射孔完井效率评价

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摘　要　在射孔完井效率评价中, 有很多影响我们进行评价的因素。通过在实践中反复探索、验证, 提出了利用储层系数消除储层差异影响并对油气藏动、静态参数综合分析以及利用评价油气层损害的产率比 (*PRJ*) 和表皮系数(*S*) 评价射孔完井效率的两套方法。经过对磨溪气田雷 一┘气藏的射孔完井效率评价, 效果明显。在评价中我们还发现评价结果对射孔优化设计在现场应用的正确性有决定性的作用, 对射孔弹的研制具有指导作用。两种方法都能对射孔完井效率进行正确评价, 第一种方法更适合在现场大量使用。

主题词　射孔完井　效率　评价　表皮系数　射孔　设计　储集层　系数

射孔完井效率的好坏一直是完井效果评价中不容易说清楚的一个问题。其困难主要体现在两个方面, 一是射孔作业与完井作业的各个环节紧密相连不易将其效果单独分离出来; 二是不同井的储层及地层流体参数各不相同, 进行井与井之间的射孔完井效率对比有一定的困难。近十年以来, 我们在射孔完井效率评价方面作了很多工作, 并在实践中反复探索、验证了很多方法。这里就我们认为比较有效的一些现场射孔完井效率评价方法提供给大家共同探讨。

射孔完井效率评价的思路

射孔完井效率评价是对完井中射孔这一环节对井产能的影响进行评价, 其实质是油气层损害评价技术。因此, 我们射孔完井效率评价就围绕着产能与油气层损害进行。

油气井产能受到很多因素影响, 在进行井与井之间产能对比的时侯, 情况更加复杂。但是在不同的储层, 我们总能找到一个能够真实反映储层或接近反映储层好坏的综合系数, 我们称为储层系数。利用这个系数消除井与井储层差异的影响(产量/ 储层系数) , 再通过对油气藏动、静态参数的综合分析, 我们就能够对不同井的射孔完井效率进行评价。例如: 利用 $W = \Phi \times H \times S_g, H \times K$ 等来反映各井储层的好坏。

一般情况下油气层损害评价最基本的评价指标有 11 个, 这些描述油气层损害程度的指标可以用一个数学通式表示它们的相互联系。知道其中一个评价指标的数值就可以用通式求得其它评价指标的数值。经过大量的实践, 我们评价射孔的油气层损害使用产率比 (*PRJ*) 和表皮系数(*S*) 。表 1 是油气层损害评价标准。

表 1　油气层损害评价标准

表皮系数评价标准				产率比评价标准		
地质模型	损害	未损害	改善	损害	未损害	改善
均质地层	> 0	0	< 0	< 1	1	> 1
非均质地层	> − 3	− 3	< − 3			

射孔完井效率评价的现场评价

下面我们以一个气田为主详细介绍射孔完井效率现场评价的全过程。

1. 射孔弹地面试验(表 2)

2. 油气藏动、静态参数结合的射孔完井效率评价

首先我们使用先进的测井软件对射孔井测井资料进行精细处理, 只有在正确计算和分析储层参数的前提下, 才能得到准确的储层系数(表 3) , 从而进行射孔优化设计和储层对比, 这里以磨溪气田为例。

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表 2 射孔弹地面试验结果对比表

射孔弹型号	药量 (g)	孔密 (孔/m)	相位 (度)	布孔格式	混凝土靶		备 注
					孔深 (mm)	孔径 (mm)	
S—51	37	16	60	螺旋	433	13.3	混凝土靶强度 54.8 MPa, 测试日期: 1990 年 5 月
S—41	22	40	120	螺旋	333	11.25	
H—5S	22	/	/	螺旋	280	12.0	
Y—73	17	20	90	螺旋	266	10	
Y—89	24.5	20	90	螺旋	404	11.0	
Y—127	37	16	90	螺旋	714	12.0	

