川南东部地区阳新统的地层破裂压力预测

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摘 要 碳酸盐岩裂缝性地层破裂压力定量预测目前仍是一道非常复杂的难题。文章应用水力压裂力学原理，紧密结合川南东部地区阳新统碳酸盐岩地层特征，探讨了该地区的地层破裂压力机理，认为该区大部分压裂酸化井人工压裂缝是在自然垂缝上延伸扩展，破裂压力近似等于其垂缝延伸压力。在水平挤压应力和扭剪应力作用下，岩体抗张强度主要受地层破碎系数和应力强度指数控制，文章建立了预测地层破裂压力的物理—数学模型，确定岩体视抗张强度，进而对地层破裂压力进行预测。经实际破裂压力资料验证，绝对误差最大5.0 MPa，一般小于3.0 MPa；相对误差最大5.0%，一般小于2.0%。

主题词 川南东部地区 早二叠世 地层破裂机理 地层破裂压力 预测

地层破裂压力是井身结构、套管下入深度、平衡钻井、井控工艺技术和防止产生井下复杂情况及压裂酸化施工设计等的重要依据。碳酸盐岩裂缝性地层破裂压力定量预测目前仍是一道非常复杂的难题。难就难在不同的构造部位受构造应力场作用的强度难以确定。主要表现在对最小水平主应力和岩体抗张强度的精确度量。从微观机理上看，岩体抗张强度主要决定于岩体受力后晶格破坏程度和围压大小。岩体晶格破坏程度主要受局部构造断裂程度和剪应力作用强度控制，而围压大小主要决定于上覆应力和残余构造水平应力。本文在前人成果的基础上，试图定量预测川南东部地区阳新统地层破裂压力。

破裂机理

川南阳新统地层属海相碳酸盐岩，经历了东吴、海西、印支、燕山和喜山期构造运动。多期多方位构造运动，造成阳新统地层裂缝广泛分布，断裂数量大。据1989年底以前的钻探资料，钻达阳新统井476口，164口在阳新统钻遇断层220条，且多分布在东部地区。

1. 破裂模型

据阳新统地层特征和钻探显示，划分为3种破裂前地质模型(表1)。

对开启型，因一般在增产作业前已具有一定的

表1 破裂前地质模型特征

模型＼项目	钻井显示	岩屑特征	电测结果	测试效果
开启型	井喷或井涌	透明方解石含量高	渗透性良好	产水或气
闭合型	无井涌和气侵	方解石含量很低	渗透性很差	无流体产出
过渡型	井涌或气侵	方解石含量较高	渗透性较好	少量流体产出或无流体产出

2 Thomas D G. Transport characteristic of suspensions; Part IV-minimum transport velocity for large particle size in round horizontal pipes. AICHE, Jour 8, 1962; 3

3 Gurley D G. Factors affects gravel packing placement in long deviated intervals. SPE 19400

4 G W 戈威尔著，权忠舆译. 复杂混合物在管道中的流动(上、下). 北京：石油工业出版社，1984

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工业产能,故作业时注入压力较低。对这类地层进行预测工作意义不大;对闭合型,一般不进行压裂酸化作业。所以,本文重点讨论过渡型地层破裂压力预测。取心资料表明:阳新统自然主裂缝多为垂缝和斜垂缝(也存在自然水平缝)。破裂模型见图1,σ_1、σ_2为水平主应力,σ_3为上覆应力。

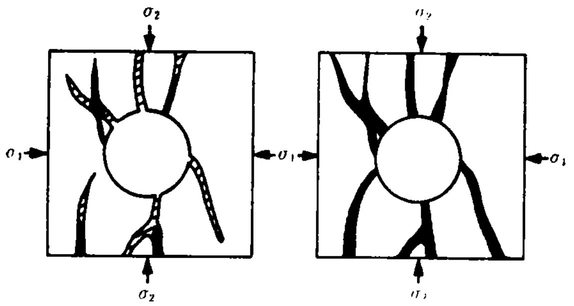

图1 地层破裂地质模型

三十多年的勘探史表明,寻找有利构造部位、有利断层及地震异常等为川南阳新统地层的有效布井原则。显然,这些地带是断裂和扭剪作用较强的地带,即自然裂缝可能发育地带。值得重视的是在这样的地质条件下所进行的压裂施工,使井筒周围裂缝起裂,实质是流体压力克服最小应力和已具破裂界面的岩体抗张强度在自然裂缝基础上的延伸扩展。因此,作者认为,一般情况下可不必考虑井筒附近裂缝起裂。

