析，并阐述了相关技术的应用情况，以期促进中国井工厂压裂技术的发展。

1 丛式水平井井网部署与段簇设计

1.1 丛式水平井井网部署

丛式水平井井网部署（图1）是页岩油气开发中重要的环节，其主要受油气田地质特点、井群产能和总体经济效益控制。主要涉及：水平井数量、井筒走向、水平段长度、井筒水平间距和垂向间距等。

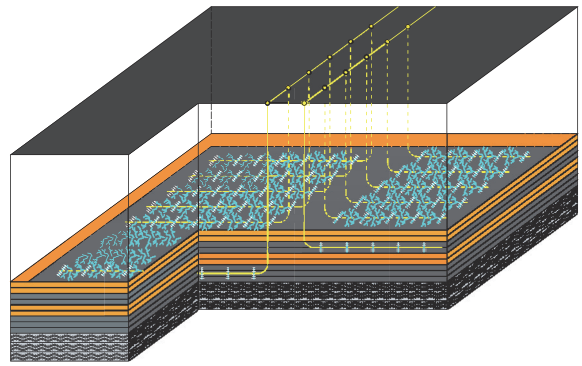

图1 井工厂井网空间布置[8]

Fig.1 Space layout of well pattern in well factory

1.1.1 水平井井筒走向

水力裂缝一般会垂直于最小水平主地应力方向延伸，但由于钻井技术和工程地质条件限制，水平井往往会与最小水平主应力方向成一定角度（见表1），致使井筒与之产生的水力裂缝不完全垂直。水平井横切裂缝与纵向裂缝相比，可以避免裂缝重叠和段间连通的可能性，最大限度的扩大储层接触面积。随着裂缝与井筒夹角的增大，裂缝间距变大，缝间渗流干扰作用降低，油气产量有增加的趋势[9]。因此，在钻井技术和储层地应力条件允许的情况下，井筒应与最小水平主应力平行或小角度相交，有利于形成垂直于井筒的多条横切裂缝，实现用一口水平井代替多口直井的目的。

1.1.2 水平井水平段长度

长水平段水平井是以大限度暴露储层为目的，通过增加储层与井筒的接触达到高产的一种井型。对于非裂缝性油藏，水平井产能可高达直井的3倍；对于裂缝性油藏，水平井产能可高达直井的12倍；对于超低渗油藏，长水平段的水平井也可以大幅度提高油气采收率。2018年，北美的水平段长度极限达到6340 m[16]，Range资源公司已经有78%的水平井水平段长度＞2438 m。2021年，川庆钻探刷新中国超长水平井记录，水平段长度达到5256 m，中国涪陵页岩气井平均水平段长2078 m。

水平井需要根据矿场情况、油藏特征、经济性的因素，选取合理长度[17]。当水平段长度＞2000 m后，钻井作业效率会快速下降[18]，故目前大量油气

表1　水平井井筒走向

Table 1　Wellbore direction in horizontal wells

区块	储层岩性	最小水平地应力方向/(°)	井筒方位/(°)	最小水平地应力与水平段角度/(°)
苏53气田区块[10]	石英砂岩	330～350	347	－3～17
塔里木哈拉哈塘油田区块[11]	缝洞型碳酸盐岩	10～20	16.52	－3.48～6.52
大牛地气田DP4井[12-13]	岩屑石英砂岩	165	156	－9
吉林油田长平3井[14]	致密砂岩	267	260	－7
鄂尔多斯盆地庆城油田H100平台[15]	细砂岩、粉砂岩、页岩	340～350	339.25	－0.75～10.75

田将水平段长度设定在1000～2000 m之间(见表2)。同时水平井水平段长度也呈现出增加的趋势,单个井平台的可动用储层范围逐渐增大。

表2　水平井水平段长度

Table 2　Length of horizontal section in horizontal wells

区块	储层岩性	开钻年份	水平段长度/m
苏里格气田[10, 19]	石英砂岩	2010	805～1256
大牛地气田盒1层[20-21]	岩屑石英砂岩	2012	1239.5(平均)
加拿大Duvernay页岩油田[22]	海相页岩、泥质灰岩	2012—2018	1300→3000
Range公司二叠系盆地[23]	—	2012—2018	951.89→3088.54
Haynesville页岩气田[24-25]	碳酸盐、泥岩	2009—2016	1350→2155
威204页岩气井区[26]	深水陆棚、钙质浅水陆棚页岩	2016—2020	1506→1965
鄂尔多斯盆地庆城油田H100平台	细砂岩、粉砂岩、页岩	2021	1900～3000

注:→表示在年份区间内水平段长度变化。

1.1.3　水平井井筒间距

井工厂裂缝扩展与干扰规律是水平井压裂的难题,目前裂缝干扰研究主要集中在裂缝间影响,关于井间距对裂缝扩展干扰研究不足。井间距是控制储层改造效果和优化井产能的关键,应在合理井间干扰范围内降低井工厂井间距[27]。当丛式水平井井筒间距较大时部分储层不能动用,过小则存在由于井的覆盖面积重叠导致井间渗流干扰、应力干扰以及单井的经济效益下降的风险。砂体规模尺度、压降泄气范围、干扰试井、水力裂缝半长是确定井间距的重要依据[28]。当储层较厚或者具有多个含油层系的情况下,采用多层布井、立体交错布井的“W”形立体布井方式,在横、纵向上选择合适的井间距,达到立体开发储层的目的。涪陵页岩气采用多层系精细开发,横向加密加长、纵向上多层系扩展,形成立体空间密织井网,有效提高储层动用率。中国每个生产平台通常布置6～8口水平井,北美成熟的井工厂平台一般可以钻16～20口井[29](见表3),大平台、大井丛已经成为了一种开发趋势。

1.2　水平井分段分簇

页岩油气、致密油气储层的水平井水平段一般

表3　水平井井筒间距

Table 3　Horizontal wellbore spacing

区块	储层岩性	井间距/m	平台井数/口
中国蜀南地区[30-32]	深水陆棚页岩	400～500	—
涪陵页岩气地区[33]	深水陆棚页岩	300～740	7～8
长宁-威远页岩气区块PT2平台[34]	深水陆棚、钙质浅水陆棚页岩	200～400	6
准噶尔盆地昌吉油田[35]	泥岩、砂砾岩	310～350	7～12
鄂尔多斯盆地庆城油田H100平台	细砂岩、粉砂岩、页岩	175～350	31
Utica页岩气田[36]	陆表海页岩	259～366	—
Bakken页岩气田[37]	黑色泥页岩	302～402	8～17
Eagle Ford页岩气[38]	泥灰岩、灰质页岩	60～150	—
北美页岩气田(平均)[39]	—	180～420	16～20