表 3 射孔施工井储层参数表

井号	储层分类	> 12%		12% ~ 6%		6% ~ 3%		加权平均	加权平均	加权平均	W
		H (m)	Φ (%)	H (m)	Φ (%)	H (m)	Φ (%)	H (m)	Φ (%)	S_g (%)	
磨 53	II	1.8	13.7	6.6	8.1	4.0	3.8	12.4	7.5	66	61
磨 60	II	3.0	14.3	0.7	8.3	5.3	5.2	9.0	8.4	69	52
磨 63	I	4.0	15.3	5.5	8.1	2.7	4.2	12.2	9.6	68	80
磨 70	II	1.0	14.5	4.8	7.4	6.6	3.5	12.4	5.9	71	52
磨 27	III			3.1	8.3	8.6	4.7	11.7	5.6	65	39

以上储层参数将作为射孔优化设计输入参数, $W = \Phi \times H \times S_g$ 值是射孔完井效率现场评价中的重要参数。

(1) 射孔优化设计的产率比 (*PRJ*) 及表皮系数 (*S*) 预测

从表 4 可以看出, 由于射孔优化设计产能参数预测是理想地质模型下的单井模拟计算结果, 因此与实际情况相比有偏差。结合表 2, 对表 4 中这种偏差的分析我们至少可以得到如下结论: ①实际 *PRJ* 的参差不齐, 说明为了获得最大的产率比, 正确地射孔设计是必要的; ②磨 60、磨 70 井预测与实际产率比相差很大, 说明射孔优化设计输入参数中的污染参数与我们估计值的相差较大; ③没有正确地输入参数就没有正确地射孔优化设计结果; ④在对一个地区射孔优化设计输入参数非常清楚的情况下, 射孔优化设计可以对射孔完井效率进行预测评价。

表 4 射孔优化设计预测与实际产能参数对比表

井号	弹型	预测产量 ($10^4 m^3/d$)	实际产量 ($10^4 m^3/d$)	预测 *PRJ*	实际 *PRJ*	预测 *S*	实际 *S*
磨 53	S—51	2.38	2.06	1.05	0.979 6	-0.47	0.46
磨 60	S—51	1.75	1.35	1.04	0.512 2	-0.36	7.51
磨 63	S—41	3.09	2.43	1.48	1.897 0	-2.95	-2.13
磨 70	S—41	3.11	1.26	1.42	0.814 0	-2.69	2.87
磨 27	S—41	1.65	0.76	1.47	/	-2.87	/

(2) 射孔完井无阻流量对比(表 5)

表 5 磨溪雷一[1] 射孔完井无阻流量对比分析表

S 公司 S—51、S—41 型弹射孔井					C 公司 Y—73 型弹射孔井				
井号	Q_{AOF} ($10^4 m^3/d$)		增值	增倍	井号	Q_{AOF} ($10^4 m^3/d$)		增值	增倍
	射孔	酸化				射孔	酸化		
磨 53	4.03	10.76	6.73	1.76	磨 55	0.93	3.06	2.13	2.29
磨 60	2.31	13.48	11.11	4.69	磨 61	0.79	7.24	6.45	8.16
磨 63	5.64	7.65	2.01	0.37	磨 21	1.95	7.56	5.61	2.88
磨 70	1.77	4.1	2.33	1.31	磨 58	1.40	9.51	8.11	5.79
磨 27	1.16	5.1	3.94	3.93	磨 18	1.45	2.71	1.26	0.87
					磨 20	1.98	13.52	11.54	5.83
平均	2.99	8.22	5.23	1.75	平均	1.42	7.27	5.85	4.1