2.压裂裂缝的扩展

川南阳新统地层压裂施工,实质是把闭合的自然裂缝撕裂后与开启裂缝连通的过程或将微开启的自然裂缝扩张后进一步延伸扩展与另外的自然裂缝相沟通的过程。下面讨论其延伸扩展方向、方式和所需压力。

(1)裂缝扩展的方向

水力压裂力学认为,裂缝延伸扩展的方向始终垂直于最小水平主应力。据文献[1],天然裂缝面当法向应力较小或裂缝面间的联接较弱时,就有可能成为止裂源,迫使裂缝延伸方向改道。对一具体的井位所控制的构造范围内,裂缝延伸扩展方向受到最小主应力和自然裂缝展布方向双重制约。当遇到法向应力较弱的自然裂缝时,主要由自然裂缝扩展方向控制压裂缝延伸方向;反之,则主要由最小应力控制压裂缝展布方向。所以,压裂缝延伸方向是很不规则的。

(2)裂缝的形态和扩展方式

据水力压裂力学:

当$\sigma_3>\sigma_1>\sigma_2$时,主要产生垂缝;

当$\sigma_3<\sigma_2<\sigma_1$时,主要产生水平缝。

据文献[2]压裂模拟实验表明,由于岩石的不均质性,水力压裂中除产生垂直于最小主应力的主裂缝外,还可产生其它方向的斜垂缝、斜平缝。在逆断层发育区,应力状况应为:$\sigma_3<\sigma_2<\sigma_1$,主要形成水平裂缝,但在自然裂缝发育带,有可能造成$\sigma_2<\sigma_3<\sigma_1$应力状况,主要形成垂缝,实质是延伸加高或扩大自然垂缝。反之,则主要形成水平缝,沟通若干自然裂缝,形成较大的裂缝系统(图2)。

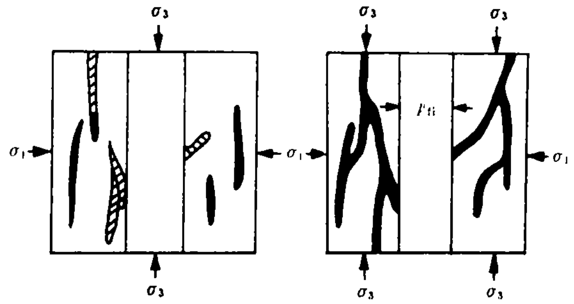

图2 人工压裂缝在自然裂缝中延伸扩展示意图

(3)裂缝扩展所需压力

据水力压裂力学,裂缝扩展所需压力为:

垂直缝:$p_{fi}=\sigma_{min}+\sqrt{2Er_{to}/\pi S(1-\mu^2)}$

$$=\sigma_{min}+\sigma_{to}^h \quad (1)$$

水平缝:$p_{fi}=\sigma_3+\sqrt{2Er_{to}/\pi R(1-\mu^2)}$ (2)

由(1)、(2)式看出,在相同条件下,水平裂缝扩展要求较高的流体压力,而垂缝扩展压力要求较小,一般小于上覆应力。川南阳新统酸化压裂资料(图3)表明:地层破裂压力一般接近上覆应力,少数井大于上覆应力,主要表现出压裂缝在自然垂缝和斜垂缝中延伸扩展的特征。

因 $\sigma_{min}=p_i+\sigma_r$ (3)

将(3)式代入(1)式,得地层破裂压力

$$p_{fi}=p_i+\sigma_r+\sigma_{to}^h \quad (4)$$

而碳酸盐岩岩石骨架上所受的主应力很难准确计算,故引入参数视岩体抗张强度σ_t^h和视抗张强度r:

