



## 高温高压储层“光油管”试油压裂一体化工艺

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## 高温高压储层“光油管”试油压裂一体化工艺

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**摘 要:** 准噶尔盆地南缘西段清水河组储层埋藏深、高温、高压, 基质物性差, 试油与压裂改造时受到超高地层压力、超高地层破裂压力、井身结构、管柱及工具结构等因素限制, 储层改造不充分。为此, 基于南缘西段深层高压油井储层特点, 采用环空替入加重液降套压、前置液顶替加重液防超压、油套双流程控压等技术措施, 形成了“光油管”试油压裂一体化工艺, 其具有降低工具失效风险、可有效监测套压和提高施工安全系数等优点。“光油管”试油压裂一体化工艺在南缘西段超深、超高压井应用了 5 井次, 工艺实施成功率 100%, 测试成功率 100%, 其中高泉 6 井压后日产油量 126.81 m<sup>3</sup>, 日产气量 8300 m<sup>3</sup>。该工艺有力支撑了准噶尔盆地南缘区块深井、超深井的安全高效试油、压裂, 可为同类型井的应用提供借鉴与指导。

**关键词:** 光油管; 试油压裂一体化; 高温高压; 超深井; 井筒完整性

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## Integrated Technology of Bare Tubing Oil Testing and Fracturing in High-Temperature and High-Pressure Reservoirs

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**Abstract:** The Qingshuihe Formation in the western section of the southern margin of the Junggar Basin has reservoirs with deep burial depth, high temperature and pressure, and poor matrix physical properties. Factors such as ultra-high formation pressure, ultra-high formation fracture pressure, casing program, strings, and tool structures limit oil testing and fracturing stimulation. Therefore, according to the reservoir characteristics of deep high-pressure oil wells in the western section of the southern margin, a series of technical measures were adopted, such as reducing casing pressure by the displacement of heavy fluid into the annulus, preventing overpressure by the displacement of heavy pad fluid, and controlling pressure by oil-casing double-flow program, so as to form the integrated technology of bare tubing oil testing and fracturing. The technology has the advantages of avoiding the risk of tool failure, effectively detecting casing pressure, and allowing higher safety factors. The integrated technology of bare tubing oil testing and fracturing was applied 5 times in ultra-deep and ultra-high pressure wells in the western section of the southern margin. The success rate for implementing the technology was 100%, and the testing success rate was 100%. Specifically, Well Gaoquan 6 had a daily oil production of 126.81 m<sup>3</sup> after fracturing, and the daily gas production was 8300 m<sup>3</sup>. This technology effectively supports the safe and efficient oil testing and fracturing of deep and ultra-deep wells in the southern margin of the Junggar Basin and provides reference and guidance for the application in similar types of wells.

**Key words:** bare tubing; integrated oil testing and fracturing; high temperature and high pressure; ultra-deep well; wellbore integrity

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“三高”井试油压裂工艺与常规油井不同,施工过程中由于工况苛刻易导致井下复杂,前期使用“两阀一封”试油测试工艺时存在井下工具失效、中高密度钻井液在高温条件下长时间静置易老化并堵塞管柱和埋卡封隔器等问题,为保障施工安全,研制了适用于不同井况的“三阀一封”、“四阀一封”和“五阀一封”测试管柱。

新疆油田南缘西段深层高温高压油气井前期主要采用“三阀一封”的试油工艺,随着勘探评价逐步深入,地质条件更加复杂,必须经过压裂改造才能获得产能。2011年西湖1井压裂后RD(rupture disks)循环阀无法开启,压井困难。目前,“多阀一封”试油工艺存在封隔器失效、钢球堵塞管柱及射孔段下部替液不干净等问题<sup>[1-4]</sup>。压裂过程中泵压高,排量受限,改造不充分,因此,“多阀一封”试油工艺无法完全满足超深超高压井试油需求。为此,笔者在分析前期“三阀一封”试油工艺难点和需求的基础上,针对南缘西段高温高压低渗油井储层特点和施工作业难点,采取环空替入加重液降低施工套压和前置液顶替加重液防超压等技术措施,形成了“光油管”试油压裂一体化工艺,最大限度地实现丢枪后油管全通畅,以满足压裂加砂改造需求<sup>[5-8]</sup>。

