以临界生产压差法进行涩北气田出砂预测研究

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摘　要　青海涩北气田出砂严重，由于钻井取心困难，难以通过岩石力学实验获得足够的岩石力学参数进行系统全面的出砂预测，通过测井获得的声波、密度、自然伽马等资料，研究了求取泊松比、弹性模量、内聚强度、内摩擦角等岩石力学参数的经验方法，建立了涩北 1号气田气井出砂和控砂预测模型。根据涩北 1号气田 20口气井开发储层出砂指数、临界生产压差预测结果统计，预测结果与现场观测结果基本吻合，从而为涩北气田出砂预测、合理选择生产压差以及优化配产提出了一种适用的理论研究方法。

关键词　涩北气田　临界压力　出砂　预测

涩北气田储气层为滨浅湖相砂泥岩互层沉积，气层岩性以粉砂岩和泥质粉砂岩为主，储层具有埋藏浅、胶结疏松、含气井段长、气层多、气水界面复杂等特点，属于第四系生物成因疏松砂岩边底水气藏。气藏欠压实、胶结差、岩性疏松，胶结物以泥质为主，泥质含量占 40%左右，平均孔隙度 31.77%，平均渗透率 571.72 $\times10^{-3}\mu m^2$，岩石粒度为粉砂级—细砂级，粒径（0.01～0.4）mm。

气井生产过程中出砂严重，大部分气井需要控制生产压差进行生产。气田不同构造及区域、不同开发层系和井区的气井临界出砂生产压差存在较大差异，目前尚未找到气田明显的出砂规律。由于，涩北气田岩芯取芯和保存困难，难以通过岩石力学实验获得足够的岩石力学参数进而进行系统全面的出砂预测，因此需寻求根据测井资料，求取岩石力学参数，进而进行出砂预测的理论与方法。

1　临界生产压差预测

考虑厚度为 h的圆性气藏径向流，根据非达西流动 Forchheier方程，得到气藏地层孔隙中的流体压力梯度方程：

$$\frac{dp}{dr}=A\frac{1}{rp}+\frac{B}{r^2p} \tag{1}$$

式中　p—压力，MPa;

r—任一点的半径，m;

A、B—中间变量符号。

考虑孔隙压力影响，弹性地层岩石材料的形变 u为：

$$(\lambda+2G)\frac{d}{dr}\left(\frac{du}{dr}+\frac{u}{r}\right)+\beta\frac{dp}{dr}=0 \tag{2}$$

将地层流体压力梯度方程（1）代入方程（2）并整理后得到：

$$\frac{d^2u}{dr^2}+\frac{1}{r}\frac{du}{dr}+\left(-\frac{1}{r^2}\right)u=-\frac{\beta}{\lambda+2G}\left(\frac{A}{P}\frac{1}{r}+\frac{B}{P}\frac{1}{r^2}\right) \tag{3}$$

方程（3）为欧拉形式的二阶非线性常微分方程，其通解为：

$$u=C_1+C_2\cdot\frac{1}{r}+\frac{a}{2}\cdot r\cdot \ln r-b$$

$$a=-\frac{\beta}{\lambda+2G}\cdot\frac{A}{P_0},\ b=-\frac{\beta}{\lambda+2G}\cdot\frac{B}{P_0} \tag{4}$$

式中　λ—Lame常数;

u—形变;

β—Biot常数;

C_1、C_2—积分常数。

假设只有初始径向应变，则有：

$$\varepsilon_r^e=\frac{du}{dr},\quad \varepsilon_\theta^e=\frac{u}{r},\quad \varepsilon_z^e=\varepsilon_{ze} \tag{5}$$