$$\sigma_t^h=\sigma_r+\sigma_{to}^h$$

$$=\sqrt{2Er/\pi S(1-\mu^2)} \quad (5)$$

将(5)式代入(4)式得：

$$p_{fi}=p_i+\sigma_t^h$$
$$=p_i+\sqrt{2Er/\pi S(1-\mu^2)} \quad (6)$$

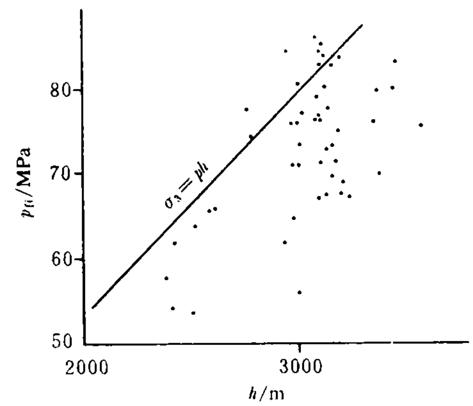

图 3　川南阳新统地层破裂压力分布图

(6)式中的 p_i 值，可由文献[3]气层压力预测公式计算，S 为压裂扩展前自然垂缝或斜垂缝高度，可设其为常量。在川南东部地区阳新统地层 μ 值一般分布在 0.28～0.34 之间，研究表明：$(1/1-\mu^2)$ 对 σ_t^h 值影响较小。E 与岩石结构和围压大小有关，但一般变化不大。所以，直接影响 p_{fi} 值的是(6)式中视比表面能 r，岩体断裂和扭剪强度又直接控制视比表面能的大小。因此，引入表征岩体断裂和扭剪强度的岩体破碎系数 ψ 和应力强度指数 n：

$$r=(1-\psi)r_{omax}=(1-\psi)r_o e^n \quad (7)$$

$$\psi=M\cdot N \quad (8)$$

①M

M 为断层断距与钻至阳顶的井离断层线间的水平距离之比。根据构造地质学，形成断层的条件为：

$$\tau=\tau_o+(\sigma-p_i)\text{tg}\ \varphi\approx\frac{\sigma_1-\sigma_2}{2}\sin 2\theta \quad (9)$$

显然，在自然裂缝发育的地方，τ_o 较低，易形成断层，若裂缝内流体压力 p_i 较高，更易形成断层，微裂缝更加发育。由(9)式看出，τ 越大，断距越大，表征着受主应力作用强度大。而在断层上下盘两侧有限范围内，岩层因断面摩擦派生引张力，岩石矿物晶体才遭受较强的晶格位错。一般情况下，离断面越近，晶格位错越大，r 越小，σ_t^h 越小。因此，M 值的大小表示局部构造部位岩体断裂程度大小。

②N

川南区域应力边界近呈直角三角形，在受水平构造应力作用的同时，还受到较大的扭剪应力场的作用。

由(9)式，并设：

$$f=\tau/(\sigma_1-\sigma_2)=\frac{1}{2}\sin 2\alpha$$

$$N=e^{f^*} \quad (10)$$

③r_o、r_{omax} 和 n

r_o 为某构造现今一般视比表面能，r_{omax} 为某构造局部地带最大视比表面能。作者研究认为：对某一构造，一般情况下，$r_{omax}\approx r_o$，但对受扭剪和断裂作用很强的地带，$r_{omax}>r_o$ 或 $r_{omax}<r_o$。由于 ψ 值仅考虑到井位附近所受剪应力场作用状况，而井位与断裂组合和构造位置关系未加考虑。所以，引入应力强度指数 n（n 取值见表 2），以定量表征 r_{omax}：

$$r_{omax}=r_o e^n \quad (11)$$

将(7)、(8)、(10)、(11)式代入(6)式整理得：

$$p_{fi}=p_i+\sqrt{[2Ee^n r_o(1-\psi)]/\pi S(1-\mu^2)} \quad (12)$$

上已述及，川南阳新统地层自然裂缝发育，可设

表 2　构造断裂特征与应力强度指数关系表

井位与构造断裂组合特征	大断裂 平行二组断裂 正交二组断裂		中小断裂											
			高点			轴部			翼部			鞍部	
井位与断层倾向关系	同向	反向	同向	反向		同向	反向		同向	反向		同向	
ψ	>0.2	>0.2	>0.2	0.2～0.5	>0.5	>0.2	≤0.3	>0.3	>0.2	≤0.4	>0.4	≤0.4	>0.4
n	-8ψ	$-\psi$～-2ψ	-6ψ～-7ψ	-0.25ψ～-0.5ψ	$-\psi$	-5ψ～-6ψ	0	-0.25ψ～-0.5ψ	-3ψ～-4ψ	0	0.25ψ～2ψ	0	$-\psi$～-2ψ

注：一般情况下，$\psi\leqslant 0.2$ 时，$n=0$。若个别井位所处构造部位存在较强扭剪时，尽管 $\psi\leqslant 0.2$，n 为 -2ψ～-8ψ。