从表5可以看出：S—51、S—41型弹射孔井平均无阻流量为$2.99\times10^4m^3/d$，而Y—73型弹射孔井平均无阻流量为$1.42\times10^4m^3/d$，从统计的角度来讲S—51、S—41型弹比Y—73型弹射孔完井效率要高。当然，油气井产量不仅与井底流通条件有关，还与地层能量以及油气物性、地层渗透率有关，而我们利用射孔来提高油气井产能主要是靠改善井底附近的油气流通条件来实现，因此，在地质条件不相近时，决不能单以产量的大小来评价射孔完井效率。从表5中可以看出S—51、S—41型弹射孔井的酸化增产倍数平均为1.75，而Y—73型弹射孔井平均酸化增产倍数为4.1，S—51、S—4型弹射孔井酸化增产倍数比Y—73型弹高2.34倍。酸化可以看成解堵和改造地层两个作用，这个数据说明S—51、S—41型弹在磨溪气田射孔完井效率比Y—73型弹高得多。Y—73型弹射孔井平均酸化增产倍数高达4.1，因此井底几乎可以肯定存在堵塞，而S—51、S—41型弹射孔井的酸化增产倍数平均为1.75，可以认为井底几乎不存在什么堵塞。酸化中的解堵作用对Y—73型弹射孔井有作用，这样Y—73型弹射孔井酸化总效果就会比S—51、S—41型弹射孔井的酸化总效果好，这充分说明S—51、S—41型弹比Y—73型弹射孔完井效率高。

(3)消除井与井之间储层差异的射孔完井效率对比分析

在磨溪气田通过大量的分析(见表6)，我们选用的消除井与井之间储层差异的储层系数为W，$W=H\times\Phi\times S_g$，单位：%。

表6　磨溪雷一[1]射孔完井效率对比分析表

S公司S—51、S—41型弹				C公司Y—89型弹				C公司Y—73型弹			
井号	W	Q_{AOF} ($10^4m^3/d$)	$\frac{Q_{AOF}}{W}$	井号	W	Q_{AOF} ($10^4m^3/d$)	$\frac{Q_{AOF}}{W}$	井号	W	Q_{AOF} ($10^4m^3/d$)	$\frac{Q_{AOF}}{W}$
磨53	61	4.03	660	磨30	33	0.64	194	磨55	27	0.93	344
磨60	52	2.31	444	磨100	52	1.90	365	磨61	43	0.79	184
磨63	80	5.64	705	磨96	81	5.49	678	磨21	89	1.95	219
磨70	52	1.77	340	磨65	49	1.03	210	磨58	53	1.40	264
磨27	39	1.16	297	磨87	39	0.71	184	磨18	38	1.45	382
				磨133	79	6.1	772	磨20	102	1.98	194
平均	56.8	2.99	526	平均	55.5	2.52	454	平均	58.7	1.42	242

不同于表5的是，表6中是消除井与井之间储层差异的单位储层系数下的无阻流量值，S—51、S—41型弹为526，Y—89型弹为454，Y—73型弹为242，这些数值已经将三种射孔弹的射孔完井效率排列出来，我们认为这样的对比能够充分说明在磨溪气田这三种射孔弹的射孔完井效率。S—51、S—41型弹射后单位储层系数下的无阻流量比Y—73型弹增加117%，比Y—89型弹增加12%，Y—89型弹射后Y—73型弹增加87%。

表6中三种射孔弹对比的时间顺序是：我们首先进行了S公司S—51、S—41型弹与C公司Y—73型弹的对比，发现在磨溪气田上大量使用的C公司Y—73型弹，其射孔完井效率大大低于S公司S—51、S—41型弹。因此要求在磨溪气田上使用当时国内射孔穿深最深的Y—89型弹，再对比发现Y—89型弹射孔完井效率大大高于Y—73型弹，但仍低于S—51、S—41型弹的射孔完井效率，这促使我们必须研制深穿透低伤害射孔弹。九十年代以来，经过不断的发展，目前国内已经拥有了Y—102、Y—127、Y—127—s等高性能射孔弹，Y—127在磨溪气田弹射孔完井效率已高于当时的S—51、S—41型弹。

3.一口井同一层段两次射孔的射孔完井效率对比(见表7)

从表7可以看到，角41井Y—73型弹射孔后无阻流量为$0.98\times10^4m^3/d$，S—51型弹补孔后无阻流量为$14.3\times10^4m^3/d$，绝对产能极大提高。由于补孔的射孔井段大于前一次射孔井段，这一结果尚不能真实的反映射孔完井效率。当我们用储层系数消除两次射孔储层差异，在单位储层系数下的无阻流量，S—51型弹是Y—73型弹的1.08倍，无疑在八角场香四气藏S—51型弹射孔完井效率高于Y—73型弹。通过这一口井的评价，再一次说明，用消除储层差异的方法进行射孔完井效率评价是正确的。