长达数千米，储层改造时需将水平段划分为多个井段，每个井段含有多个射孔簇，形成了水平井多段多簇压裂改造技术。

1.2.1　裂缝长度

日产量通常随着水力裂缝长度的增加而增高，但是增加的幅度不断下降，因此存在最佳裂缝长度，其受到压裂方法、地应力分布、水平井分布的影响，在最佳裂缝长度后增产效果和压裂投入不成正比[40]。

对于单口水平井压裂，当裂缝半长沿水平井分布为两端长中间短情况时（见图2），类似于U形布缝方式，外侧的裂缝对于总产量的贡献大于内侧裂缝的贡献[41]，更好的扩大了流体椭圆渗流区域，降低了流体渗流阻力[42]。

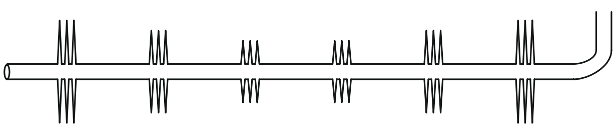

图2　裂缝长度沿井筒分布规律

Fig.2　Distribution law of fracture length along wellbore

对于单个压裂段而言，U形布缝外侧裂缝较长，控制范围较大，中间裂缝对于产量影响较少。数值模拟表明，U形布缝累计产能＞反U形布缝累计产能＞锯齿形布缝累计产能（见图3）[43]。

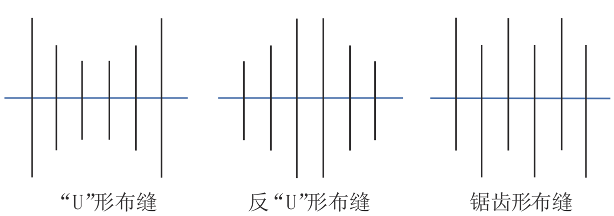

图3　布缝方式

Fig.3　Fracture arrangement

对于多井压裂，在设计井间距与裂缝长度时应考虑压裂过程中井间裂缝互相干扰的影响，使得相邻井裂缝内部的压裂液互相沟通而支撑剂未沟通的程度，有效利用井间应力干扰使裂缝复杂化[44]。裂缝长度可以出于强化平面有利干扰原则，按照井距的2/3～3/4设计裂缝半长，实现缝长交叉，避免超长缝长引起的不利干扰[44]。庆城县南庄乡西233井区水平井优化裂缝半长为80～180 m。滨425区块[45]以3年累计产油量优化裂缝半长为70～90 m。陈汾君等[46]对新场气田沙二气藏中四口井进行产能优化，指出其最优裂缝长度为70～110 m。

国内外对于裂缝间距与缝长设计时，大多采用等间距和缝长，且在产能预测的时候进行一定简化与近似，考虑井间干扰与缝间干扰较少，与现场的实际情况存在一定差距。

1.2.2　簇间距

簇间距对油气产能影响较大，通常随着簇间距增大，井间干扰减小，单裂缝产量增高，但是总体经济效益较低。裂缝间距越小，缝间应力干扰严重，但储层沟通更为充分，初期产能较高[47-48]，后期产量递减较快。由于地层厚度、天然裂缝、地应力、脆性指数等的非均匀性，往往会导致地质甜点和工程甜点区域不连续。现场压裂实践认为，在甜点区射孔压裂会最大程度实现裂缝开启和缝网改造[49]，因此，在布置簇间距时应尽量避免缝间应力干扰产生的副作用，又能沟通甜点区域[50]。

当采用非均匀簇间距设计时，不同的裂缝间距组合对水平井产量影响很大。采用两侧裂缝间距较小，而井筒中部裂缝间距较大的时候，产能明显优于其他情况，这是因为水平井两端裂缝渗流控制区域大于井中间段的控制区域（见图4）。

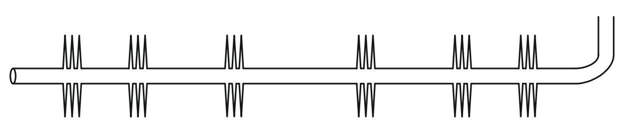

图4　簇间距沿井筒分布规律

Fig.4　Distribution law of cluster spacing along wellbore

裂缝间距设计一般基于整体经济效益评价、产能模拟最大化的结果[51]，同样也需要考虑主应力差、可压性等因素的影响。当水平最大与最小主应力较接近，尤其是水平应力非均质系数＜0.2时较易形成复杂裂缝[52]。因此，确定裂缝间距时需要考虑诱导应力和裂缝距离的关系，使得诱导应力可以大于裂缝张开的压力[53-54]。

表4可以看出目前射孔簇间距在合理范围内呈现缩短的趋势，缩短簇间距可以让簇间应力干扰增强，裂缝转向和裂缝复杂度得到提高，簇间储层得到更充分利用。

1.2.3　射孔簇数

在使用水力压裂技术改造油气储层的过程中，通常在一个水平压裂段中使用多个射孔簇去降低

表4 水平井簇间距

Table 4 Horizontal cluster spacing

区块	年份	簇间距/m
Midland Basin[55]	2010—2017	16.7→7.6
长宁页岩气[56]	2014—2019	27→16
鄂尔多斯盆地庆城油田H100平台	2021	8～20
Eagle Ford[57]	2014—2017	16.7→4
威页X-4HF页岩气井[58]	2020	8.4～9.9
Permian Basin[59-60]	—	16→4.5

注:→表示在年份区间内簇间距变化。

单口井的总压裂段数。但是由于1/3的压裂簇无效,因此,应合理的设计簇数与单个段长。

在簇间距一致的条件下,簇数越多产生的无效裂缝越多,产量越低;需要在单段内尽量选岩性及力学性质相似的井段布置射孔簇。射孔簇位置应以地质甜点为前提,优选段内岩性、物性、脆性、地应力差异性较小的区域,尽量选择天然裂缝发育的区域,避免对产层、非产层段同时射孔。在压裂实践中,应由简单的追求压裂波及体积转变为在有限的波及内尽可能提高体积裂缝密度,由井控储量模式转变为缝控储量模式,增加产能[61]。

表5列举了一些典型页岩油气区块的单段长度和簇数,目前在储层改造过程中形成了单段簇数增多,簇间距缩短的加密切割发展趋势。

表5 水平井分段段长与单段簇数

Table 5 Section length and cluster number of single segment in horizontal wells

区块	储层岩性	分段段长/m	单段簇数
Permian Basin页岩气区块[59]	硅质页岩	90～108→30～35	平均3→平均10
Bakken页岩气区块[62]	黑色泥页岩	70～105	6～15
加拿大Duvernay页岩气田[63-64]	海相页岩、泥质灰岩	平均90→平均49	6～7
长宁-威远国家级页岩气[65]	深水、浅水陆棚页岩	17.49～50.26	—
吉木萨尔页岩油[66-67]	灰色泥岩、夹砂质泥岩	60～90	5～12
鄂尔多斯盆地庆城油田	细砂岩、粉砂岩、页岩	15～50	3～5

