

美国页岩气水平井水基钻井液研究与应用进展

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摘要 水平井钻井是推动美国页岩气大规模开发的核心技术之一, 美国在页岩气水平井初期使用油基钻井液成功钻探页岩水平井。迫于油基钻井液环保和成本高的压力, 美国对页岩气水平井水基钻井液进行了研究并推广应用。介绍了美国典型的3个页岩气区块水基钻井液研究情况。Haynesville地区选用更接近井下环境 1.38 MPa分压的CO₂侵、12%低密度固相污染和204℃、48 h条件评价钻井液抗污染能力; 通过模拟钻井液流入、井底静止和流出过程中井温和压力变化的新方法测试钻井液在井眼中的流变性。而Fayetteville和Barnett地区采用扫描电子显微镜(SEM)分析浸泡后岩石的形貌研究钻井液与岩石的作用机理, 进而研究水基钻井液配方。Haynesville地区现场应用时, 在CO₂侵和井底204℃高温条件下, 机械钻速比使用油基钻井液的邻井提高8.5%; Fayetteville和Barnett地区应用纳米硅醇封堵水基钻井液时, 滑动钻速分别是9.2~15.4 m/h和7.4~24.6 m/h, 复合钻速30.8~77.0 m/h。

关键词 页岩气; 水平井; 水基钻井液; 钻井液配方; SEM分析

美国是世界上页岩气勘探开发最成功的国家之一, 水平井钻井是推动美国页岩气大规模开发的核心技术之一。而页岩气水平井钻井面临井壁失稳、长水平段摩阻高和井漏三大技术难题。在页岩气初期开发, 美国使用油基钻井液钻井很好的解决了这些难题, 油基钻井液主要优点是对地层井眼稳定具有广普适用性和长水平井段的润滑效果好, 能明显减少非生产作业时间(NPT)和提高钻井效率; 然而其缺点是环保性能差和成本偏高^[1-3]。

迫于油基钻井液环保性能差和成本高的压力, Halliburton、Schlumberger和Baker Hughes三大钻井液服务公司分别针对不同的页岩气地层开发相应的水基钻井液技术。Halliburton研发了SHALEDRILT-M系列钻井液, 其中SHALEDRIL-H适合Haynesville页岩, 用于解决恶劣作业工况问题, SHALEDRIL-F适合Fayetteville页岩, 用于解决层状结构泥页岩的井眼稳定问题, SHALEDRIL-M适合Barnett和Marcellus页岩, 用于解决钻屑完整性问题^[4]。Schlumberger公司开发了改进型聚合物Kla-shield钻井液以满足钻井和环境要求, 其主要特点是具有对裂缝性页岩超强加固能力^[5]。Baker Hughes开发了一种新型的Latidril钻井液, 该技术是在常规水基钻井液基础上加入一种特殊的广谱井壁稳定剂和润滑剂^[6]。

环保和成本低的水基钻井液已经在美国页岩气水平井中尝试使用并取得较好的效果, 目前中国在页岩气水平井的水平段全部使用油基钻井液, 室内开展相关水平井运用水基钻井液研究, 并将成果先期主要应用在井眼稳定的地层当中。在当今低油价背景下, 解决页岩气大规模开发同样也面临环保和成本的双重挑战, 相关水基方面的研究也刚刚起步。因此, 美国在页岩气水平水基钻井液方面的技术值得借鉴。

1 美国几个页岩区块的矿物组分及水基钻井液应用比例

美国页岩气的产区有Haynesville、Fayetteville、Barnett、Marcellus和Eagle Ford等区域, 地层矿物组分差别很大。页岩气水平井水基钻井液设计的关键是考虑井眼稳定的地层矿物组分及其含量, 进而在钻井液性能要求方面有所侧重。

1.1 美国5个页岩气区块矿物组分分析

从表1美国Haynesville、Fayetteville、Barnett、Marcellus和Eagle Ford页岩气区块矿物组分(X衍射数据)结果可以看出, 5个区块的石英含量分别为21%、40%、33%、47%和29%, 除Eagle Ford地区没有伊利石外, 其他4个区块伊利石含量分别为42%、24%、41%和25%, Marcellus和Eagle Ford地区蒙脱石