表7　角 41 井射孔完井效率分析表

射孔弹型号	日　期	射厚 (m)	储层参数 Φ (%)	K ($10^{-3}\mu m^2$) 岩心	K ($10^{-3}\mu m^2$) 测井	S_w (%)	HK ($m\times10^{-3}\mu m^2$)	无阻流量 ($10^4m^3/d$)	$\frac{Q_{AOF}}{HK}$
Y—73	1989 年 1 月 18 日	6	13.1	1.34	0.94	37.2	5.64	0.98	0.173 758
S—51	1990 年 8 月 12 日	50.0	12.0	0.94	0.72	38.4	39.64	14.3	0.361 111
增倍(S- C)/C		8.1					6.02	13.59	1.08

4. 试井分析的射孔完井效率评价(见表 8)

从表 8 可以看到, S—41、S—51 型弹射孔井的平均产率比为 1.05, 即这四口井的平均产量已达到理想裸眼井产量, 比 Y—73 型弹射孔井两口井平均产率比高 0.33, 也就是说 S—41、S—51 型弹射孔井的产能比 Y—73 型弹平均提高 33%。由上表的数据通过计算可知, S—41、S—51 型弹射孔井平均实际产量为 1.754 6×$10^4m^3/d$, 如这四口井采用 Y—73 型弹, 当产率比为 0.723 2 时, 只能获得平均实际产量 1.208 5×$10^4m^3/d$, 即说明这四口井采用了 S—41、S—51 型弹射孔, 使气井产量平均增加 5 461 m^3/d, 四口井每天增加总产量 2.184 4×$10^4m^3/d$。

表 8　磨溪雷一[1] 射孔完井效率试井分析结果表

井号	弹型	p_i (MPa)	p_{wf} (MPa)	H (m)	K ($10^{-3}\mu m^2$)	Q_g ($10^4m^3/d$)	PRJ	酸化前 S	酸化后 S
磨 53	S—51	32.66	27.50	8.4	0.61	2.057 6	0.979 6	0.46	-3.86
磨 60	S—51	31.96	25.58	3.7	1.46	1.349 3	0.512 2	7.51	-1.39
磨 63	S—41	32.15	28.59	9.5	0.47	2.425 1	1.897 0	-2.13	-3.21
磨 70	S—41	32.33	23.14	5.8	0.37	1.256 0	0.814 0	2.87	-4.18
平　均						1.754 6	1.050 0	2.178	-3.16
磨 56	Y—73	32.34	20.78	9.6	0.339	0.621 6	0.234 5	30.61	-1.49
磨 85	Y—73	32.78	30.54	10.4	1.92	4.552 7	1.212 0	-1.63	-3.38
平　均							0.723 2	14.49	-2.44

从表 8 还可以看到, S—41、S—51 型弹射孔井的表皮系数较低, 几口井的 S 值都较稳定, 变化范围较小(-2.13~7.51), 说明 S—41、S—51 型弹性能稳定、穿透深、射孔完井效率高。而 Y—73 型弹射孔井表皮系数(S)值高, 变化范围大(-1.63~30.61)。说明 Y—73 型射孔弹性能不稳定、穿透浅、射孔完井效率差。尤其是磨 56 井经过解堵酸化, 表皮系数由 30.61 降为-1.49, 地层平均渗透率提高 5.6 倍, 由 0.33 上升为 2.17, 气产量由 0.62×$10^4m^3/d$ 升至 5.79×$10^4m^3/d$, 提高了 8.3 倍。酸化前 S—41、S—51 型弹射孔井的平均 S 为 2.178, 酸化后降低为-3.16。酸化前 Y—73 型弹射孔井的平均 S 为 14.49, 酸化后降低为-2.44。通过以上分析, 我们认为 S—41、S—51 型弹射孔完井效率比 Y—73 型弹高。