注:→表示该区块变化趋势。

2 井工厂水力压裂常用的压裂方式

井工厂常见的压裂方式为双井同步压裂、双井拉链式压裂和多井组合压裂等。

2.1 双井同步压裂技术

同步压裂技术(见图5)即在压裂过程中,同时对两个及以上平行的相邻井进行压裂,压裂液和支撑剂在两口井之间的运移距离最短,从而使得不同的井之间产生沟通效果,大大提高了裂缝的导流能力,同时可以增加水力裂缝网络密度和增加压裂作业时产生的表面积,产生更加复杂的三维裂缝网络[68]。目前同步压裂技术不只限于2口深度相似且距离接近的井,已经可以满足3～4口水平井同时压裂[69]。

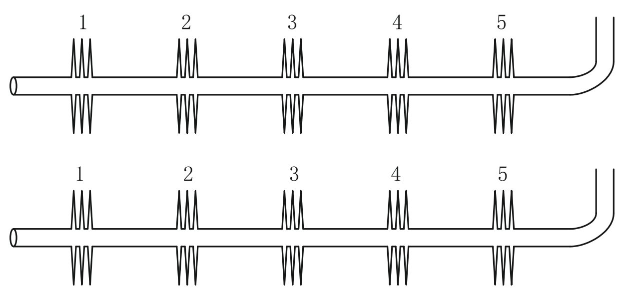

图5 双井同步压裂(压裂顺序如图中1→5)

Fig.5 Dual-well simultaneous fracturing (fracturing sequence as 1→5)

同步压裂技术在美国Barnett页岩气井开发得到了广泛应用,显著提高了页岩气井的产能[66]。俄克拉荷马州东部的Woodford页岩地区采用了同步水力压裂开发策略,盆地西部地区的初始产量增加了20%,东部地区增加了72%[70]。美国得克萨斯州沃斯堡盆地公布的数据显示,在相邻的两口页岩气水平井中采用同步压裂技术,产量得到显著提高。苏53区块致密砂岩气田采用工厂化同步压裂储层改造措施,优选6口水平井实施双井同步压裂,单井日产气量11.80×10⁴ m³/d,比苏53区块13年投产水平井产气量高0.49×10⁴ m³/d[71]。

2.2 双井拉链式压裂技术

双井拉链式压裂即在多井平台上一口井进行压裂作业,一口井进行电缆桥塞射孔作业,两口井交替压裂,同时在另外一口井中下入裂缝监测设备实时监测裂缝参数,可以降低非生产时间。详细作业即对于1、2两口井进行拉链压裂作业,电缆等设备在1、2井中交替使用同时完成下桥塞和坐封作

业，在压裂其他井时1、2井进行钻磨桥塞等其他作业，而后在都完成钻磨桥塞等作业后统一放喷排液。拉链压裂产生的微地震事件明显多于单井压裂产生的微地震事件，丛式井平台拉链式压裂可以大幅度改造储层达到增产的目的，同时采用拉链式压裂井间的应力干扰有利于裂缝发生转向生成更好的裂缝网络[72]。

2.2.1 传统拉链式压裂

传统的双井拉链式压裂（见图6）即将两口水平井射孔簇安放在相同位置，使得各个裂缝相对生成，可以最大限度的提高每个裂缝尖端的应力扰动，但是该扰动仅限于裂缝尖端区域[73]。

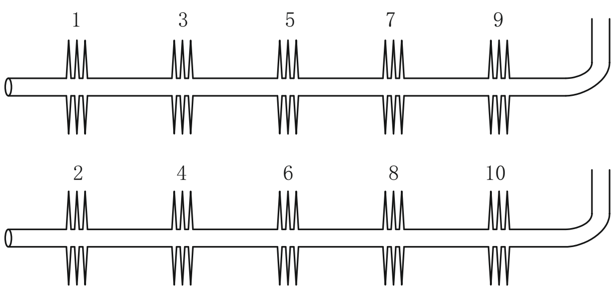

图6 双井拉链压裂（压裂顺序如图中1→10）

Fig.6 Dual-well zipper fracturing (fracturing sequence as 1→10)

2.2.2 改进拉链压裂

传统拉链式压裂虽然可以减小水平应力各向异性，但是实际操作过于复杂，改进的拉链式压裂（见图7）将拉链式压裂与交替压裂结合，将裂缝设计为交错模式，使得形成更多的复杂裂缝[74-75]。改进拉链压裂中诱导应力对裂缝扩展影响较小，裂缝宽度分布较均匀，同时其可以产生较大的诱导应力，但是主应力方向变化较小，最佳裂缝间距小于顺序压裂与交替压裂[76]。

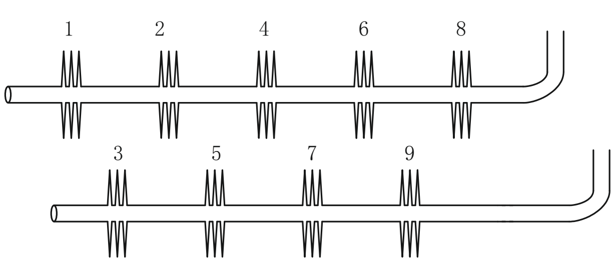

图7 改进的双井拉链压裂（压裂顺序如图中1→9）

Fig.7 Improved dual-well zipper fracturing (fracturing sequence as 1→9)

2013年，中国石油首次应用拉链式压裂技术对长宁平台进行页岩气工厂化压裂，平均每天压裂3.16段，极大地提高了压裂时效[77]。涪陵页岩气田井工厂技术设计双井拉链压裂与双机组同步压裂方式，较好的完成了建平台、钻井、压裂、产气的开发要求。威远W202H2区块采用多井拉链作业，在444 d内完成103级（299簇）压裂，注入流体189023 m^3与支撑剂6677 m^3，节约成本约600万美元[78]。焦石坝区块目前已经完成了40多个多井平台、200口井、4000级改进式拉链压裂工作，单井平均产出流量38.5×10^4 m^3/d，工期缩短30%～40%，单井产能和施工效率明显提高[79]。美国Eagle Ford采用拉链压裂方式使初始产量提高了20%～40%[80]。墨西哥北部盆地运用改进式拉链水力压裂技术，经过32级水力压裂后，单口水平井初始产量为4160桶/天，初始产量达到常规井的15倍以上，90 d累计产量为常规产量的14倍以上[81]。

2.3 多井组合压裂

在多井压裂中，如果两口井产生的应力正面相交则可能导致应力抵消，减缓裂缝的延伸，而当斜向相交情况下，可以通过剪切形成新的裂缝，促进压裂的效果[82]。因此可以通过不同的压裂顺序，利用缝间应力干扰，提高压裂效果。

