砂岩、石灰岩抗喷嘴射流冲蚀实验研究

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摘　要　砂岩和石灰岩是石油天然气钻井破岩的主要对象, 它的物理力学性质已有系统的测定方法和定量分级。但是, 它抗喷嘴射流冲蚀破碎的内涵关系和临界压力值还没有定量指标。通过大量的实验研究和综合分析, 得出了砂岩、石灰岩和抗压强度与抗喷嘴射流冲蚀破岩压力的临界值在 19.1~ 26.9 之间。为钻井水力参数的设计提供了可靠数据, 同时为开采作业提供了理论依据。

主题词　石油　天然气　钻井参数　砂岩　喷嘴　射流　冲蚀作用　破岩机理

石油天然气钻井作业的主要破碎的地层是砂岩和灰岩, 近些年来石油天然气钻井界研究最多的, 而且难度最大的是如何更有效地破碎井底岩石的新方法, 以及向井底传输能量和利用井底能量问题。国内外对钻井地层的岩石力学性质[1], 不同岩石的高效破岩机理和方法, 水射流与机械破岩的组合方式[2], 钻头的机械和水力两个破岩方面的研究[3]均取得了引人瞩目的成果。随着高压水射流破岩技术在石油天然气钻井中的应用, 为了充分发挥钻头喷嘴这个"水力机械"的破岩作用, 人们进行了新型射流喷嘴的研究与应用, 以提高喷嘴射流的瞬时冲击压力和井底液流脉动特性来提高破岩效率为目的, 取得了应用性成果。但是喷嘴射流冲蚀破碎不同物理力学性质之间的内涵关系和冲蚀破岩的临界压力值, 没有进行系统研究和定量指标。针对这个问题我们对砂岩、石灰岩进行了喷嘴射流冲蚀破岩的实验研究。

实　验　研　究

1. 实验条件

实验是在自行设计的"高压水射流综合实验机"上进行的, 用清水作为冲洗液, 实验岩心为实际井下取心的砂岩和灰岩, 软砂岩为露头岩心。主要实验参数为:

(1) 喷嘴压降: 5~ 30 MPa;
(2) 喷距: 20 mm;
(3) 射流冲蚀时间: 15 s;
(4) 喷嘴直径: 3 mm;
(5) 流量: 1.5~ 3 L/s;
(6) 井底回压: 0~ 8 MPa;
(7) 实验岩心物理力学性质, 如表 1 所示。

表 1　岩石物理力学性质表

Table 1. Physical– mechanical property of the rock

岩　石	可钻性 (m/h)	抗压强度 (MPa)	弹性模量 (10^4 MPa)	泊松比	渗透率 ($10^{-3}\mu m^2$)	孔隙度 (%)	硬　度 (MPa)	塑　性 系　数	抗拉强度 (MPa)
软砂岩	0.726	33.44	0.90	0.164	0.45	11.59	850	3.5	2.68
硬砂岩	0.587	60.25	0.60	0.040	0.11	10.27	710	1.72	4.08
致密砂岩	0.439	75.20	1.15	0.110	0.05	8.96	920	2.35	4.70
软灰岩	0.190	105.00	5.90	0.185	0	1.47	1 170	1.25	5.93
硬灰岩	0.160	147.00	8.10	0.260	0	0.85	1 510	1.59	9.35

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2. 实验方法

喷嘴射流冲蚀破岩的实验是在一稳定的喷嘴射流条件下, 寻找不同岩石物理力学性质的破岩规律和破岩临界压力值。实验方法是实验数据真实可靠的保证, 冲蚀岩石在每组实验时重复 3~ 5 次, 以求射流冲蚀破岩的可靠, 然后求平均值。体积的测量是先用 180 目金刚砂充填破碎坑, 然后以分度为 1 mg 的 TG 628 型分析天平测量充填冲蚀破碎坑的金刚砂重量, 将重量除以相对密度, 就可计算出金刚砂的体积(即岩石冲蚀破碎体积) 。