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表 1 美国 5 个页岩气区块矿物组分分析

Table 1 Mineral composition analysis of 5 shale gas blocks in US

区块	蒙脱石/%	伊利石/%	高岭石/%	绿泥石/%	方解石/%	石英/%	白云石/%	长石/%	黄铁矿/%	菱铁矿/%	岩盐/%	伊蒙混层比/%	阳离子交换容量/%
Haynesville	—	42	—	—	13	21	5	2	17	—	—	—	—
Fayetteville	—	24	—	1	—	40	10	1	—	—	—	24	8
Barnett	—	41	2	6	—	33	—	6	—	6	6	28	—
Marcellus	4	25	—	—	—	47	3	10	5	6	—	—	—
Eagle Ford	6	—	2	—	55	29	2	2	4	—	—	—	5

含量分别为 4% 和 6%^[7-9]。

1.2 美国 4 个页岩气区块水平井水基钻井液应用比例

依据文献[8]~[10], 美国的 Haynesville (统计 2003—2011 年初 238 口水平井钻井液使用情况)、Barnett、Marcellus (统计 2008—2011 年初 225 口水平井钻井液使用情况) 和 Eagle Ford (统计 2003—2011 年中 238 口水平井钻井液使用情况), 水基钻井液所占的比例分别是 14%、20%、36% 和 19% (表 2)。

表 2 美国 4 个页岩气区块水平井水基钻井液使用比例

Table 2 Percentages of WBM for horizontal wells in 4 shale gas blocks in US

区块	水基/%	油基/%	合成基/%
Haynesville	14	86	—
Barnett	20	80	—
Marcellus	36	—	64
Eagle Ford	19	76	5

从文献资料统计数据看出, 尽管水基钻井液技术在进步, 美国页岩气的水平井还是以油基钻井液占多数, 水基钻井液占少数。而近几年有关页岩水平井水基钻井液应用的文献报数量有所增加。

2 Haynesville 区块页岩特征、水基配方性能评价和应用

2.1 页岩气区块特征

Haynesville 地区页岩气区域从路易斯安那州西南部到得克萨斯州东部约 23220 km², 技术可采储量达 71075 万亿 m³, 是北美最大的页岩气区块之一。Haynesville 地区页岩是黑色富含有机质。Haynesville 地区页岩气区块在井温和地层压力等方面显著区别于其他北美的页岩气区块, 其埋深在 3234~4312 m, 井底温度接近 193℃。由于 Haynesville 地层含 CO₂, 因此需要高钻井液密度^[8-11]。

2.2 水平井水基钻井液配方

配方: 清水+2.85%膨润土+0.14%NaOH+(0.85~1.14)%高温解絮剂(起高温分散作用)+(0.57~0.86)%表面活性剂

(对高温钻井液性能有很好改善, 起热稳性作用)+1.43%稀释剂(改性磺化丹宁处理剂)+1.43%页岩稳定剂(聚胺类处理剂)+0.57%聚合物降滤失剂(纤维降失水剂)+0.43%缓蚀剂(减少 CO₂ 对钻具腐蚀作用)+(108.57~140.00)%重晶石加重到 1.86~2.10 g/cm³。

2.3 水基钻井液老化及抗污染实验

选用 1.38 MPa 的 CO₂ 污染、12%低密度固相污染和 204℃ 高温 48 h 老化新方法评价钻井液高温老化后流变参数(表 3), 从苛刻污染数据可以看出钻井液流变性能稳定。

2.4 水基钻井液模拟井下情况流变性评价

模拟钻井液从井眼中流入、到达井底、井底静止和流出过程中温度及压力变化, 测试钻井液的流变性能如表 4 所示。

从表 4 的实验数据可以看出, Haynesville 地区页岩气水基钻井液在不同温度和压力未发生胶凝现象, 钻井液有较好的热稳定性。

2.5 水基钻井液分散性测试

Haynesville 地区页岩水基钻井液配方测试页岩滚动回收率都在 98% 以上(表 5), 水基钻井液滚动后的岩屑与油基钻井液滚动后的岩屑接近(图 1), 说明该水基钻井液有较好的抑制分散能力。

2.6 水平井水基钻井液现场应用情况

水基钻井液应用在路易斯安那州 Boiser 页岩顶部从 3295.6 m 开始到 Haynesville 页岩底部的 5482.4 m。由于复杂的井眼设计, 水基钻井液在裸眼段浸泡 45 天, CO₂ 侵 (> 800 mg/L) 对钻井液的流变性有轻微影响, 在 CO₂ 侵入量最高(脱气器不能正常工作), 钻井液黏度增加, 通过补充配方处理剂使其恢复正常钻井液性能。在井底温度大于 204℃ 时, 机械钻速比邻井使用油基钻井液高 8.5%^[11-12], 钻井液性能见表 6。