将方程（4）代入方程（5）得到各有效应变为：

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$$\varepsilon_r^e = -C_2 \cdot \frac{1}{r^2} + \frac{a}{2} \ln r + \frac{a}{2}$$

$$\varepsilon_\theta^e = C_1 \frac{1}{r} + C_2 \cdot \frac{1}{r^2} + \frac{a}{2} \ln r + - b \frac{1}{r}$$

$$\varepsilon_z^e = \frac{\sigma_{ze} - \beta \cdot P_r}{\lambda + 2G} \tag{6}$$

弹性材料的应力—应变方程为:

$$\sigma_r = \lambda \Delta^e + 2G\varepsilon_r^e + \beta \cdot P$$

$$\sigma_\theta = \lambda \Delta^e + 2G\varepsilon_\theta^e + \beta \cdot P$$

$$\sigma_z = \lambda \Delta^e + 2G\varepsilon_z^e + \beta \cdot P$$

$$\Delta^e = \varepsilon_r^e + \varepsilon_\theta^e + \varepsilon_z^e \tag{7}$$

将方程 (6) 代入方程 (7) 便可得到气藏弹性岩石的应力解。根据油藏的内外边界条件 $\sigma_r |_{r=r_w} = P_{wf}, \sigma_r |_{r=r_e} = \sigma_{re}$,可确定积分常数 C_1、C_2,经简化后得到弹性应力解。

$$\sigma_r = b(\lambda + G) \ln r - 2GC_2 \frac{1}{r^2} + 2(\lambda + G) C_1 + \frac{b}{2}(\lambda + 2G) + \frac{\lambda}{\lambda + 2G}(\sigma_{ze} - \beta p_r) + \beta P$$

$$\sigma_\theta = b(\lambda + G) \ln r + 2GC_2 \frac{1}{r^2} + 2(\lambda + G) C_1 + \frac{b}{2}\lambda + \frac{\lambda}{\lambda + 2G}(\sigma_{ze} - \beta p_r) + \beta P \tag{8}$$

$$\sigma_z = b\lambda \ln r + 2\lambda C_1 + \frac{b}{2}\lambda + (\sigma_{ze} - \beta pr) + \beta P$$

式中 ε_r^e、ε_θ^e、ε_z^e—分别为径向、切向和垂向弹性应变;
σ_r、σ_θ、σ_z—径向、切向和垂向应力,MPa;
r_e、r_w—油藏和井筒半径,m;
P_r、P_{wf}—分别为油藏边界压力和井底流压,MPa;
σ_{ze}—远处地层垂向应力,MPa;
σ_{re}—远处地层径向应力,MPa。

使用方程 (8) 计算表明,在井壁上切向应力最大,径向应力最小。将 $r = r_w$ 代入切应力方程可得到井壁的切应力 $\sigma_{\theta w}$,孔壁上的径向应力 $\sigma_{rw} = p_{wf}$。岩石的破坏判据采用考虑地层孔隙流体压力的莫尔—库仑破坏准则:

$$\sigma_1 - \beta \cdot p = 2S_0 \tan\alpha + (\sigma_3 - \beta \cdot p) \tan^2\alpha \tag{9}$$

将 σ_1 用 $\sigma_{\theta w}$ 替换,σ_3 用 σ_{rw} 替换可得到关于井底流压 P_{wf} 的临界平衡方程,认为 $r_e \gg r_w$,求解可得到出砂临界生产压差模型:

$$\Delta P_c = P_r - \frac{2C_0 \tan\alpha - \frac{2\mu}{1-\mu}\sigma_{ze} - \frac{2\mu}{1-\mu}\beta P_r}{\frac{2\mu}{1-\mu}\beta - 2} \tag{10}$$

式中 σ_1、σ_3—莫尔-库仑准则中的最大、最小应力,MPa;
$\sigma_{\theta w}$、σ_{rw}—井壁上的切向、径向应力,MPa;
$\triangle P_c$—出砂临界生产压差,MPa。

2 经验出砂预测方法

经验方法是定性出砂预测,通过测井资料分析、室内岩心试验、现场资料统计分析和必要的计算来预测地层是否可能出砂和出砂的程度。这些方法主要包括声波时差法、出砂指数法、斯伦贝谢法和组合模量法。