实验冲蚀破岩压力是根据岩石类别确定最低冲蚀压力值, 砂岩从 5 MPa 开始, 灰岩从 15 MPa 开始, 每次实验增加 1 MPa 逐渐达到冲蚀破岩临界压力值为止。回压是通过调节出水口控制阀来实现的。

3. 实验结果分析

(1) 井底无回压的实验结果分析

在石油天然气钻井中, 机械破碎井底岩石是破岩的主导方式, 十几年来, 国内外大量研究与应用表明, 钻头喷嘴射流是冲蚀破岩的重要手段, 而且取得了应用成果。但是对于不同的岩石射流冲蚀破岩的临界压力值为多大, 至今没有定量指标, 在实验中首先以抗压强度为标准进行定量分析, 因为抗压强度反映了很多因素的综合影响。有岩石的矿物成分, 颗粒大小, 胶结物, 容量, 孔隙度等, 都将影响其抗压强度。

抗压强度还受实验方法与物理环境的影响, 如试件尺寸、形状、加载速率、温度、围压等因素的影响。在压缩条件下, 试件中应力分布的复杂性, 出现了张性破裂, 剪切破裂等破坏形式, 因此它具有很强的代表性。所以我们采用比例法(即 $K=$ 冲蚀破岩压力值/ 抗压强度的百分比数) 分析, 结果如表 2 所示。

表 2　冲蚀破岩临界压力值与抗压强度结果表

Table 2. Results of critical rock– washing– breaking pressure value and compression strength

岩石指标	软砂岩	硬砂岩	致密砂岩	软灰岩	硬灰岩
临界压力 (MPa)	9	15	20	21	28
K(%)	26.9	24.9	26.6	20.1	19.1

为了直观, 我们把五种岩石的主要物理力学性质与喷嘴射流冲蚀破岩的临界压力值关系进行分析, 如图 1 至图 4 所示。图中的横坐标 1、2、3、4、5 分别代表软砂岩、硬砂岩、致密砂岩、软灰岩和硬灰岩。结果表明, 岩石抗冲蚀破岩临界值(p_0) 随岩石的抗压强度(p_p) 、抗拉强度(p_t) 和硬度(p_n) 的增加而增大, 随孔隙度(φ) 的增加而降低, 所以岩石的抗压强度、抗拉强度、孔隙度是影响喷嘴射流冲蚀破岩的重要因素。

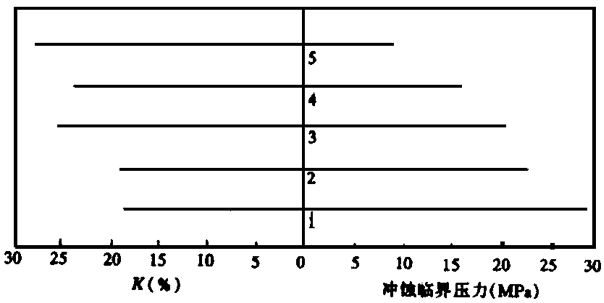

图 1　不同岩石的冲蚀破岩临界压力值(p_0) 及 K 的关系图

Fig. 1. Relationship between critical rock– washing– breaking pressure value (p_0) and K for different rocks.

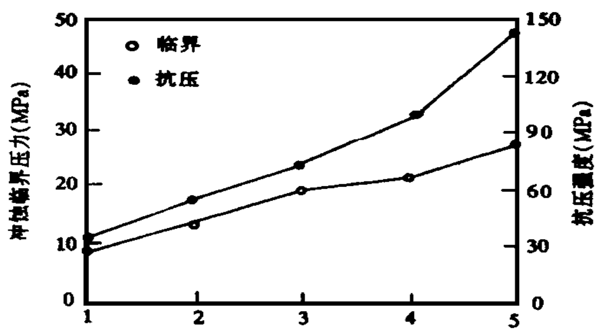

图 2　p_0 与 p_p 关系曲线图

Fig. 2. Relationship between p_0 and p_p.