3 Fayetteville 页岩特征、水基配方的性能评价和应用

3.1 区块特征

Fayetteville 页岩气区域页岩地区埋深在 1232~2464 m, 评估天然气储量达 11886 万亿 m³, 井底温度 49~104℃^[11-12]。虽然 Fayetteville 页岩地区埋深浅、井温也不高, 但地层水敏性很强, 这是由于 Fayetteville 地区页岩矿物中伊蒙混层矿物比

表3 Haynesville地区页岩气区块水基钻井液老化及抗污染性能评价

Table 3 Aging and contamination performance of WBM in shale gas block of Haynesville area

序号	流变系数						塑性黏度/ (mPa·s)	动切力/Pa	静切力/Pa			常压失水/mL	高温高压失水 (204℃)/mL	pH值	剪切力/Pa
	600 r/min	300 r/min	200 r/min	100 r/min	6 r/min	3 r/min			10 s	10 min	30 min				
1	122	67	47	27	5	3	55	6	5	7	9	4	—	10.5	—
2	85	48	34	19	4	3	37	5.5	4	5	6	4.4	20	9.1	37.5
3	89	47	32	18	3	2	42	2.5	3	5	7	5.0	20	8.7	47.5
4	116	67	49	29	6	4	49	9	6	7	8	4.6	18	9.0	45
5	182	108	80	49	12	9	74	19	10	16	18	3.4	16	8.9	67.5

注:1号—第2.2节中2.1 g/cm³配方65℃滚动3 h,49℃下采用范氏黏度计测量3~600 r/min的读数;2号—第2.2节中2.1 g/cm³配方65℃滚动3 h,204℃老化48 h,49℃下采用范氏黏度计测量3~600 r/min的读数;3号—第2.2节中2.1 g/cm³配方+CO₂(1.38 MPa分压)65℃滚动3 h,204℃老化48 h,49℃下采用范氏黏度计测量3~600 r/min的读数;4号—第2.2节中2.1 g/cm³配方+6%低密度固相65℃滚动3 h,204℃老化48 h,49℃下采用范氏黏度计测量3~600 r/min的读数;5号—第2.2节中2.1 g/cm³配方+12%低密度固相65℃滚动3 h,204℃老化48 h,49℃下采用范氏黏度计测量3~600 r/min的读数;其中4和5号的低密度固相选用以Haynesville露头和Bossier钻屑D₅₀小于10 μm以1:1比例混合。

表4 Haynesville地区页岩气水基钻井液高温高压流变性

Table 4 Rheological properties of HTHP of shale gas WBM in Haynesville area

序号	条件	悬浮稳定性	流变系数					
			600 r/min	300 r/min	200 r/min	100 r/min	6 r/min	3 r/min
1	49℃,0 MPa	12	146	85	63	40	11	11
2	93℃,35 MPa	10	104	62	49	33	12	10
3	149℃,52.5 MPa	12	84	51	42	31	13	12
4	204℃,70 MPa	14	71	43	36	28	13	13
5	204℃,70 MPa,24 h	12	87	53	43	31	13	12
6	149℃,52.5 MPa	10	97	60	48	34	12	11
7	93℃,35 MPa	10	125	77	60	40	13	11
8	49℃,0 MPa	10	169	102	78	50	15	12

注:测试钻井液均采用第2.2节中2.1 g/cm³配方。

表5 Haynesville地区页岩滚动回收率

Table 5 Shale rolling recovery rates in Haynesville

序号	密度/(g·cm ⁻³)	回收率/%
1	1.86	98.0
2	1.98	98.7
3	2.10	98.5

注:页岩选自Haynesville地区Bossier地层5~10目页岩,称取30 g,热滚后过40目筛网。



图1 水基钻井液滚动后的岩屑(a)与油基钻井液滚动后的岩屑(b)对比

Fig. 1 Cutting roll recovery rate contrast between WBM(a) and OBM(b)

表6 典型的Haynesville地区页岩气水平井水基钻井液应用性能

Table 6 Application performance of WBM for shale gas horizontal wells in Haynesville area

序号	井深/m	密度/(g·cm ⁻³)	流变系数						塑性黏度/ (mPa·s)	动切力/ Pa	静切力/Pa			常压失水/mL	高温高压失水/mL	pH值
			600 r/min	300 r/min	200 r/min	100 r/min	6 r/min	3 r/min			10 s	10 min	30 min			
1	3832	1.80	101	60	45	30	8	7	41	9.5	3.5	6.5	8.0	5	16.2	10.4
2	4578	1.99	115	66	48	30	8	7	49	8.5	4.0	6.0	6.5	2	14.0	9.3