在多井组合压裂中拉链压裂较为流行，即一口井进行泵送，另外一口井进行电缆作业，减少了压裂过程中的停机时间，提高了作业效率。通常情况下，一次压裂作业的井不超过4口，单层3口井拉链压裂按照是否考虑中间井筒的延后可以分为两种[83-84]（见图8、图9）。

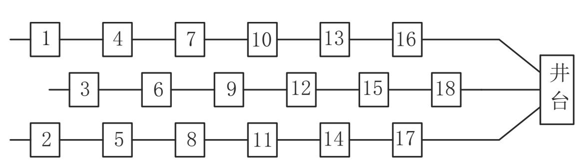

图8 单层3口井拉链压裂

Fig.8 Zipper fracturing of three wells in single formation

单层4口井拉链压裂按照相邻井分组和间隔井分组可分为两种[83-84]：第一种是将4口井分为两组，1、3两口井先进行拉链压裂，而后2、4两口井再进行拉链压裂（见图10）；另外一种是可以将两口井拉链压裂扩展到多井压裂，压裂作业从井场边缘由外向内，优先两侧井压裂可以减少中间区域的水平应力

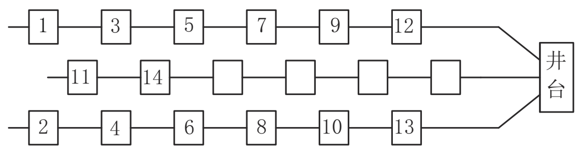

图9　单层3口井拉链压裂(中间井筒延后)

Fig.9　Zipper fracturing of three wells in single formation (with intermediate shaft lag)

差,为形成复杂裂缝和降低断层滑动风险提供条件(见图11)。

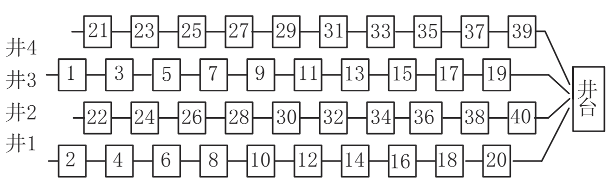

图10　单层4口井拉链压裂(间隔井为一组)

Fig.10　Zipper fracturing of four wells in single formation (spaced wells are grouped)

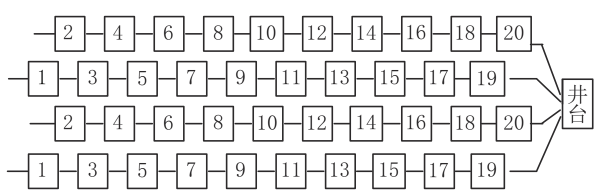

图11　单层4口井拉链压裂(相邻井为一组、且从井场边缘向内压裂)

Fig.11　Zipper fracturing of four wells in single formation (adjacent wells are grouped together and fractured inwards from the edge of the well site)

常规的3、4口井的拉链压裂方式更容易使得产生的水力裂缝向着天然存在的薄弱面靠近,增加了裂缝之间的干扰程度,限制了新的裂缝的产生数量,而中间井筒延后和由边缘向内压裂的拉链压裂方式(参见图9~11)消除了裂缝偏向薄弱面的问题,可以使裂缝均匀的生长,降低了井间干扰对于裂缝扩展的影响[83]。

当井场处于较厚储层或多个储层时,通常需要采用多层立体开发压裂,各产层产生的裂缝应该控制在各自附近位置,防止裂缝窜到相邻产层;可以在满足“W”型布井基础上,压裂中采用交叉的原则,从上到下再从上到下,降低裂缝间互相干扰,提高井网开采效率[85](见图12)。美国QEP资源开发公司在Permian盆地采用多层立体开发,相比于传统单层开发模式,成本降低19%[86]。

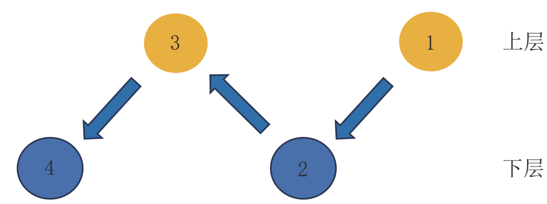

图12　上、下两层拉链压裂示意

Fig.12　Diagram of zipper fracturing in upper and lower strata

3　发展展望

(1)目前井工厂水力压裂井网布置主要采用丛式水平井布置,其主体思路为:井筒与最小水平主应力平行或小角度相交,使得裂缝近似于垂直井筒,最大可能扩大裂缝接触面积;选取经济合理的水平段长度,增大储层与井筒接触面积;合理布置井筒间距与平台井数,达到既可以充分动用储层又不会产生单井覆盖面积重叠的问题。目前大平台、大井丛已经成为了一种开发趋势。

(2)在水平井多段多簇压裂作业中,宜采用两端长中间短的裂缝长度布置方式。目前的分段分簇原则主要为:单段内岩性、物性、主应力、脆性差异性较小,段内避免对于产层、非产层的同时射孔压裂改造;射孔簇选择以地质甜点为前提,优选段内岩性、地应力一致区域,合理降低裂缝间距使得簇间储层得到充分利用。目前在储层改造过程中单段簇数增多,簇间距缩短,即水平井分段压裂技术整体在合理范围内呈现加密切割储层的趋势。

(3)井工厂水力压裂相对于单口井压裂更加强调施工效率与相邻井筒的裂缝干扰,相比于顺序压裂、交替压裂,拉链压裂工艺可以提供较快施工速度、降低裂缝干扰,更适合井工厂压裂。

(4)针对目前对于井间裂缝扩展应力干扰研究较少;在对于井网设计时,裂缝间距和缝长存在部分简化与近似的问题,建议有针对性的发展立体井网井间裂缝干扰预测、井丛压裂孔簇设计理论。

参考文献(References):

[1]　张金成,孙连忠,王甲昌,等.“井工厂”技术在我国非常规油气开发中的应用[J].石油钻探技术,2014,42(1):20-25.
ZHANG Jincheng, SUN Lianzhong, WANG Jiachang, et al. Application of multi-well pad in unconventional oil and gas devel-

opment in China[J]. Petroleum Drilling Techniques, 2014,42(1):20-25.

[2] 王敏生,光新军.页岩气"井工厂"开发关键技术[J].钻采工艺,2013,36(5):1-4.
WANG Minsheng, GUANG Xinjun. Key technologies of shale gas development by "well factory"[J]. Drilling & Production Technology, 2013,36(5):1-4.