2.1 声波时差法

利用纵波时差预测地层出砂情况:当 $\Delta t_v < 312\mu s/m$ 时,地层稳定不出砂;当 $312\mu s/m \le \Delta t_v \le 345\mu s/m$ 时,地层可能出砂;当 $\Delta t_v \ge 345\mu s/m$ 时,地层砂岩不稳定,极易出砂。

2.2 组合模量法

组合模量法是根据声波测井和密度测井资料,计算岩石的弹性组合模量,进而进行出砂预测,地层岩石的组合模量为:

$$E_c = \frac{9.94 \times 10^5 \times \rho_r}{\triangle t_v^2} \tag{11}$$

当 $E_c \ge 2.0 \times 10^4$MPa时,地层不出砂;当 1.5×10^4MPa$\le E_c \le 2.0 \times 10^4$MPa时,地层轻微出砂;当 $E_c \le 1.5 \times 10^4$MPa时,地层严重出砂。

2.3 出砂指数法

出砂指数 B反映岩石体积弹性模量 K和切变弹性模量 G之和,出砂指数越大,地层越不易出砂。

$$B = K + \frac{4}{3} G \tag{12}$$

根据现场经验,当 $B \ge 2.0 \times 10^4$MPa时地层不出砂或出砂轻微;当 2.0×10^4MPa $> B > 1.4 \times 10^4$MPa时,地层出砂;当 $B \le 1.4 \times 10^4$MPa时,地层严重出砂。

2.4 斯伦贝谢法

斯伦贝谢法主要考察岩石剪切模量与体积模量的乘积,R值越大岩石强度越大,地层稳定性越好,越不易出砂。当 $R < 5.9 \times 10^7 MPa^2$ 时,地层可能出砂。

$$R = K \cdot G \tag{13}$$

式中 Ec—岩石弹性组合模量,MPa;
K、G—岩石体积和切变切变弹性模量,MPa;
R—斯伦贝谢比,MPa^2;
B—出砂指数,MPa。

3 出砂预测结果及分析

3.1 单井预测结果分析

涩北气田的层系划分为：零层组 410m～630m，I层组 630m～930m，II层组 946m～1114m，III层组 1142m～1397m，Ⅳ层组 1423m～1599m，采用上述方法对涩 3-8井进行了各层组的出砂预测。将预测点取平均值后可以得到不同开发层系的经验出砂预测平均结果，如表 1所示。通过预测可知，涩 3-8井不同开发层系的出砂可能性均较大，但随着井深加深，出砂趋势略有减弱。

根据涩 3-8井临界生产压差纵向分布预测结果，对预测结果曲线取“主线”，反应临界压差的变化趋势：随着埋藏深度的增加，出砂趋势减弱，临界生产压差逐渐变大。对各开发层系的预测结果取平均值，得到从上到下 5个不同开发层系的平均临界生产压差分别为 1.16MPa；1.39MPa；1.72MPa；1.97MPa；2.17MPa。

表 1 涩 3-8井不同开发层系经验法出砂预测结果

开发层系	纵波时差 us/m	判断结论	出砂指数 10^4MPa	判断结论	组合模量 10^4MPa	判断结论	斯伦贝 10^7MPa^2	判断结论
零	505.38	易出砂	0.34	严重出砂	0.888	严重出砂	0.219	出砂
I	467.37	易出砂	0.398	严重出砂	1.064	严重出砂	0.294	出砂
II	422.11	易出砂	0.482	严重出砂	1.328	严重出砂	0.432	出砂
III	395.41	易出砂	0.538	严重出砂	1.508	轻微出砂	0.536	出砂
Ⅳ	372.8	易出砂	0.589	严重出砂	1.672	轻微出砂	0.633	出砂