5. 综合分析

在正确地得到射孔弹性能和油气藏动、静态参数的情况下, 我们所进行的射孔完井效率评价: 射孔优化设计的产率比(PRJ)及表皮系数(S)预测、无阻流量对比、消除井与井之间储层差异的射孔完井效率对比分析、试井分析的射孔完井效率评价其结论一致。消除井与井之间储层差异的射孔完井效率对比分析比其它方法评价更加客观、合理, 几乎可以在所有的油气井中进行。

以上评价方法对油井也适用, 只需将无阻流量变为采油指数以及各种计算变为油井的计算公式即可。

结　论

(1) 建立油气藏动、静态射孔参数评价参数之间的关系或有足够的动态测试参数, 那么我们就能够对射孔完井效率进行评价。

(2) 射孔完井效率评价能够指导我们正确地进行射孔优化设计及射孔枪弹系列的改进。

(3) 对射孔完井效率的评价, 可以促使我们优化选择最佳的射孔方式以提高射孔井产量。

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recognizing the mechanism of causing the mud shale wall instability, to designing the new sloughing-prevention drilling fluid system and to improving the original one, so as to solve the problem about the mud shale wall instability. On the basis of analyzing the transfer function between drilling fluid and mud shales and its mechanism, the influence of the transfer function on the borehole wall stability is discussed in detail. It is considered that the water molecule and solute transfer between drilling fluid and mud shales occurs by means of three mechanisms as diffusion, advection and osmose; the hydraulic pressure difference and chemical potential energy difference are the major driving forces; and the osmotic pressure derived from the chemical potential energy difference is of a transient nature. The borehole wall stability can be influenced by the transfer function between drilling fluid and mud shales through these ways of changing the interaction between shales and pore fluid, the formation pore pressure and the water content and cementation integrity of the shales near borehole wall.

SUBJECT HEADINGS: Drilling fluid, Shale, Hole stabilization, Analysis

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A RESEARCH ON THE HYDRAULIC FRACTURING IN LOW PERMEABILITY GAS RESERVOIR

Wang Fengjiang and Shan Wenwen (Langfang Branch of Research Institute of Petroleum Exploration and Development). *NATUR. GAS IND.* v. 19, no. 3, pp. 61~ 63, 5/25/99. (ISSN 1000- 0976; **In Chinese)**

ABSTRACT: A great deal of natural gas was found in low and extra-low permeability reservoirs and the hydraulic fracturing is the necessary means to realize its economic development. Because the unfavourable factors encounted in the hydraulic fracturing in gas reservoirs are more than those in oil reservoirs, the good results can't be achieved in many of the hydraulic fracturing works. According to this, the factors influencing fracturing results and their action mechanisms are analyzed, mainly including: the origin and mechanism of formation damage; the influence factors, action mechanism and influence level of the diverting capacity of proping agent; the technical shortcomings easily found in the fracturing design; and the influence of the gas well management after fracturing on propped fractures. On the basis of the analysis mentioned above, the principal problem that must be solved for the hydraulic fracturing in low permeability gas reservoir is to decrease the damage of fracturing fluid so as to increase the diverting capacity of fractures. For this reason the thought and methods of the design and implementation of the hydraulic fracturing in low permeability gas reservoir are proposed, they are: optimizing the formulation of fracturing fluid and the procedure of adding gel breaker and utilizing the propping agent with excellent performance; grasping the key basic parameters and using pseudo-three-dimensional software to enhance the reliability of the fracturing design, carrying out operating parameter design according to the gas reservoir characteristics and the diverting capacity of fractures to raise the suitability of the fracturing design; and setting up a set of complete operating procedures so as to perfect and improve the hydraulic fracturing techniques for low permeability gas reservoir.

SUBJECT HEADINGS: Low permeability pools, Hydraulic fracturing, Fracturing fluid, Fracturing propping agent, Fracturing design, Research

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PERFORATED COMPLETION EFFICIENCY EVALUATION

Li Aimin (Scientific and Technological Department, SPA) and Zhou Di (Logging Company, SPA). *NATUR. GAS IND.* v. 19, no. 3, pp. 64~ 67, 5/25/99. (ISSN 1000 - 0976; **In Chinese)**