[3] 任勇,钱斌,张剑,等.长宁地区龙马溪组页岩气工厂化压裂实践与认识[J].石油钻采工艺,2015,37(4):96-99.
REN Yong, QIAN Bin, ZHANG Jian, et al. Practice and understanding of industrial fracturing for shale gas of Longmaxi Formation in Changning region[J]. Oil Drilling & Production Technology, 2015,37(4):96-99.

[4] 马新华,谢军.川南地区页岩气勘探开发进展及发展前景[J].石油勘探与开发,2018,45(1):161-169.
MA Xinhua, XIE Jun. The progress and prospects of shale gas exploration and exploitation in southern Sichuan Basin, NW China[J]. Petroleum Exploration and Development, 2018,45(1):161-169.

[5] 肖佳林,李奎东,高东伟,等.涪陵焦石坝区块水平井组拉链压裂实践与认识[J].中国石油勘探,2018,23(2):51-58.
XIAO Jialin, LI Kuidong, GAO Dongwei, et al. Practice and cognition on zipper fracturing of horizontal well group in Jiaoshiba Block, Fuling[J]. China Petroleum Exploration, 2018,23(2):51-58.

[6] 赵明宸,徐赋海,姜亦栋,等.东辛油田盐227块致密砂砾岩油藏井工厂开发技术[J].油气地质与采收率,2014,21(1):103-106.
ZHAO Mingchen, XU Fuhai, JIANG Yidong, et al. Study and application on development technique for tight conglomerate reservoir, Yan227 block[J]. Petroleum Geology and Recovery Efficiency, 2014,21(1):103-106.

[7] Naizhen L, Ming L. Well-plant operation model: Case study of tight-gas sands in Sulige Gas Field, NW China[C]//SPE/IATMI Asia Pacific Oil & Gas Conference and Exhibition. OnePetro, 2015.

[8] 邹才能,丁云宏,卢拥军,等."人工油气藏"理论,技术及实践[J].石油勘探与开发,2017,44(1):144-154.
ZOU Caineng, DING Yunhong, LU Yongjun, et al. Concept, technology and practice of "man-made reservoirs" development[J]. Petroleum Exploration and Development, 2017,44(1):144-154.

[9] 曲占庆,赵英杰,温庆志,等.水平井整体压裂裂缝参数优化设计[J].油气地质与采收率,2015,19(4):106-110.
QU Zhanqing, ZHAO Yingjie, WEN Qingzhi, et al. Fracture parameters optimization in integral fracturing of horizontal well[J]. Petroleum Geology and Recovery Efficiency, 2015,19(4):106-110.

[10] 叶成林.苏里格气田水平井参数优化及效果评价——以苏53区块为例[J].石油天然气学报,2012,34(01):107-110.
YE Chenglin. Parameter optimization and effect evaluation of horizontal wells in Sulige Gas Field: A case study of Block Su 53[J]. Journal of Oil and Gas Technology, 2012,34(1):107-110.

[11] 刘辉,袁学芳,文果,等.超深碳酸盐岩油藏水平井套管分段酸压技术实践[J].钻采工艺,2016,39(5):33-35,102.
LIU Hui, YUAN Xuefang, WEN Guo, et al. Practice of stage acid frac in cased horizontal well in ultradeep carbonate reservior[J]. Drilling & Production Technology, 2016, 39(5): 33-35,102.

[12] 邢景宝.大牛地气田水平井分段压裂技术研究与应用[J].钻采工艺,2011,34(2):25-28.
XING Jingbao. Fracturing technology for horizontal well in Daniudi Gas Field[J]. Drilling&Production Technology, 2011,34(2):25-28.

[13] 任广磊,周涌沂,陈奎,等.大牛地气田大98井区水平井开发技术政策研究[J].油气地质与采收率,2015,21(5):90-93.
REN Guanglei, ZHOU Yongyi, CHEN Kui, et al. Research on horizontal well development technology policy of Da98 well area in Daniudi Gas Field[J]. Petroleum Geology and Recovery Efficiency, 2015,21(5):90-93.

[14] 李金平.小井眼长水平段水平井摩阻扭矩分析方法研究[J].中外能源,2013,18(9):58-62
LI Jinping. Research on analytical method of friction and torque for horizontal well with long slim-hole horizontal section[J]. Sino-Global Energy, 2013,18(9):58-62.

[15] 刘建,惠晨,樊建明,等.鄂尔多斯盆地合水地区长6致密砂岩储层现今地应力分布特征及其开发建议[J].地质力学学报,2021,27(1):31-39.
LIU Jian, HUI Chen, FAN Jianming, et al. Distribution characteristics of the present-day in-situ stress in the Chang 6 tight sandstone reservoirs of the Yanchang Formation in the Heshui Area, Ordos Basin, China and suggestions for development[J]. Journal of Geomechanics, 2021,27(1):31-39.

[16] 张家希,于家庆,何跃文,等.北美非常规油气超长水平井优快钻井技术及实例分析[J].钻探工程,2021,(8):1-11.
ZHANG Jiaxi, YU Jiaqing, HE Yuewen, et al. North America unconventional long lateral well fast-drilling technology with case study[J]. Drilling Engineering, 2021,(8):1-11.

[17] 薛婷,黄天镜,成良丙,等.鄂尔多斯盆地庆城油田页岩油水平井产能主控因素及开发对策优化[J].天然气地球科学,2021,32(12):1880-1888.
XUE Ting, HUANG Tianjing, CHENG Liangbing, et al. Dominating factors on shale oil horizontal well productivity and development strategies optimization in Qingcheng Oilfield, Ordos Basin[J]. Natural Gas Geosicence, 2021,32(12):1880-1888.

[18] 陈志鹏,梁兴,王高成,等.旋转地质导向技术在水平井中的应用及体会——以昭通页岩气示范区为例[J].天然气工业,2015,35(12):64-70.
CHEN Zhipeng, LIANG Xing, WANG Gaocheng, et al. Application of rotary geosteering technology in horizontal wells and its implication: A case study of the Zhaotong shale gas demonstration area of Yunnan[J]. Natural Gas Industry, 2015,35(12):64-70.

[19] Luo C, Jia A, Guo J, et al. Analysis on effective reservoirs and length optimization of horizontal wells in the Sulige Gasfield[J]. Natural Gas Industry B, 2016,3(3):245-252.

[20] 何世明,汤明,熊继有,等.小井眼长水平段水平井摩阻扭矩控制技术[J].西南石油大学学报(自然科学版),2015,37(6):85-92.
HE Shiming, TANG Ming, XIONG Jiyou, et al. Friction and

torque control technology for slim and long horizontal well[J]. Journal of Southwest Petroleum University (Science & Technology Edition), 2015,37(6):85-92.

[21] 陈作,何青,王宝峰,等.大牛地气田长水平段水平井分段压裂优化设计技术[J].石油钻探技术,2013,41(6):82-85.
CHEN Zuo, HE Qing, WANG Baofeng, et al. Design optimization of staged fracturing for long lateral horizontal wells in Daniudi Gas Field[J]. Petroleum Drilling Techniques, 2013, 41(6):82-85.