## 1 试油压裂工艺难点与需求

新疆油田南缘西段高泉地区白垩系清水河组以南部物源为主,储层埋藏深,地层压力130~145 MPa,地层温度140~150℃,基质孔隙度1.2%~16.5%,基质渗透率0.01~0.20 mD,岩性复杂,非均质性强,天然裂缝不同程度发育<sup>[9-11]</sup>。试油压裂的工艺难点主要包括:1)储层环境复杂。随着新疆油田南缘勘探评价加快推进,储层温度压力逐年升高,新疆油田南缘储层压力相比塔里木库车山前高出近20 MPa,严重制约试油、改造和建产;清水河组储层弹性模量高,闭合应力高,水力裂缝缝窄,加砂压裂困难,且受井身结构限制,压裂施工泵压高。2)受井身结构限制。南缘西段油井以四开井身结构为主, $\phi 139.7$  mm油层尾管长700~1119 m,区块标准化井身结构如图1所示,油层尾管直径及长度限制了大通径油管下深,压裂施工排量受限,区块平均施工排量3.0~4.5 m<sup>3</sup>/min,泵压高达111~129 MPa,泵压超高,施工风险高。同时,高温下密度大于2.30 kg/L试油工作液的性能难以保障,易发生测试封隔器与

测试阀堵塞、工具埋卡等井下复杂,小井眼中复杂处理难度大、风险高,在超高地层压力、超高地层破裂压力(破裂压力达大于160 MPa)等综合因素影响下,南缘西段试油、压裂改造面临极大难度与风险,亟需开展工艺优化,保障施工安全<sup>[11-13]</sup>。

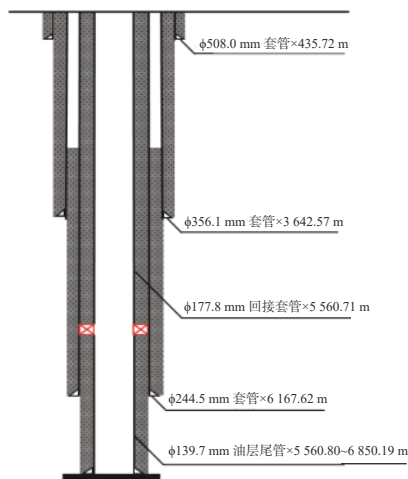


图1 南缘西段井身结构示意图

Fig.1 Casing program in the western section of the southern margin

## 2 前期试油工艺认识

### 2.1 “三阀一封”试油工艺

新疆油田南缘西段高温高压油井试油改造以降低试油成本、缩短试油周期和保障施工安全为主,前期采用“三阀一封”射孔压裂试油工艺。管柱组合为 $\phi 114.3$  mm油管 $\times 12.7$  mm $\times 715$  m+ $\phi 114.3$  mm油管 $\times 10.9$  mm $\times 4 600$  m+ $\phi 88.9$  mm油管 $\times 9.5$  mm $\times 200$  m+ $\phi 73.0$  mm油管 $\times 7.0$  mm $\times 955$  m+2号RD循环阀+1号RD循环阀+RDS阀+RTTS封隔器+存储式压力计+ $\phi 73.0$  mm $\times 5.5$  mm油管4根+减震器+ $\phi 73.0$  mm $\times 5.5$  mm油管4根+减震器+机械丢枪接头+筛管+射孔枪组。

RDS阀、RD循环阀与RTTS封隔器内径均为38.0 mm,考虑缩径产生的节流效应,计算其在不同排量下的节流压差和施工泵压,结果如表1所示。由表1可以看出,在相同排量条件下,“三阀一封”试油管柱的施工泵压比光油管试油管柱高7.96~10.32 MPa,压裂过程中会出现排量受限、加砂难度大等问题。