垂缝或斜垂缝初始裂缝高度 $S\approx 10$ cm，并将 $E=0.696\times 10^5$ MPa（西南石油学院钻头教研室资料），$1-\mu^2\approx 0.9$，$\pi\approx 3.14$ 代入（12）式得预测地层破裂压力物理—数学模型：

$$p_{ft}=p_t+0.7017\times 10^2\sqrt{e^n r_o(1-\psi)} \qquad (13)$$

应用实例

对临峰场构造阳新统地层破裂压力进行预测。

1. r_o 确定

据文献[3]，计算出每口井 p_t 值。选定受力和断裂分布简单的井作为确定该构造上 r_{omax}。基于这一选井原则，以临 22 井为基准井。

将该井 $p_t=42.01$ MPa，$\alpha=15°$，$M=0.1252$，$N=1.2840$，$n=0$，$p_{ft}\approx p_{fi}=67.12$ MPa，代入（13）式计算得：

$$r_o=\frac{(p_{ft}-p_t)^2}{(0.7017\times 10^2)^2(1-\psi)}$$
$$=0.1526\ \text{MPa}\cdot\text{cm}$$

2. 临 5 井地层破裂压力预测

将临 5 井，$p_t=33.95$ MPa，$M=0.1250$，$N=1.4500$，$n=0$，$r_o=0.1526$ MPa · cm，代入（13）式计算得：

$$p_{ft}=p_t+0.7017\times 10^2\sqrt{e^n r_o(1-\psi)}$$
$$=33.95+0.7017\times 10^2\cdot\sqrt{e^0\cdot 0.1526(1-0.1250\times 1.450)}$$
$$=58.75\ \text{MPa}$$

临 5 井阳新统地层预测破裂压力值与实际地层破裂压力值相比，其绝对误差 $\Delta p_{ft}=0.67$ MPa，相对误差 $\delta=1.15\%$。

用此方法对川南东部地区共 12 个构造 40 口井阳新统地层破裂压力进行预测，与实际地层破裂压力相比，绝对误差最大 5.0 MPa，一般小于 3.0 MPa，相对误差最大 5.0%，一般小于 2.0%。同时，对 1993 年川南东部地区钻探阳新统井地层破裂压力预测，以待实际压裂施工进一步验证。

结束语

（1）据水力压裂力学和构造地质学，紧密结合川南阳新统地层特征，探讨了川南东部地区阳新统地层破裂压力机理，认为该区大部分压裂酸化井，地层破裂压力近似等价于其延伸压力。

（2）本文充分考虑岩体断裂程度和扭剪应力强度，引入地层破碎系数和应力强度指数概念，建立了视比表面能物理—数学模型，确定岩体视抗张强度，进而对地层破裂压力预测，应用于实际，拟合性较好。

（3）建议加强对应力强度指数作进一步研究，以利更好地指导生产实践。

在本文撰写中，承蒙郭元庆高级工程师，李荣生工程师审阅、修改，在此表示衷心感谢。

符号说明

p_{fi}——实际地层破裂压力，MPa；
σ_{min}——最小水平主应力，MPa；
E——岩石弹性模量，MPa；
r_w——岩石比表面能，MPa · cm；
S——垂缝或斜垂缝高度，cm；
μ——泊松比；
R——水平裂缝半径，cm；
p_i——主裂缝内流体压力，MPa；
σ_r——岩石骨架上所受的主应力，MPa；
σ_t^b——视岩体抗张强度，MPa；
σ_{to}^b——岩体抗张强度，MPa；
ψ——岩体破碎系数；
M——断裂强度因子；
N——扭剪应力强度因子；
θ——最大水平主应力与断层面上正应力之间的夹角，(°)；
n——应力强度指数；
r——视比表面能，MPa · cm；
r_{omax}——某构造上局部地带现今最大视比表面能，MPa · cm；
r_o——某构造上现今一般视比表面能，MPa · cm；
τ——剪应力，MPa；
τ_o——抗剪强度，MPa；
σ——断层面上所受正应力，MPa；
φ——岩石摩擦系数；
α——最大水平主应力与主裂缝法线间的夹角，(°)；
p_{ft}——预测的地层破裂压力，MPa；
p_t——预测的气层压力，MPa；
f——剪应力强度系数。

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computer data collection system, the oil and water fractional flow can be measured automatically and continually. With highly accuracy, automation and large capacity of data collection, this method is suit for testing relative permeability (steady and unsteady state, two or three phase)and other core flow.

SUBJECT HEADINGS: microflow, fractional flow automatic measurement, realative permeability, experimental method.

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Sun Bao-wei (*China National Petroleum Development Corporation*), Zhang Shao-huai: RESEARCH ON MATHEMATICAL AND COMPUTER MODELINGS FOR GRAVEL PACKING IN DEVIATED WELLS, NGI 14(2), 1994: 40~43

ABSTRACT: Drilling the deviated and horizontal wells is perspective technique for oil-gas exploration and development, being highly efficient and profitable especially for heterogenous reservoirs or complicated geographic environment in fields. During completing the deviated wells many problems appear in gravel packing for sand control as follows: (1)Resulting in bridge blinding by settling often as gravel has not filled up the whole space; (2)Damaged strata resulted from the fluid with sands flowing into formation, and by the fluid' s filtration bridge blinding is formed again at the same time; (3)As gravel has not packed up, wellbore caving happens often. A mathematical model abstracts from the process of gravel packing in deviated wells, relying on the conservation of either momentum or mass and the consideration of all factors affecting gravel packing. Computer modeling has been done as theory and computing formula are given for model forecasting. Such this feasible method is found out for optimum seeking for packing parameters.