达24%(表1),因此油基钻井液是该地区最成功可靠的首选,仅有部分井应用水基钻井液。

3.2 水平井水基钻井液配方及性能

纳米硅醇封堵钻井液配方:水+1.42%硅酸钾+1.71%磺化沥青+2.29%改性褐煤+0.57%聚阴离子纤维素+0.57%改性淀

粉+0.14%黄原胶+2.85%架桥材料(钠微米封堵材料)+2.85%乙二醇+4.28%重晶石到 1.08 g/cm^3 ,水基钻井液性能如表7所示。测试温度为 49°C ,钻井液密度为 1.08 g/cm^3 ,塑性黏度为 $21\sim 22\text{ mPa}\cdot\text{s}$,动切力为 $17.5\sim 19.0\text{ Pa}$,静切力 10 s 、 10 min 、 30 min 分别是 4.5 、 $6.0\sim 6.5$ 、 $7.0\sim 7.5\text{ Pa}$,常压失水 4.8 mL 。

表7 Fayetteville页岩气水平井抑制水基钻井液性能
Table 7 Properties of WBM in Fayetteville shale gas horizontal wells

序号	井深/m	密度/ ($\text{g}\cdot\text{cm}^{-3}$)	流变系数						塑性黏度/ ($\text{mPa}\cdot\text{s}$)	动切力/ Pa	静切力/Pa			失水/ mL	pH值
			600 r/min	300 r/min	200 r/min	100 r/min	6 r/min	3 r/min			10 s	10 min	30 min		
1	1774	1.08	77	56	47	36	10	9	21	17.5	4.5	6.0	7.0	4.8	10.7
2	2321	1.08	82	60	47	35	10	9	22	19.0	4.5	6.5	7.5	4.8	10.9

注:流变性测试温度 49°C 。

3.3 水基钻井液浸泡实验

Fayetteville地区页岩水基钻井液、清水和抑制钻井液浸泡24 h与未浸泡页岩对比结果如图2所示。

从图2(d)可以看出,与原始页岩相比,该页岩水基钻井液浸泡后产生微裂隙。但与常规抑制钻井液和清水浸泡结果对比可以明显看出,该钻井液有一定的裂缝愈合能力,裂隙开度仅几十微米。

3.4 水基钻井液LSM实验

用Fayetteville地区水基钻井液进行线性膨胀率测试(LSM),并与其他3种水基钻井液进行对比,结果如图3所示。

从70 h的LSM测试结果可以看出,Fayetteville钻井液几乎没有页岩膨胀。

3.5 水基钻井液现场应用

将Fayetteville地区页岩水平井的水基钻井液应用在阿肯色州Van Buren县,该地区页岩是极易剥落水化导致高的低

密度固相含量、扭矩和摩阻。Fayetteville页岩抑制水基钻井液应用在Fayetteville地层底部1078 m到Fayetteville地层顶部3080 m,滑动钻井钻速 $9.2\sim 15.4\text{ m/h}$,复合钻机械钻速 $30.8\sim 77.0\text{ m/h}$,现场应用的性能如表7所示^[13-15]。

4 Barnett页岩特征、水基配方性能评价和应用

4.1 区块特征

Barnett地区位于Fort Worth盆地,约 12950 km^2 ,覆盖得克萨斯州的21个县,评估天然气储量达 12459 万亿 m^3 ,被认为是北美页岩气产能增长贡献最大的地区。Barnett页岩地区埋深在 $2156\sim 3080\text{ m}$,井底温度 $52\sim 107^\circ\text{C}$ 。Barnett地区以前很少使用水基钻井液主要原因是Barnett地区伊蒙混层比28%(表1),页岩活性高。使用水基钻井液井下复杂情况多,增加了非生产作业时间。油基钻井液成为该地区首选,使用水基钻井液必须经作业者同意并签署责任协议^[11-15]。