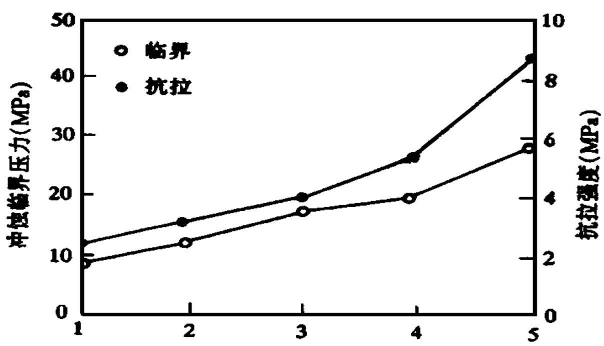

图 3　p_0 与 p_t 关系曲线图

Fig. 3. Relationship between p_0 and p_t.

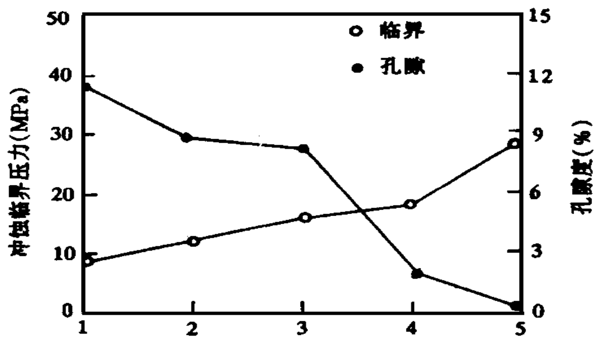

图 4　p_0 与 φ 关系曲线图

Fig. 4. Relationship between p_0 and φ.

(2) 井底有回压的实验结果分析

钻井过程中井底总是存在着一定的回压来平衡地层流体压力。理论与实验证明, 井底回压(p_r) 是影响射流冲蚀破岩的重要因素, 井底只要有回压, 冲蚀破碎体积急剧下降, 随着回压的增大, 这种下降趋于平缓, 如图 5 所示。由岩石力学性质知道, 随着回压的增大, 岩石的强度增加, 所以岩石就难于冲蚀破碎。

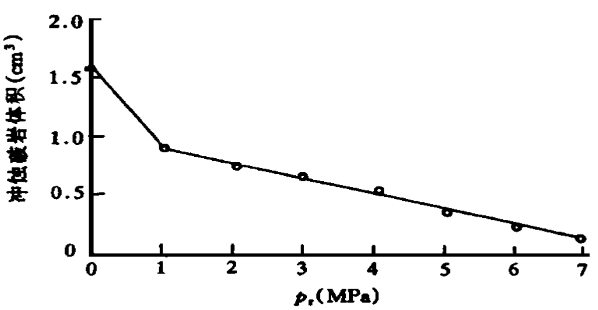

图 5　p_r 对冲蚀破岩的影响

Fig. 5. Effect of p_r on breaking rock by washing.

冲蚀破岩机理

1. 冲蚀破岩的基本条件

喷嘴射流要达到冲蚀破岩的目的有两个基本条件, 第一是射流压力必须超过岩石的内部胶结强度, 能够在岩石的某些部位产生微裂纹; 第二是射流的水力冲蚀能量能够有效地扩展裂纹, 并能把岩石颗粒(岩屑) 及时有效地冲离基岩, 形成冲蚀破碎体积。

2. 射流冲击压力的冲蚀破岩作用

在射流的冲击范围内, 井底岩石表面受到射流冲击压力作用时, 直接以冲蚀作用于岩石矿物晶体颗粒, 经岩石微孔隙施加液压力于颗粒隙面。当射流冲击压力作用大于岩石抗破碎强度时, 岩石就会被冲蚀剥裂, 于是应力在被破坏的岩石裂缝处又重新分配, 随着射流冲击压力的增大, 岩石被冲蚀破碎的体积越大。同时射流的压力越大, 产生的脉动压力也随着增大, 由于射流的脉动作用, 在岩石内部将产生周期性的交变应力, 有利于岩石的冲蚀破碎。