SUBJECT HEADINGS: deviated wells, gravel packing, mathematical modeling, computer modeling, computing method.

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Jiang Zi-ang (*South Sichuan Gas Field of Sichuan Petroleum Administration*), Zhang Yong-hong, Lai Wen-hong, Liao Yi: FORECASTING FRACTURE PRESSURE IN STRATA OF YANGXIN SERIES IN THE EASTERN AREA OF SOUTH SICHUAN, NGI 14(2), 1994: 44~47

ABSTRACT: Quantitive forecasting the break down pressure in carbonatite fractured strata is still a knotty problem. Hydraulic stimulation mechanics is used while it is taken into account of the characteristic of carbonatite formation in Yangxin series in the eastern area of South Sichuan. In this district strata fracture pressure mechanism is discusses on. In most fracture acidizing wells hydraulic fracture extends through natural verticle fracture, with its extension pressure be approximately equal to fracture pressure. As the actions of horizontal extrusion, torsion and shear stresses, the rock tensile stress is affected by formation crush coeifficient and stress intensity exponent. A physics-mathematics model is for forecasting formation fracture pressure to determine the apparent tensile stress of rocks. With data of actual fracturing pressure, the prediction pressure is proved that the absolute error is generally less than 3. 0 MPa, 5. 0 MPa of the maximum; the fractional error is generally less than 2. 0%, 5. 0% of the maximum.

SUBJECT HEADINGS: eastern area of South Sichuan, Yangxin series, fracture mechanism, forecasting pressure.

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Zheng Yong-gang (*Chengdu Science-Technology University*), Hao Jun-fang, Wang Zhi-ping: THEORETICAL ANALYSIS OF MOVING CASINGS TO IMPROVE DISPLACEMENT EFFICIENCY IN CEMENTING JOB, NGI 14(2), 1994: 48～51

ABSTRACT: An eccentric annulus is assumed as cuneiform area, and fluid mechanics and the flow equation for the power-law fluid in the cuneiform area are utilized for the analysis of flow field which is produced by mud and cement slurry while casings are being rotated and moved up and down. How the casing movement affects displacement efficiency is also studied. It is concluded that the fluid in an annulus is in shear state because of the casings movement. Back flows can be formed at the wide side clearance in an annulus with the casing rotating. For the destruction of mud gelatination structure by two actions of shear and back flow, the bypassed mud in the narrow clearance can be removed so that the displacement rate becomes higher than before. Calculation and analysis of the flow in the movement of casings in an annulus have shown that the shear and back flow actions are directly proportional to either the flow behavoir or the casing movement speed. So, it is beneficial to increase the displacement effciency by the destruction of mud gelatination structure and the removal of the bypassed mud.

SUBJECT HEADINGS: moving casings, cementing, displacement efficiency.

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Zhou Chun-hu (*Xian Petroleum Institute*), Zhao Gang, Yang Wei-yu: DISCUSSION ON THE FRACTURING TECHNOLOGY OF LOW PERMEABILITY SANDSTONE GAS BEARING FORMATION, NGI 14 (2), 1994: 51～54

ABSTRACT: Hydraulic fracturing is key to reform and develop low permeability gas bearing formation, which has been done a large quantity fracturing construction at home and abroad, but the effect is worse than this measure used in oil fields. Some gas formation production even was reduced after fracturing, and flowing with some harmful tendencies, such as sands was brought out, fracturing fluid can' t be dissolved completely, etc. Based on internal and external fields reality, the main factors affected the stimulation results, which including liquid leakoff, formation and fissures damaged, proppant crushed and flowback into wellbore, fluid compatibility, fluid flowback and gas well management, are discussed in the poper. Hydraulic fracturing is difficult to link up more natural fissures, which is damaged is an important resason of effecting fracturing result. So, in order to link up fissures effecturally and unharmfully, the high energy gas fracturing (HEGF) and hydraulic fracturing are combined to reform low permeability gas bearing formation synthetically.

SUBJECT HEADINGS: low permeability sandstone gas bearing formation, hydraulic fracturing, high energy gas fracturing, technology discussing.

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