### 2.2 “三阀一封”试油工艺前期应用

西湖1井前期试油压裂采用“三阀一封”的射

表 1 不同试油管柱节流压差与施工泵压预测  
Table 1 Prediction of throttling differential pressure and pump pressure for different oil testing string

| 排量/<br>(m <sup>3</sup> ·min <sup>-1</sup> ) | 节流压差/<br>MPa | “光油管”施工<br>泵压/MPa | “三阀一封”管柱<br>施工泵压/MPa |
|---------------------------------------------|--------------|-------------------|----------------------|
| 2.5                                         | 7.96         | 109.46            | 117.42               |
| 3.0                                         | 8.55         | 111.96            | 120.51               |
| 3.5                                         | 9.14         | 118.17            | 127.31               |
| 4.0                                         | 9.73         | 125.06            | 134.79               |
| 4.5                                         | 10.32        | 132.58            | 142.90               |

孔测试联作管柱,由于受压裂冲蚀、高密度压井液和高温沉淀的影响,RDS(rupture disks safety)阀无法开启,循环压井困难、封隔器起出困难。RDS 阀的结构如图 2 所示。

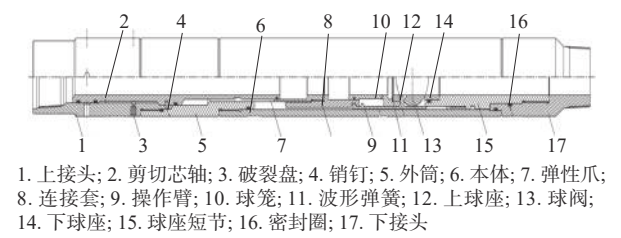


图 2 RDS 阀的结构  
Fig.2 Structure of RDS valve

排量 4.5 m<sup>3</sup>/min、平均砂比 15%、支撑剂视密度 3 350 kg/m<sup>3</sup>、支撑剂浓度 240 kg/m<sup>3</sup> 条件下,模拟计算 RDS 阀内部冲蚀云图如图 3 所示。由于 RDS 阀存在变径导致涡流,弹性爪根部易受冲蚀<sup>[14-16]</sup>,压

裂 5 h,冲蚀导致 RDS 阀壁厚减少达 11.6 mm,存在冲蚀破损或断裂导致芯轴无法下行、球阀无法关闭、循环通道无法开启的风险。因此,“三阀一封”试油工艺的适应性较差,需设计适用性更强的试油工艺。

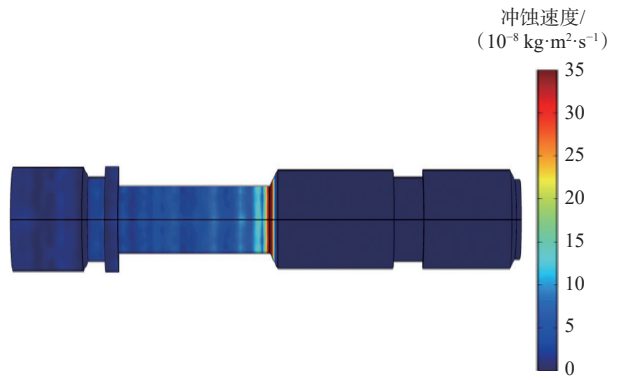


图 3 RDS 阀冲蚀云图  
Fig.3 RDS valve erosion cloud map

3 高温高压试油压裂一体化设计

3.1 管柱设计

依据南缘西段的井身结构,将试油压裂管柱设计为  $\phi 114.3\text{ mm}\times 12.7\text{ mm}$  油管+ $\phi 114.3\text{ mm}\times 10.9\text{ mm}$  油管+ $\phi 88.9\text{ mm}\times 9.5\text{ mm}$  油管+ $\phi 73.02\text{ mm}\times 7.0\text{ mm}$  油管+存储式压力计+ $\phi 73.0\text{ mm}\times 5.5\text{ mm}$  油管 4 根+减震器+ $\phi 73.02\text{ mm}\times 5.5\text{ mm}$  油管 4 根+减震器+机械丢枪接头+筛管+射孔枪组,最大限度实现大通径,丢枪后油管全通径以适应加砂压裂改造需求。试油压裂管柱所用油管的参数见表 2。