3.2 预测结果分析

采用涩 3—8井同样方法，共研究了涩北 1号气田 20口气井的出砂预测资料，如表 2所示。通过对 20口气井不同开发层系临界生产压差取平均值后，得到涩北一号气田平均临界生产压差分别为零层系 1.086MPa；I层系约 1.35MPa；II层系约 1.71MPa；III层系约 1.93MPa；Ⅳ层系约 2.14MPa。

涩北 1号气田目前投入生产的气井，主力开发层系为 III、Ⅳ开发层系。根据气井的生产测试资料，经过涩北 1号气田 14口生产气井 III开发层系的实际临界出砂生产压差的统计，求得平均值为 1.89MPa，而预测值为 1.93MPa，相对误差仅 2%，预测结果与实际值基本吻合。

4 结论与建议

(1) 针对涩北气田特征及出砂预测存在的问题，研究出一套使用测井资料估算岩石力学参数进而进行出砂和临界生产压差预测的方法，通过涩北 1号气田部分气井的计算，预测结果与现场实际观测结果对比表明，该方法用于涩北气田的出砂预测是可行的。

表 2 20口井临界生产压差统计平均值

井号	临界生产压差 (MPa)				
	零	I	II	III	Ⅳ
涩 2-5	1.11	1.43	1.84	2.00	
涩 2-9		1.33	1.68	1.96	
涩 2-14	0.92	1.35	1.59	1.81	
涩 3-2-4	0.84	1.16	1.5	1.79	
涩 3-3	1.09	1.37	1.77	2	1.95
涩 3-7	1.14	1.33	1.69	1.94	2.1
涩 3-8	1.16	1.39	1.72	1.97	2.17
涩 3-13	1.85	1.47	1.92	2.11	2.38
涩 3-15	0.83	1.16	1.63	1.82	2.05
涩 3-21	1	1.36	1.68	1.88	2.09
涩 4-8	1.12	1.26	1.65	2.05	2.19
涩 4-9	1.92	1.69	1.98	2.17	2.35
涩 4-16	1.09	1.43	1.88	2.1	2.44
涩 23			1.56	1.8	2.11
涩 25	0.85	1.17	1.56	1.95	
涩 26	1.01	1.39	1.27	1.25	1.55
涩 30	1.21	1.48	1.91	2.14	2.31
涩试 2	0.77	1.46	1.68	2.01	2.27
新涩试 3	0.92	1.23	2	1.79	1.98
新涩试 4	0.71	1.13	1.6	1.86	2.12
平均值	1.0856	1.3468	1.7055	1.925	2.1382

(2) 计算结果表明，随着气层深度的增加，岩石压实强度增大，出砂临界生产压差增大，即对于较深的开发层系气井，可以适当放大生产压差进行优化生产。根据涩北 1号气田 20口 (下转第 53页)

新统岩心反向实验渗透率开始时下降明显，后下降趋缓，显示流体反向流动时有微粒运移现象，但很快形成了较坚实的桥堵，正向流动时渗透率变化小，显示无明显的微粒运移。阳新统岩心正反向岩心渗透率差别大，岩心存在有较明显的不均质性。

以上分析结果与表 1中速敏实验评价结果对比可以看出，二者一致性良好。

3 地质分析辅助判断

在流体作用下，易运移的储层微粒一般是储层岩样中，被胶结的粘土矿物微粒或依附于孔隙内表面的松散颗粒。因此用储层岩心的相关地质资料，主要是岩心矿物成分、胶结状态的观察分析结果，可以辅助判断，岩心有无易运移的地层微粒及微粒运移发生的难易程度。

一般来讲，碎屑含量高，胶结弱的储层岩心，易产生微粒运移，导致岩心速敏损害；含泥质重的岩心，由于粘土含量相对较高，胶结弱，也易产生微粒运移现象；酸不溶物含量大的岩心，在酸化后返排时发生微粒运移可能影响酸化效果。

表 1中，川中大安寨岩心与其它储层相同渗透率级岩心相比速敏性明显较强，就可能与其矿粒及酸不溶物含量较高有关，其矿粒及酸不溶物含量分别为 2.55%～36.47%、4.16%～42.48%，平均 9.78%、12.7%。而川东石炭系只有 0.26%～7.9%，平均 2.6%[4]。