3. 射流对岩石孔隙和裂缝的劈裂冲蚀破岩

砂岩和灰岩在石油天然气钻井中大多数属于碎屑沉积岩, 由于各种碎屑颗粒胶结不完全等原因, 在颗粒之间形成了孔隙空间。当岩石的孔隙空间随着射流的渗入, 从而在岩石孔隙空间形成新的施力方式, 即产生劈裂。由于岩石的抗压强度与抗拉强度相比较, 抗压强度远远大于抗拉强度, 一般抗拉强度是抗压强度的 2% ~ 10%, 这就是脆性断裂的特性[4, 5]。所以用断裂力学理论来分析, 这种冲蚀劈裂破岩是充分利用了岩石的脆性, 是射流压力在岩石孔隙空间内施加压应力, 造成对孔隙和裂纹的拉伸应力作用, 以及浸润与渗透作用和对裂纹尖端的夹劈作用, 促使岩石中的微孔隙向微裂纹发育成长, 大大地降低了岩石的强度。从而起到了劈裂冲蚀岩石的作用, 在强大的拉伸应力作用下瞬间超过了强度极限而使岩石发生破坏。

结论与建议

(1) 喷嘴射流对岩石冲击压力的大小, 射流的脉动特性是影响射流冲蚀破岩效率的先决条件;

(2) 砂岩和灰岩的抗压强度、抗拉强度和孔隙度的物理力学性质是影响射流冲蚀破岩的三个重要因素;

(3) 在实验条件下, 喷嘴射流对砂岩的冲蚀砂岩临界压力平均值是 25. 8% , 灰岩的临界压力平均值是 19. 6% ;

(4) 井底回压直接影响喷嘴射流冲蚀破岩的效果, 随着围压的增大而降低;

(5) 建议对深井的地层进行岩石的精确分级, 并系统研究不同岩石性质和井深条件下岩石抗喷嘴射流冲蚀破岩临界值的定量指标, 为水力参数设计提供可靠数据, 同时为开采作业提供了理论依据。

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压裂后压力测试资料分析解释技术*

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摘　要　随着水力压裂技术的发展, 压后评估技术越来越受到广泛重视。压裂停泵后井口压力或井底压力的递减规律反映了裂缝本身及其周围地层的情况, 因此可以应用压后压力测试资料分析解释有关参数。针对压裂后压力递减资料分析技术, 提出了一种新的数学拟合方法, 并研制了一套 Windows 环境下的解释软件, 应用该软件可以获得压裂后裂缝长度(或半径)、裂缝宽度、压裂液滤失系数、压裂液效率、裂缝闭合时间、压力递减比等有关评价参数。实例计算表明, 本方法比传统的曲线拟合方法更为简便可靠。

主题词　压裂　压力降　裂缝宽度　裂缝导流能力　压裂液　滤失　流变性　计算机程序

随着水力压裂技术的发展, 压后评估技术越来越受到广泛重视, 相应的压后测试方法和解释技术也需进一步地发展和完善。在大规模压裂前, 进行一次小规模的压裂测试和解释, 对于取得压裂所需要的参数和及时修改大规模压裂设计是非常必要的, 这也是近年来压后评估技术受到广泛关注的重要原因。前人的研究都是用 Nolte 提出的典型曲线拟合来分析解释压裂后压力递减资料, 但曲线拟合方法与人为操作有很大关系, 具有较大的误差和局限性。为此, 本文提出了一种新的数学拟合方法, 发展了压裂后压力递减资料分析技术, 并研制了一套 Windows 环境下的解释软件。实例计算表明, 本方法比传统的曲线拟合方法更简便、更精确。

压裂参数的计算方法

小型压裂或压裂停泵后, 井口压力和井底压力下降, 其速度肯定反映出裂缝本身及其周围地层的情况, 因此可以利用压力递减资料分析并求出有关参数。

1. 拟合压力的计算

小型压裂或压裂停泵后, 如果假设: 裂缝的高度不变, 地层是线弹性体, 层间无滑动, 排量不变, 注幂律液体到裂缝中, 停泵后, 裂缝不再延伸, 裂缝自由闭合, 则可以导出关井后任意两个时间差的压力差为[2, 5]:

$$\Delta p(\delta_0, \delta) = p^* G(\delta_0, \delta) \tag{1}$$

其中, $\Delta p(\delta_0, \delta) = p(\delta_0) - p(\delta)$　　(2)

$$G(\delta_0, \delta) = \frac{4}{\pi}[g(\delta) - g(\delta_0)] \tag{3}$$

$$g(\delta) = \begin{cases} \frac{4}{3}[(1+\delta)^{\frac{3}{2}} - \delta^{\frac{3}{2}} - 1] \ (\text{高效率}) \\ (1+\delta)\sin^{-1}(1+\delta)^{-0.5} + \delta^{0.5} \ (\text{低效率}) \end{cases} \tag{4}$$

$$\delta = \frac{t}{t_0} \tag{5}$$

传统的曲线拟合方法是根据压力递减资料, 应用时间函数 $G(\delta_0, \delta)$ 作出样板曲线, 同时作出压差函数 $\Delta p(\delta_0, \delta)$ 与无因次关井时间 δ 的关系曲线, 将样板曲线与压差曲线进行拟合, 求出拟合压力 (p^*)。显然, 曲线拟合方法与人为操作有关, 一般具有较大误差和局限性, 且操作不便。为此, 本文提出一种新的数学拟合方法来计算拟合压力 (p^*), 即构造目标函数为:

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string embrittlement and drill pipe stiking induced by high pressure, high yield and high hydrogen sulfide content are analyzed. Through an analysis of several complicated wells such as well Huanglong 4 and well Yun' an 4-1 etc., the several aspects on which the particular emphasis should be laid for the drilling technique of the next round of exploratory wells in the new area in East Sichuan are proposed. Following the changed downhole situation to alter the drilling design (or to re-design the engineering), casing program and lost circulation controlling and handling measures as well as to strengthen the contingent of full-time skilled personnel are emphasized.

SUBJECT HEADINGS: Sichuan Basin, East, Drilling, Drilling design, Casing program, Lost circulation control, Technique, Analysis.

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CALCULATION OF THE OPTIMAL PLACEMENT LOCATION OF VIBRATION DAMPER FOR DEEP-HOLE DRILL STRING

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ABSTRACT: Vibration damper is one of the main tools for protecting drill string from breakage, so its placement location is a technic problem of great interest in engineering. For this purpose, taking the whole drill string as the object of study and considering the rigidity of derrick and wire rope and the damping effect of mud, the mechanical model for analyzing the vibration of whole deep-hole drill string is set up and the compressional vibration of drill string is analyzed and calculated by using dynamic finite element method. The optimal placement location of the vibration damper is defined on the basis of the intrinsic frequency, response displacement and axial force value of drill string. Through analysis and calculation of the typical deep-hole drill string used in Daqing oil field, the optimal placement location of vibration damper at the interval of 3000-4000 m is given, while the past knowledge that the optimal placement location of vibration damper is that near to the bit is corrected. It is shown by field test that the damping effect is obvious, playing an important role in reducing drill tool breaking accident.

SUBJECT HEADINGS: Deep well, Drilling, Bottomhole assembly, Damper, Location, Calculation.

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DIRECTLY PREDICTING THE CHANCES OF CONTROLLING GAS MIGRATION IN GAS WELL'S ANNULUS AFTER CEMENTING BY USE OF ANALYTIC METHOD

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NATUR. GAS INS. v. 17, no. 5, pp. 48~51, 9/25/97. (ISSN 1000-0976; **In Chinese**)

ABSTRACT: How to accurately predict the gas channelling in annulus is always a studying object at home and abroad. A certain result in predicting gas channelling has been obtained by the predicting method of whether the gas channelling will occur after cementing, proposed by Dowell Schlumberger, i. e. overall evaluating the chances of controlling gas migration (CCGM) in annulus after cementing through comprehensively analyzing several parameters being able to influence gas channelling. But this method is resulted from the statistics and analysis based on a vast amount of the gas well data from foreign oil and gas fields and it is offered in a manner of slide rule for the use at site, so it brings a certain difficulties in applying and improving this technique for the oil and gas field development in China. In this article, the analysis of this method is mainly introduced, the analytic formula of applying this technique is proposed and the method to further perfect this technique is pointed out.