ABSTRACT: There are many influence factors in perforated completion efficiency evaluation. Through exploring and verifying in practice for many times, two methods are proposed in the paper, one is to eliminate the influence of reservoir difference between wells by use of the reservoir coefficient and to carry out a comprehensive analysis of dynamic and static parameters of oil and gas reservoir; the other is to evaluate the perforated completion efficiency by productivity ratio and skin factor which are used for appraising oil & gas formation damage. Through the perforated completion efficiency evaluation of Lei-1^1 gas reservoir in Moxi field, it is proved that its result is satisfying. The evaluated result is also very important for the application of

the optimal perforation design to the practice and for the development of perforating charge. Both the methods can be used for correctly appraising the perforated completion efficiency and the first is more suitable for being largely adopted in the fields.

SUBJECT HEADINGS: Perforated completion, Efficiency, Evaluation, Skin factor, Perforation, Design, Reservoir, Coefficient

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A NEW MODEL FOR ESTIMATING ACID FRACTURE CONDUCTIVITY

Gong Ming (Technological Centre of Exploration and Production, Mobil Corporation, USA) . *NATUR. GAS IND.* v. 19, no. 3, pp. 68~ 72, 5/ 25/ 99. (ISSN 1000- 0976; **In Chinese)**

ABSTRACT: Acid fracturing is one of the common stimulation methods used for enhancing the single well productivity of carbonate reservoirs. The length and conductivity of the acid fracture are the principal indices for evaluating the effectiveness of acid fracturing treatment. On the basis of the roughness and rock strength on the fracture surface after acidization, a new theoretical model for estimating or predicting the acid fracture conductivity is proposed in the paper. The model is developed in three steps: the first, the kurtosis of the asperity distribution curve of fracture surface is used for characterizing the surface roughness and converting the asperity distribution into the contact area; the second, the fracture closure under closure stress is calculated according to the contact area and the rock strength on the fracture surface, and the damage of the rock strength by acid etching is also considered in the meanwhile; and the third, the fracture conductivity is calculated by use of the well-known cubic law. By comparison with a serie of the experimental results of the acid fracture conductivity, the conductivities under various closure stresses are accurately culculated by use of the model through adopting the actually measured parameters. In comparison to the common Nierode-Kruk correlation in which the actually measured parameters were also used, the theoretical model shows a tremendous improvement on the accuracy of estimating the acid fracture productivity. The new model is simple and easy to be used, by which the basis and convenience can be provided for the mathematical simulation of acid fracturing reservoirs.

SUBJECT HEADINGS: Acid fracture, Fracture height, Fracture conductivity, Fracture width, Surface roughness, Closure stress

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SINGLE-WELL TWO-ZONE BOREHOLE INTERZONAL LIFT PRODUCING TECHNOLOGY

He Zunyi (Research Institute of Drilling and Produetion Technology) . *NATUR. GAS IND.* v. 19, no. 3, pp. 73 ~ 76, 5/ 25/ 99. (ISSN 1000- 0976; **In Chinese)**

ABSTRACT: Multiple-zone oil and gas fields are widely distributed over Sichuan Basin, being of the properties as multiple-pay-zone, highly-scattered gas reservoirs and wells, multiple gas-water concurrent producing zone and the complicated gas-water, pressure and interconnection relations, thus causing repeated construction in oil and gas fields a long construction cycle, a difficult management and a high expense. Single-well multiple-zone production is the strategic trend of expanding the oil and gas production technology, being of practical significance for the small multiple-zone oil and gas field development. By taking the well Jia-34 in Huangjiachang gas field for example, the thought and method of design as well as the cognizance and analysis about the single-well two-zone borehole interzonal lift producing technology are proposed in the paper, including: an analysis of the basic conditions and production status of the operating well; the principal contents and procedure of technological means; the fundamental thought of performance reverse design; and the technological test and analysis. By way of on-the-spot experiment, it is proved that an assumption of interzonal direct gas lift for the non-flowing gas-and water-bearing formation by means of the high-pressure natural gas coming from the other formation is realized through applying the single-well two-zone borehole interzonal lift producing technology and that the adopted design method, technological process, each technical means and downhole tools are conformable to the process requirements and basic conditions of the well. Such a technological process is also suitable for the oil wells.