4 结论

(1) 速敏评价实验，是判断储层岩心有无微粒运移现象的基本方法。速敏实验中，岩心渗透率只要随流体流速增加发生明显变化 (降低或增加) 均可认为，岩心存在不同状态的微粒运移现象，并可确定由于微粒运移而导致岩心渗透率明显变化的临界流速。

(2) 正反向流动评价实验，是判断岩心在一定流速下，是否产生微粒运移的有效方法。根据正反向流动实验曲线中，渗透率的变化，可以判断微粒运移状况。交叉型曲线意味着岩心有明显的微粒运移；渗透率的波动，显示了岩心中细小微粒运移时，喉道处堵塞与解堵频频发生的过程。

(3) 可利用储层岩矿成分分析及胶结状态下观察的结果等地质分析资料，来预测或验证岩心微粒运移现象的发生状况。

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井单井纵向临界压差预测结果的统计分析，涩北 1号气田零、Ⅰ、Ⅱ、Ⅲ、Ⅳ层系的平均临界生产压差分别为 1.086MPa; 1.35MPa; 1.71MPa; 1.93MPa和 2.14MPa。

(3) 为了得到更具有普遍意义的预测结果，应该进一步扩大预测井号范围，研究不同开发层系临界生产压差的平面分布特征。

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DISCUSSION ON OIL - GAS ORIGIN IN DIXI REGION, JUNGGAR BASIN [1)]

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ABSTRACT: Through the evaluation on Carboniferous, Permian and Jurassic source rock in Dixi region of Junggar Basin, and the analysis on the oil & gas geochemical characteristics, the oil and gas origin and their distribution in this region are clarified so as to provide advantageous guidance for further exploration. By adopting the method of oil - rock and oil - oil correlation and applying carbon isotope and biomarker combining with data of physical property etc, the oil and gas of this region are classified and their origins are also approached. The oil and gas source correlation shows that the crude oil of this region may be divided into 2 types with the first one originating from Permian Pindiquan formation source rock of north Dongdaohaizi sag and Shinan sag, and the second one from Carboniferous source rock of these sags. The gas in the region can be classified into 2 types: the first one is the same source as the first type crude oil; the second one originated from Carboniferous and Jurassic source rock of north Dongdaohaizi as well as Shinan sags and is dominated by the former.

KEY WORDS: Junggar Basin, crude oil, gas, origin

GAS - WATER DISCERNMENT OF FEIXIANGUAN FORMATION OOLITIC BANK GAS RESERVOIR IN NORTHEAST SICHUAN REGION [1)]

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ABSTRACT: The technique of COBEN prestack reservoir inversion and gas reservoir hydrocarbon detection is based on discrete media geophysical model proposed by Russian scientist В П Сибиряков. The greatest peculiarity of this technique is that the prestack seismic data is specially processed under the prerequisite of no well constraint, from which the porosity, AVD and DR anomaly etc. capably reflecting parameters of reservoir physical property and oil - gas - bearing nature, are inversed; and again the reservoir physical property prediction research effectively launched by using the above parameters. This technique is utilized to conduct reservoir prediction and gas - water discernment for survey lines of northeast Sichuan areas as Dukouhe, Qilixia, Pusadian, Wubaochang, Yangjiaping, Luojiaba and Dongsheng etc. fairly corresponding to the well circumstances, and the regional prediction has been confirmed in north Qili area. This technique is an effectual method in gas - bearing formation prediction.