表 2 南缘西段试油管柱所用油管的参数  
Table 2 Tubing parameters used for oil testing string in the western section of the southern margin

| 油管外径/<br>mm | 钢级   | 壁厚/<br>mm | 内径/<br>mm | 线质量/<br>(kg·m <sup>-1</sup> ) | 抗内压/<br>MPa | 抗外压/<br>MPa | 管体屈服强度/<br>kN | 段长/<br>m |
|-------------|------|-----------|-----------|-------------------------------|-------------|-------------|---------------|----------|
| 114.3       | P110 | 12.70     | 88.90     | 32.14                         | 147.5       | 149.8       | 3 074         | 715      |
| 114.3       | P110 | 10.92     | 92.46     | 28.13                         | 126.8       | 131.1       | 2 689         | 4 600    |
| 88.9        | P110 | 9.53      | 69.84     | 18.90                         | 142.2       | 145.1       | 1 800         | 200      |
| 73.0        | P110 | 7.01      | 58.98     | 11.61                         | 127.4       | 11.60       | 1 103         | 955      |

3.2 三轴安全系数校核

针对南缘西段高温高压油井压裂、试油、关井等工况,采用 Wellcat 软件模拟计算带封隔器管柱与“光油管”管柱在相同工况条件下抗拉、抗压、抗外挤强度的三轴安全系数<sup>[17-18]</sup>,结果如图 4 所示。

1)采用带封隔器管柱时,由于封隔综合效应导

致附加应力,井口及封隔器上部安全系数低。同时,为确保油管柱及封隔器安全,环空补压需达到 60 MPa,才能保证三轴安全系数大于 1.50,现场实施保障难度大,并且使用带封隔器的管柱,封隔器与 RDS 阀、RD 循环阀等井下工具会造成管柱缩径,使压裂及试油过程中存在冲蚀风险。

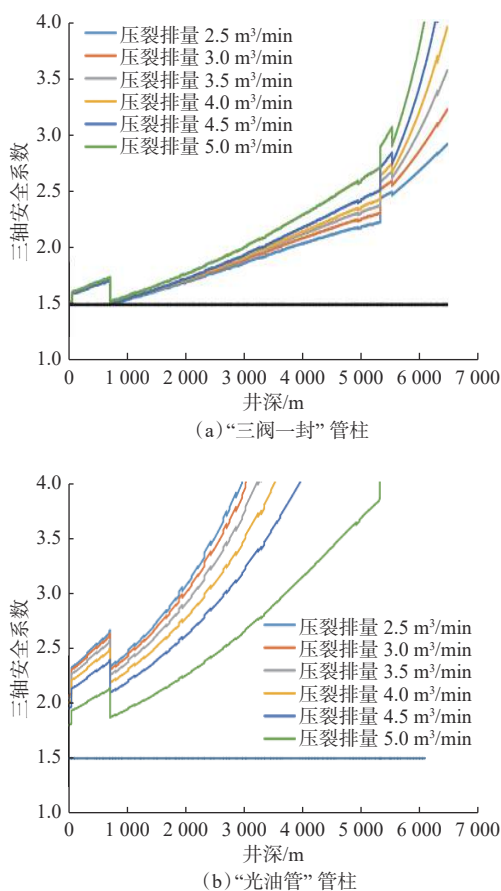


图4 不同排量下不同试油压裂管柱三轴安全系数

Fig.4 Triaxial safety factor of different oil testing fracturing string under different displacement