SUBJECT HEADGINS: Well cementing, Cementing, Cement channelling, Channelling prevention, Cement slurry, Prediction.

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AN EXPERIMENTAL RESEARCH ON SANDSTONE AND LIMESTONE RESISTING WASHING ACTION OF NOZZLE FLUIDICS

Xiong Jiyou and Liao Rongqing (Southwest

Petroleum Institute) and Zhang Junwei (Zhongyuan Petroleum Exploration Bureau). NATUR. GAS IND. v. 17, no. 5, pp. 52~ 55, 9/25/97. (ISSN 1000-0976; **In Chinese)**

ABSTRACT: Sandstone and limestone are the main targets cut by oil and gas well drilling and for their physical mechanical property there have been systematic determination method and quantitative gradation. But for their connotative relation and critical pressure value in resisting crushing by nozzle fluidics washing there is not yet a quantitative index. From a vast amount of experimental researches and comprehensive analysis, it has been obtained that the compression strength of the sandstone and limestone and their critical values of rock-breaking pressure resisting nozzle fluidics washing are 19. 1-26. 9, which provides a reliable data for the design of drilling hydraulic parameter and also a theoretical basis for production operation.

SUBJECT HEADINGS: Petroleum, Natural gas, Drilling parameter, Sandstone, Nozzle, Fluidics, Washing action, Rock breaking mechanism.

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ANALYTICAL AND INTERPRETATIVE TECHNIQUE OF THE PRESSURE TEST DATA AFTER FRACTURING

Zhang Ping, Guo Dali, Chen Wenbin and Zhao Jinzhou (Southwest Petroleum Institute). *NATUR. GAS IND*. v. 17, no. 5, pp. 55~ 57, 9/25/97. (ISSN 1000-0976; **In Chinese)**

ABSTRACT: In pace with the development of hydraulic fracturing technique, more and more attention is paid to the evaluating technique after fracturing. The decline law of the wellhead pressure or bottom hole pressure after termination of pumping reflects the situation of fractures themselves and formation around them, so relevant parameters can be analyzed and interpreted by using the pressure test data after fracturing. Aiming at the analytic technique of the pressure decline data after fracturing, a new mathematical fitting is proposed and a set of interpretation software for Windows is developed. By use of this software, the relevant evaluation parameters, such as fracture length (or radius), fracture width, fracturing fluid filtrate loss coefficient, fracturing fluid efficiency, fracture closure time and pressure decline ratio etc. can be obtained. An example calculated shows that this method is even more simple, convenient and reliable than the traditional curve fitting method.

SUBJECT HEADINGS: Fracturing, Pressure drop, Fracture width, Fracture conductivity, Fracturing fluid, Filtrateloss, Rheology, Computer program.

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DESIGN OF OIL AND GAS PIPELINE LAYING WITH ELASTIC BENDING

Deng Daoming and Yuan Zongming (Southwest Petroleum Institute). *NATUR. GAS IND*. v. 17, no. 5, pp. 58~ 63, 9/25/97. (ISSN 1000-0976; **In Chinese)**

ABSTRACT: The pipeline laid with elastic bending should satisfy the condition of strength and deformation, while the heated pipeline with convex elastic bending must also satisfy that of longitudinal stability. The basis of calculating the elevation of pipe trench with elastic bending is the elastic deflection curve of pipeline which is generally fitted approximately by the design units in China by using circular arc curve, while an accurate quartenary deflection curve was used by the former Soviet Union. In this paper, a series of practical design formulas of these two methods are systematically presented, in which, the formula for defining minimum elastic bending radius on the basis of strength condition is different from that recommended in the design standard for oil and gas pipeline structure in China, and the formula for calculating the elevation of pipe trench is also different from that introduced in existent literatures, and the relevant formulas are appraised too. By making rational use of these formulas, both the safety and a better economic benefits obtained can be guaranteed.

SUBJECT HEADINGS: Oil and gas gathering, Pipeline, Elasticity, Pipeline design, Calculation method.

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