KEY WORDS: reservoir, parameter, inversion, detection, technique

DISCUSSION ON CO_2 FRACTURING STIMULATION OF ZHONGYUAN OIL FIELD [2)]

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ABSTRACT: Hydraulic fracturing is the major measure of exploration and production for low permeable reservoirs, which is decided by the geological characteristics of Zhongyuan oil field. The production increasing is not ideal for the low - pressure and water - sensitive reservoirs and the deep condensate gas reservoirs to use the conventional fracturing techniques and the water - base fracturing fluid for stimulation. To solve the problems, new ways are explored. Zhongyuan oil field imports the CO_2 tank truck and CO_2 boosting pumps made by American SS Com.. Cooperating with Schlumberger, it is completed to equip the surface workflow of CO_2 fracturing and modify the fracturing trucks of CO_2 injected by pumps. Under the guide of Schlumberger technicians, the jobs of CO_2 fracturing are conducted for 5 wells. On basis of the jobs, we sum the experiences and lessons of the previous jobs, complete the design and operation of CO_2 foam fracturing for 5 wells independently and achieve preliminary success.

KEY WORDS: fracturing, low - permeable reservoir, foam, CO_2

SEBEI GAS FIELD SANDING PREDICTION BY CRITICAL PRODUCING PRESSURE DROP [1)]

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ABSTRACT: Qinghai Sebei gas field is severely sanded. Because of hard drill - coring, it is difficult to obtain sufficient rock - mechanical parameters by this experiment conducting systematical and overall prediction. Through such data as sonic wave, density, and natural gamma etc obtained by well logging, the empirical method of finding such rock - mechanical parameters as Poisson ratio, elastic modulus, cohesion strength, internal - friction angle etc. has been studied, and the sanding and sand - controlling prediction model of no. 1 Sebei gas field wells established. Based on the prediction result statistics of sanding index and critical producing pressure drop of the developing reservoir in no. 1 Sebei gas field 20 wells, the prediction result is basically coincident with that of on - site observation, thus an applicable method of theoretical research on sanding prediction, reasonable selecting the producing pressure drop, and optimizing the allocation is proposed for Sebei gas field.

KEY WORDS: Sebei gas field, critical pressure, sanding, prediction

PARAMETER DESIGN OF ' GAS RECOVERY BY LIQUID DRAINAGE ' TECHNIQUE WITH GAS LIFT BY GAS - LIFT VALVE FOR GAS WELLS 2)

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ABSTRACT: The liquid drainage by induced flow of gas wells with gas lift by gas - lift valve is different from the oil recovery of oil wells with gas lift by gas - lift valve because they have different flow states in the bore - holes. It is difficult for induced flow of gas wells to achieve success if simply following the design mode of oil recovery of oil wells with gas lift by gas - lift valve. Based on the working principle of gas - lift valve, the characteristics and the affecting factors of ' gas recovery by liquid drainage ' technique with gas lift are described. The parameters of ' gas recovery by liquid drainage ' technique with induced flow by gas - lift valve are designed. And the corresponding program is made. Good results of application have been achieved.

KEY WORDS: gas - lift valve, gas recovery by liquid drainage, technique parameter

MOVABLE WATER EXPERIMENTS OF QIAO - BAI GAS RESERVOIRS 2)

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ABSTRACT: Tight gas reservoirs usually have high content of irreducible water, but some gas wells also produce water. It is difficult to explain the phenomena. The centrifugal capillary pressure method, the performance method of gas - drive water, and the nuclear magnetic resonance method are used to determine the irreducible water saturation of the gas reservoir. The well logging method is used to determine the original water saturation. Then, the movable water saturation can be determined. According to the percolation experiments with the typical cores acquired from Qiaokou and Baimiao tight gas reservoirs of Zhongyuan Oilfield, the water saturation of the cores decreases and the effective permeability of gas phase increases gradually as the gas flow rate increases. Therefore, the water saturation is not a constant for a gas reservoir that has big original water saturation, which explains the reason why the gas wells in the tight gas reservoirs produce water.

KEY WORDS: irreducible water, low permeable gas reservoir, capillary pressure, fluid, nuclear magnetic resonance

OPTIMIZATION METHOD OF FOAMING AGENT AND ITS INJECTING CONCENTRATION BASED ON MINIMUM FLOW