[22] 李国欣,罗凯,石德勤.页岩油气成功开发的关键技术、先进理念与重要启示——以加拿大都沃内项目为例[J].石油勘探与开发,2020,47(4):739-749.
LI Guoxin, LUO Kai, SHI Deqin. Key technologies, engineering management and important suggestions of shale oil/gas development: Case study of a Duvernay shale project in Western Canada Sedimentary Basin[J]. Petroleum Exploration and Development, 2020,47(4):739-749.

[23] Lu H, Zhang C, Yuan Z, et al. The strategy of production operation for extended lateral shale wells[C]. Proceedings of the SPE Annual Technical Conference and Exhibition, Calgary, Albeta, Canada, 2019.

[24] Hammes U, Hamlin H S, Ewing T E J A B. Geologic analysis of the Upper Jurassic Haynesville Shale in east Texas and west Louisiana[J]. AAPG bulletin, 2011,95(10):1643-1666.

[25] 万玉金,何畅,孙玉平,等.Haynesville页岩气产区井位部署策略与启示[J].天然气地球科学,2021,32(2):288-297.
WAN Yujin, HE Chang, SUN Yuping, et al. Well deployment strategy and enlightenment of Haynesville shale gas play[J]. Natural Gas Geosicence, 2021,32(2):288-297.

[26] 邹才能,赵群,丛连铸,等.中国页岩气开发进展、潜力及前景[J].天然气工业,2021,41(1):1-14.
ZOU Caineng, ZHAO Qun, CONG Lianzhu, et al. Development progress, potential and prospect of shale gas in China[J]. Natural Gas Industry, 2021,41(1):1-14.

[27] 叶海超,光新军,王敏生,等.美页岩油气低成本钻完井技术及建议[J].石油钻采工艺,2017,39(5):552-558.
YE Haichao, GUANG Xinjun, WANG Minsheng, et al. Low-cost shale oil and gas drilling and completion technologies used in the North America and the suggestions[J]. Oil Drilling & Production Technology, 2017,39(5):552-558.

[28] Zhu J, Forrest J, Xiong H, et al. Cluster spacing and well spacing optimization using multi-well simulation for the lower Spraberry shale in Midland basin[C]. Proceedings of the SPE Liquids-Rich Basins Conference-North America, Midland, Texas, US, 2017.

[29] 严向阳,李楠,王腾飞,等.美国致密油开发关键技术[J].科技导报,2015,33(9):100-107.
YAN Xiangyang, LI Nan, WANG Tengfei, et al. Key technologies for tight oil development in the United States[J]. Science & Technology Review, 2015,33(9):100-107.

[30] Gao S, Liu H, Ye L, et al. A new method for well pattern density optimization and recovery efficiency evaluation of tight sandstone gas reservoirs[J]. Natural Gas Industry B, 2020,7(2):133-140.

[31] LI Guoxin, QIN Jianhua, XIAN Chenggang, et al. Theoretical understandings, key technologies and practices of tight conglomerate oilfield efficient development: A case study of the Mahu Oilfield, Junggar Basin, NW China[J]. Petroleum Exploration and Development, 2020,47(6):1275-1290.

[32] 石林,张鲲鹏,慕立俊.页岩油储层压裂改造技术问题的讨论[J].石油科学通报,2020,5(4):496-511.
SHI Lin, ZHANG Kunpeng, MU Lijun. Discussion of hydraulic fracturing technical issues in shale oil reservoirs[J]. Petroleum Science Bulletin, 2020,5(4):496-511.

[33] 焦方正.页岩气"体积开发"理论认识、核心技术与实践[J].天然气工业,2019,39(5):1-14.
JIAO Fangzheng. Theoretical insights, core technologies and practices concerning "volume development" of shale gas in China[J]. Natural Gas Industry, 2019,39(5):1-14.

[34] 雍锐,常程,张德良,等.地质-工程-经济一体化页岩气水平井井距优化——以国家级页岩气开发示范区宁209井区为例[J].天然气工业,2020,40(7):42-48.
YONG Rui, CHANG Cheng, ZHANG Deliang, et al. Optimization of shale-gas horizontal well spacing based on geology-engineering-economy integration: A case study of Well Block Ning209 in the National Shale Gas Development Demonstration Area[J]. Natural Gas Industry, 2020,40(7):42-48.

[35] 文乾彬,杨虎,石建刚,等.昌吉油田致密油长位移丛式水平井钻井技术[J].新疆石油地质,2014,35(3):356-360.
WEN Qianbin, YANG Hu, SHI Jiangang, et al. Drilling technology of large displaced cluster horizontal well for tight oil in Changji Oilfield, Junggar Basin[J]. XinJiang Petroleum Geology, 2014,35(3):356-360.

[36] Craig Cipolla, Constance Gilbert, Aviral Sharma, et al. Case history of completion optimization in the Utica[C]. Proceedings of the SPE Hydraulic Fracturing Technology Conference and Exhibition, Society of Petroleum Engineers, Texas, 2018.

[37] 丁麟,程峰,于荣泽,等.北美地区页岩气水平井井距现状及发展趋势[J].天然气地球科学,2020,31(4):559-566.
DING Lin, CHENG Feng, YU Rongze, et al. Current situation and development trend of horizontal well spacing for shale gas in North America[J]. Natural Gas Geosicence, 2020, 31(4):559-566.

[38] Hou L, Zou C, Yu Z, et al. Quantitative assessment of the sweet spot in marine shale oil and gas based on geology, engineering, and economics: A case study from the Eagle Ford Shale, USA[J]. Energy Strategy Reviews, 2021,38:100713.

[39] Energy Information Administration, US Department of Energy. Review of emerging resources: US shale gas and shale oil plays[R]. 2011.

[40] Hao MQ, Hu YL, et al. Predicting and optimising the productivity of multiple transverse fractured horizontal wells in ultra-low permeability reservoirs[C]//International Petroleum Technology Conference, OnePetro, Beijing, 2013.

[41] LI Longlong, YAO Jun, LI Yang, et al. Productivity calculation and distribution of staged multi-cluster fractured horizontal wells[J]. Petroleum Exploration and Development, 2014, 41(4):504-508.

[42] 王志平,朱维耀,高英,等.水平井-直井整体压裂组合井网产量预测模型的建立与应用[J].特种油气藏,2012,19(3):

101-103.
WANG Zhiping, ZHU Weiyao, GAO Ying, et al. Establishment and application of recovery predictional model for integrally fractured pattern of horizontal-vertical well[J]. Special Oil & Gas Reservoirs, 2012,19(3):101-103.