2)采用“光油管”管柱,相同工况条件下全井三轴安全系数大于2.00,相比于带封隔器管柱安全系数更高;若不加封隔器,则存在压裂过程中套管超压与试油作业时关井后套管超压的风险<sup>[19-21]</sup>。

### 3.3 压裂过程降套压设计

“光油管”试油压裂过程中,井口处套管是整个井筒的薄弱点,计算不同工况、不同环空液体密度下的套压(见表3)。油套环空为密度1.00 kg/L清水时,压裂过程中套压95.91 MPa,压裂安全余量为3.09 MPa(套管限压99 MPa);油套环空为密度1.20 kg/L盐水时,压裂过程中套压83.08 MPa,压裂安全余量为15.92 MPa。由此可以看出,提高环空液体密度,可有效降低套压,保障压裂过程中井筒安全。综合考虑储层配伍性及成本控制,压裂前环空替入密度1.20 kg/L的KCl+NaCl复配盐水加重液,以提高井口限压。

### 3.4 油层套管精细控压设计

利用Wellcat软件计算不同工况条件下油层套管的安全系数,考虑试油及生产过程中套管控压状

表3 不同工况下的套压

Table 3 Casing pressure under different working conditions

| 序号 | 工况                      | 套压/<br>MPa | 悬挂器位置<br>压力/MPa | 油层中部<br>压力/MPa |
|----|-------------------------|------------|-----------------|----------------|
| 1  | 井筒试压<br>(回接套管抗内压强度80%)  | 99.00      | 153.60          | 163.09         |
| 2  | 压裂<br>(环空液体密度1.00 kg/L) | 95.91      | 150.54          | 160.00         |
| 3  | 压裂<br>(环空液体密度1.20 kg/L) | 83.08      | 148.61          | 160.00         |
| 4  | 压裂<br>(环空液体密度1.30 kg/L) | 76.67      | 147.64          | 160.00         |

况,油层套管抗外挤安全系数大于1.125,抗内压安全系数大于1.150,满足射孔、压裂、纯油关井等工况下的安全要求;同时,压裂前环空替入密度1.20 kg/L的盐水,纯油、纯气工况下套压最高控制在99 MPa,油层套管可满足排量3.5~4.5 m³/min的压裂要求。

### 3.5 油套管控压地面双流程控制设计

“光油管”工艺试油条件下油套连通,针对油层套管超压风险,优化设计定型了140 MPa油套管控压地面双流程,如图5所示。油管流程与套管流程分别在高压端并联、低压端并联,油气可通过油管、套管流程同时经除砂器、油嘴管汇、热交换器、分离器等装置进行生产作业,提高了生产效率,能够实现油套同时生产、套管应急泄压和正反压井,可通过地面设备保障试油全过程的井筒安全。

## 4 现场应用

“光油管”试油压裂一体化技术先后在准噶尔盆地南缘西段应用了5井次,下面以高泉6井为例,介绍具体应用情况。高泉6井井储层埋深6530.00~6537.00 m,φ177.8 mm套管下深0~5560.00 m,φ139.7 mm套管下深5560.00~6758.27 m,地层压力144.26 MPa,破裂压力175.2 MPa,计算出A环空中为1.20 kg/L盐水时套压最高为99.00 MPa。采用φ114.3 mm油管+φ88.9 mm油管+φ73.0 mm油管+存储式压力计+丢枪射孔管柱进行压裂施工,优选射孔弹,增大射孔深度,降低破裂压力,管柱增加了丢枪装置,丢枪后实现管柱全通径。

高泉6井压裂前采用φ2.0 mm油嘴试产,油压24.3 MPa,最高日产油量4.68 m³。压裂前全井筒替入密度1.20 kg/L的复配盐水,前置液阶段采用密度1.20 kg/L盐水造缝,以降低井口破裂压力,顶替液



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