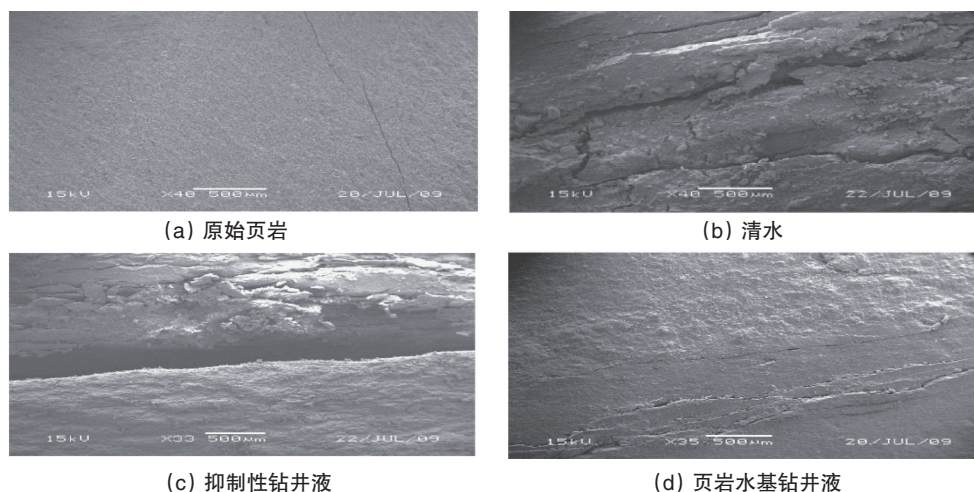


图2 原始页岩和3种液体浸泡24 h后效果

Fig. 2 Original shale and the shale were soaked in 3 fluids after 24 hours

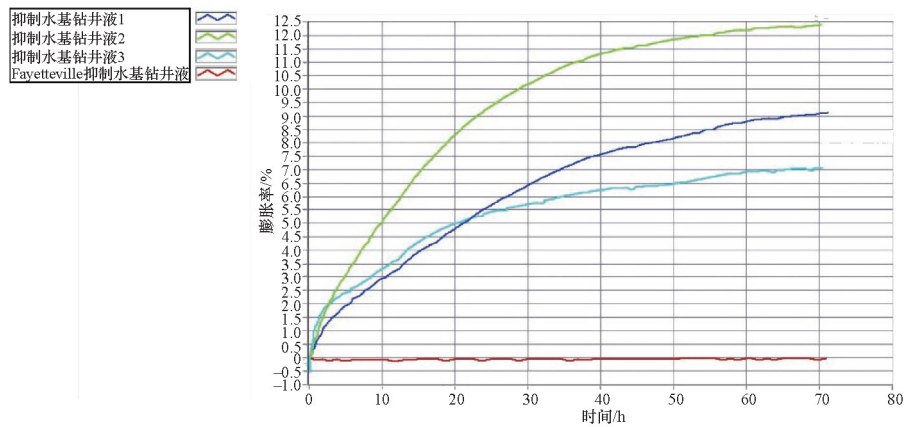


图3 Fayetteville抑制水基钻井液与其他3种水基钻井液LSM对比
Fig. 3 LSM inhibition of WBM and the other 3 WBM Fayetteville contrast

4.2 水基钻井液配方及性能

纳米硅醇封堵钻井液配方:水+(1.42~2.84)%硅酸钠+1.42%磺化沥青+1.71%褐煤+0.28%聚阴离子纤维素+0.28%改性淀粉+0.14%黄原胶+2.85%架桥材料(钠微米封堵材料)+2.85%乙二醇+1.99%润滑剂+4.28%重晶石加重到1.08 g/cm³,水基钻井液性能如表8所示。

4.3 Barnett地区页岩气的水平井水基钻井液现场应用

Barnett地区抑制页岩水基钻井液应用在得克萨斯州的Denton县,该区主要难点是页岩微裂隙导致的井眼失稳、高的低密度固相含量、扭矩和摩阻。页岩水基钻井液应用井段从308~2772 m,滑动钻井钻速7.4~24.6 m/h,复合钻机械钻速30.8~77.0 m/h^[15-35],现场应用典型钻井液性能如表9所示。

表8 Barnett地区抑制水基钻井液性能对比
Table 8 Property comparison of the inhibitive WBMs

序号	配方	密度/ (g·cm ⁻³)	流变系数				塑性黏度/ (mPa·s)	动切力/ Pa	静切力/Pa		常压失水/ mL	页岩回 收率/%
			600 r/min	300 r/min	6 r/min	3 r/min			10 s	10 min		
1	抑制水基钻井液1	1.08	75	45	7	5	30	7.5	2.5	4	3.6	62
2	抑制水基钻井液2	1.08	55	35	6	5	20	7.5	2.5	3	2.8	79
3	Barnett抑制水基钻井液1	1.08	82	49	8	6	33	8.0	3.0	4	5.0	93
4	Barnett抑制水基钻井液2	1.08	87	52	8	6	35	8.5	3.0	4	5.4	99