[43] 宋彦志,杨倩,任哲雨,等.页岩气藏压裂水平井产能计算及其影响因素[J].大庆石油地质与开发,2023,42(3):1-9.
SONG Yanzhi, YANG Qian, REN Zheyu, et al. Productivity calculation and its influencing factors of fractured horizontal well in shale gas reservoir[J]. Petroleum Geology & Oilfield Development in Daqing, 2023,42(3):1-9.

[44] 李国欣,覃建华,鲜成钢,等.致密砾岩油田高效开发理论认识、关键技术与实践——以准噶尔盆地玛湖油田为例[J].石油勘探与开发,2020,47(6):1185-1197.
LI Guoxin, QIN Jianhua, XIAN Chenggang, et al. Theoretical understandings, key technologies and practices of tight conglomerate oilfield efficient development: A case study of the Mahu oilfield, Junggar Basin, NW China[J]. Petroleum Exploration and Development, 2020,47(6):1185-1197.

[45] 蒋宝云,周玉龙,陈莉,等.滨425区块非均质油藏压裂裂缝参数优化[J].科学技术与工程,2021,21(22):9322-9329.
JIANG Baoyun, ZHOU Yulong, CHEN Li, et al. Optimization of fracture parameters for heterogeneous reservoir in B425 Block [J]. Science Technology and Engineering, 2021, 21(22):9322-9329.

[46] 陈汾君,汤勇,刘世铎,等.低渗致密气藏水平井分段压裂优化研究[J].特种油气藏,2012,19(6):85-87.
CHEN Fenjun, TANG Yong, LIU Shiduo, et al. Study on the optimization of staged fracturing of a horizontal well in a tight gas reservoir with low permeability[J]. Special Oil & Gas Reservoirs, 2012,19(6):85-87.

[47] Guo C, Wei M, Liu H. Study of gas production from shale reservoirs with multi-stage hydraulic fracturing horizontal well considering multiple transport mechanisms[J]. PLoS One, 2018, 13(1):e0188480.

[48] Cipolla CL, Lolon EP, Mayerhofer MJ, et al. Fracture design considerations in horizontal wells drilled in unconventional gas reservoirs[C]//SPE Hydraulic Fracturing Technology Conference, the Woodlands, USA, 2009.

[49] 吴百烈,周建良,曹砚锋,等.致密气水平井分段多簇压裂关键参数优选[J].特种油气藏,2016,23(4):127-130.
WU Bailie, ZHOU Jianliang, CAO Yanfeng, et al. Key parameter optimization of horizontal well multi-stage multi-cluster fracturing in tight gas reservoir[J]. Special Oil & Gas Reservoirs, 2016,23(4):127-130.

[50] Ambrose R J, Hartman R C, Diaz-Campos M, et al. New pore-scale considerations for shale gas in place calculations[C]//SPE unconventional gas conference, Pittsbergh, Pa, 2010.

[51] Marongiu-Porcu M, Wang X, Economides M J. Delineation of application: Physical and economic optimization of fractured gas wells[C]//SPE Production and Operations Symposium, Oklahoma, 2009.

[52] 白晓虎,齐银,陆红军,等.鄂尔多斯盆地致密油水平井体积压裂优化设计[J].石油钻采工艺,2015,37(4):83-86.
BAI Xiaohu, QI Yin, LU Hongjun, et al. Optimization design for volume fracturing of horizontal wells in tight oil reservoir of Ordos Basin[J]. Oil Drilling & Production Technology, 2015, 37(4):83-86.

[53] 贾长贵,路保平,蒋廷学,等.DY2HF深层页岩气水平井分段压裂技术[J].石油钻探技术,2014,42(2):85-90.
JIA Changgui, LU Baoping, JIANG Tingxue, et al. Multi-stage horizontal well fracturing technology in Deep Shale Gas Well DY2HF[J]. Petroleum Drilling Techniques, 2014, 42(2):85-90.

[54] 周德华,焦方正,贾长贵,等.JY1HF页岩气水平井大型分段压裂技术[J].石油钻探技术,2014,42(1):75-80.
ZHOU Dehua, JIAO Fangzheng, JIA Changgui, et al. Large-scale multi-stage hydraulic fracturing technology for Shale Gas Horizontal Well JY1HF [J]. Petroleum Drilling Technology, 2014,42(1):75-80.

[55] Xiong H. The effective cluster spacing plays the vital role in unconventional reservoir development: Permian Basin case studies [C]//SPE Hydraulic Fracturing Technology Conference and Exhibition, the Woodlands, USA, 2020.

[56] 赵志恒,郑有成,范宇,等.页岩储集层水平井段内多簇压裂技术应用现状及认识[J].新疆石油地质,2020,41(4):499-504.
ZHAO Zhiheng, ZHENG Youcheng, FAN Yu, et al. Application and cognition of multi-cluster fracturing technology in horizontal wells in shale reservoirs[J]. Xinjiang Petroleum Geology, 2020,41(4):499-504.

[57] Evans S, Halliburton F, Siddiqui S, et al. Impact of cluster spacing on infill completions in the Eagle Ford[C]. Proceedings of the Unconventional Resources Technology Conference, Houston, Texas, 2018.

[58] 张鑫,李军,张慧,等.威荣区块深层页岩气井套管变形失效分析[J].钻采工艺,2021,44(1):23-27.
ZHANG Xin, LI Jun, ZHANG Hui, et al. Analysis on casing deformation failure in deep shale gas wells in Weirong Shale Gas Play[J]. Drilling & Production Technology, 2021,44(1):23-27.

[59] Jaripatke O A, Barman I, Ndungu J G, et al. Review of Permian completion designs and results[C]. Proceedings of the SPE Annual Technical Conference and Exhibition, 2018.

[60] Barraza J, Capderou C, Jones M C, et al. Increased cluster efficiency and fracture network complexity using degradable diverter particulates to increase production, Permian Basin Wolfcamp shale case study [C]. Proceedings of the SPE Annual Technical Conference and Exhibition, 2017.

[61] 李龙,陈显举,彭安钰,等.贵州正安地区常压页岩气压裂关键技术[J].钻探工程,2022,49(5):189-193.
LI Long, CHEN Xianju, PENG Anyu, et al. Key technologies for hydraulic fracturing of normal pressure shale gas in the Zheng'an area of Guizhou[J]. Drilling Engineering, 2022,49(5):189-193.

[62] Ling K, Wu X, Han G, et al. Optimising the multistage fracturing interval for horizontal wells in Bakken and Three Forks Formations[C]. Proceedings of the SPE Asia Pacific Hydraulic Fracturing Conference, Beijing, 2016.

[63] Thomson J, Zaslavsky G, Leshchyshyn T. Completion design production case study in the Duvernay Shale Formation[C].

Proceedings of the SPE Annual Technical Conference and Exhibition, Dubai,UAE, 2016.

[64] 赵志恒,郑有成,范宇,等.页岩储集层水平井段内多簇压裂技术应用现状及认识[J].新疆石油地质,2020,41(4):499-504.
ZHAO Zhiheng, ZHENG Youcheng, FAN Yu, et al. Application and cognition of multi-cluster fracturing technology in horizontal wells in shale reservoirs[J]. Xinjiang Petroleum Geology, 2020,41(4):499-504.

[65] 范宇,周小金,曾波,等.密切割分段压裂工艺在深层页岩气Zi2井的应用[J].新疆石油地质,2019,40(2):223-227.
FAN Yu, ZHOU Xiaojin, ZENG Bo, et al. Application of intensive staged fracturing technology in deep shale gas Well Zi-2[J]. Xinjiang Petroleum Geology, 2019,40(2):223-227.

[66] 周双君,朱立鑫,杨森,等.吉木萨尔页岩油区块防漏堵漏技术[J].石油钻探技术,2021,49(4):66-70.
ZHOU Shuangjun, ZHU Lixin, YANG Sen, et al. Technology for preventing and controlling circulation loss in the Jimusar Shale Oil Block[J]. Petroleum Drilling Techniques, 2021,49(4):66-70.

[67] 王磊,盛志民,赵忠祥,等.吉木萨尔页岩油水平井大段多簇压裂技术[J].石油钻探技术,2021,49(4):106-111.
WANG Lei, SHENG Zhimin, ZHAO Zhongxiang, et al. Large-section and multi-cluster fracturing technology for horizontal wells in the Jimsar shale oil reservoir[J]. Petroleum Drilling Techniques, 2021,49(4):106-111.

[68] Mutalik P, Gibson R W. Case history of sequential and simultaneous fracturing of the Barnett shale in Parker County[C]. Proceedings of the SPE Annual Technical Conference and Exhibition, Denver, USA, 2008.

[69] 申贝贝,何青,陈付虎,等.大牛地气田同步压裂工艺应用研究[J].重庆科技学院学报(自然科学版),2015,17(4):58-60.
SHEN Beibei, HE Qing, CHEN Fuhu, et al. The research of simultaneous fracturing technology in Daniudi Gas Field[J]. Journal of Chongqing University of Science and Technology (Natural Sciences Edition), 2015,17(4):58-60.

[70] Waters G, Dean B, Downie R, et al. Simultaneous hydraulic fracturing of adjacent horizontal wells in the Woodford Shale[C]. Proceedings of the SPE Hydraulic Fracturing Technology Conference, the Woodlands, USA, 2009.

[71] 叶成林.苏53区块工厂化钻井完井关键技术[J].石油钻探技术,2015,43(5):129-134.
YE Chenglin. Key Technologies of factory drilling and completion in Su53 Block[J]. Petroleum Drilling Techniques, 2015, 43(5):129-134.

[72] 钱斌,张俊成,朱炬辉,等.四川盆地长宁地区页岩气水平井组"拉链式"压裂实践[J].天然气工业,2015,35(1):81-84.
QIAN Bin, ZHANG Juncheng, ZHU Juhui, et al. Application of zipper fracturing of horizontal clusters wells in the Changning shale gas pilot zone, Sichuan Basin[J]. Natural Gas Industry, 2015,35(1):81-84.

[73] Yu L, Wu X, Hassan N M S, et al. Modified zipper fracturing in enhanced geothermal system reservoir and heat extraction optimization via orthogonal design[J]. Renewable Energy, 2020, 161:373-385.

[74] Rafiee M, Soliman M Y, Pirayesh E. Hydraulic fracturing design and optimization: A modification to zipper frac[C]//SPE Annual Technical Conference and Exhibition, Texas, USA, 2012.

[75] Algarhy A, Soliman M, Heinze L, et al. Design aspects of optimized zipper frac[C]//53rd US Rock Mechanics/Geomechanics Symposium, New York, USA, 2019.

[76] Tian W, Li P, Dong Y, et al. Numerical simulation of sequential, alternate and modified zipper hydraulic fracturing in horizontal wells using XFEM[J]. Journal of Petroleum Science and Engineering, 2019,183:106251.

[77] 天工.中国石油首个页岩气工厂化压裂先导试验成功[J].天然气工业, 2014,34(1):85.
TIAN Gong. The successful pilot test for the first shale gas industrialized fracturing in PetroChina[J]. Natural Gas Industry, 2014,34(1):85.

[78] Ming L. Continuous operation model in multi-well pad W202H2: First shale gas factory in Block Weiyuan, SW China[C]. Proceedings of the IADC/SPE Asia Pacific Drilling Technology Conference, Singapore, 2016.

[79] 肖佳林,李奎东,高东伟,等.涪陵焦石坝区块水平井组拉链压裂实践与认识[J].中国石油勘探,2018,23(2):51-58.
XIAO Jialin, LI Kuidong, GAO Dongwei, et al. Practice and cognition on zipper fracturing of horizontal well group in Jiaoshiba block, Fuling[J]. China Petroleum Exploration, 2018, 23(2):51-58.

[80] Jacobs T. The shale evolution: Zipper fracture takes hold[J]. Journal of Petroleum Technology, 2014,66(10):60-67.

[81] Murillo G G, León J M, Leem J, et al. Successful deployment of unconventional geomechanics to first zipper hydraulic fracturing in low-permeability turbidite reservoir, Mexico[C]. Proceedings of the EUROPEC 2015, Madrid, Spain, 2015.

[82] 叶登胜,李建忠,朱炬辉,等.四川盆地页岩气水平井压裂实践与展望[J].钻采工艺,2014,37(3):42-44.
YE Dengsheng, LI Jianzhong, ZHU Juhui, et al. Practice and prospect of horizontal well fracturing technology in Sichuan shale gas reservior[J]. Drilling & Production Technology, 2014,37(3):42-44.

[83] Patel H, Cadwallader S, Wampler J. Zipper fracturing: Taking theory to reality in the Eagle Ford Shale[C]. Proceedings of the Unconventional Resources Technology Conference, San Antonio, Texas, 2016.

[84] Meng H, Wang X, Ge H, et al. Balanced stress fracturing theory and its application in platform well fracturing during unconventional oil and gas development[J]. Energy Reports, 2022, 8:10705-10727.

[85] Pankaj P. Characterizing well spacing, well stacking, and well completion optimization in the Permian Basin: An improved and efficient workflow using cloud-based computing[C]. Proceedings of the Unconventional Resources Technology Conference, Houston, Texas, 2018.

[86] 张金成.第一性原理思维法在页岩气革命中的实践与启示[J].钻探工程,2022,49(2):1-8.
ZHANG Jincheng. First principle thinking promotes innovation of shale gas revolution[J]. Drilling Engineering, 2022,49(2):1-8.

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