注: Barnett抑制水基钻井液1中硅酸盐含量1.42%, Barnett抑制水基钻井液2中硅酸盐含量2.84%,流变性测试温度27℃;相对其他抑制水基钻井液1和2, Barnett抑制水基钻井液有较高的页岩回收率,通过抑制和化学封堵有效控制黏土的分散。

表9 Barnett页岩气水平井的抑制水基钻井液应用性能
Table 9 WBM application properties of Barnett shale gas horizontal wells

序号	井深/m	密度/ (g·cm ⁻³)	流变系数						塑性黏度/ (mPa·s)	动切力/ Pa	静切力/Pa		常压失 水/mL	pH
			600 r/min	300 r/min	200 r/min	100 r/min	6 r/min	3 r/min			10 s	10 min		
1	2147	1.09	61	41	32	22	9	7	20	10.5	4.5	12.5	6.0	11.2
2	3602	1.10	62	43	34	24	8	6	19	12	3.5	8.0	5.4	11.1

注:流变性测试温度49℃。

5 结论

从统计数据和资料分析可以看出,美国在Haynesville、Barnett、Marcellus和Eagle Ford地区水基钻井液所占的比例

分别是14%、20%、36%和19%,应用水基钻井液取得较好的效果。由于美国在油基钻井液的回收利用、防漏堵漏和油基废弃物处理方面仍具有较强的优势,而油基钻井液本身有地

层适用性广和超强润滑效果等优点,所以页岩气水平井油基钻井液使用比例仍占多数。水基钻井液主要在美国页岩气水平井环保要求严格、有大量钻井数据,水基可以解决井壁失稳或井壁本身较稳定的区块推广使用。随着技术的进步,预计美国水基钻井液应用比例会越来越高。

美国页岩气的水平井钻井经历从油基到水基钻井液的发展阶段,中国相对还处于起步阶段。目前,中国国内页岩气水平井在水平段全部采用油基钻井液钻井,同样也面临环保和成本的挑战,并且由于中国油基钻井液研究起步较晚,油基钻井液的防漏堵漏和油基废弃物配套处理技术还不完善。因而,中国页岩气水平井要实现高效低成本开发,同样需要研究页岩水平井水基钻井液。借鉴于美国页岩气的水平井水基钻井液研究和应用取得的进展,指导中国在研究页岩水平井水基钻井液中应考虑如下关键技术要点。

1) 收集应用页岩区块岩心或岩屑进行 X 射线衍射 (XRD) 分析矿物组分,判断是活性页岩还是非活性页岩,对活性页岩开展毛细水吸附测试、线性膨胀率测试、亚甲基蓝测试、页岩滚动回收率测试和 SEM 分析;对非活性页岩开展亚甲基蓝测试、裂缝扩展测试、布氏硬度测试、页岩滚动回收率测试和 SEM 分析^[36-50]。

2) 结合测井数据,考虑关键的影响因素,包括井下温度、液体密度、盐水侵、CO₂ 侵、井身结构,并考虑可能出现的问题(如含薄盐层或石膏)、环境要求和限制条件量身定做设计页岩水基钻井液配方。

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Advances and application of horizontal-well water-based mud in US shale gas reservoirs

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Abstract Horizontal drilling is one of the core technologies in US shale gas large scale exploration. Oil based mud (OBM) was applied successfully at the beginning, however, due to its environmental reason and high cost, water based mud (WBM) was developed and applied. Three typical WBM cases for shale gas are introduced in this article. In the Haynesville area, a condition close to downhole environment is used to evaluate drilling fluid anti-contamination properties, including 1.38 MPa CO₂, 12% solid and hot rolling at 204°C for 48 h. Rheological properties are tested by stimulating well temperature and pressure variations during the processes of fluid flowing in, staying static in bottom hole, and flowing out. In Fayetteville and Barnett areas, the interaction mechanism between WBM and shale is investigated to form drilling fluid formulation using SEM so as to analyze the morphology of soaked rocks. In Haynesville, with CO₂ contamination and 204°C temperature, the ROP increases by 8.5%, compared with adjacent OBM well. In Fayetteville and Barnett, the sliding drilling speeds are 9.2–15.4 m/h and 7.4–24.6 m/h, respectively and the rotating speed is 30.8–77.0 m/h when using nano-silica-alcohol WBM. The development and application of US shale gas horizontal well WBM are worth learning by China.

Keywords shale gas; horizontal well; water based drilling fluid; drilling fluid formula; SEM analysis

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