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压裂充填防砂井产能预测方法*

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摘要 产能预测是进行压裂防砂优化设计的基础。首先预测压裂对产能的影响，得到压裂增产倍数；计算射孔孔眼砾石层及环空砾石层的附加表皮因数，用砾石充填后产能比考虑炮眼和筛套环空砾石充填对产能的影响；压裂增产倍数与砾石充填产能比的乘积即为压裂充填防砂后的总产能比。根据防砂前流入动态可得压裂充填防砂后的流入动态曲线。采用该方法对吐哈油田颜6—8井进行了产能预测，计算结果与实际产能基本吻合。

关键词 防砂 产能预测 增产倍数 产能比 表皮因数

压裂充填防砂是一种水力压裂与井筒砾石充填相结合的新型防砂技术。通过压裂建立短而宽的高导流能力裂缝，改变井筒附近渗流方式，通过井筒砾石充填建立有效的挡砂屏障，发挥压裂的增产作用与砾石层的挡砂作用，达到既增产又防砂的目的[1]。

压裂充填防砂后油井产能预测是进行压裂充填防砂设计及经济效果预测的基础，而对压裂防砂井产能预测方法研究不多。下面以油井防砂前的流入动态为基础，通过压裂增产倍数和砾石充填产能比计算总产能比，建立压裂充填防砂后油井的流入动态预测模型。

1 压裂充填防砂井井筒附近特征

对压裂充填防砂井，压裂后继续进行管内充填，使炮眼及筛管与套管的环空中充满砾石。由于压裂充填井作业后产量一般较高，井底附近尤其是充填砾石的炮眼内流体流速很高，炮眼砾石层及环空砾石层的流动阻力不可忽略，砾石层势必对油井产能造成影响。压裂充填防砂井井底附近结构见图1。

压裂充填防砂对产能有2方面的影响：一是压裂造成的高导流能力裂缝的增产作用；二是由于井筒砾石充填增加流动阻力而造成的减产作用。因此，压裂防砂井的产能预测可以从这2个方面进行考虑。

2 压裂充填防砂井产能预测方法

压裂对油井产能的影响可通过增产倍数来考虑，而井筒砾石充填对油井产能的影响则通过防砂产能比来考虑。将压裂充填防砂视为压裂与砾石充填的复合，用总产能比表示压裂充填防砂后油井产能与防砂前产能的比值，则总产能比为增产倍数与防砂产能比的乘积

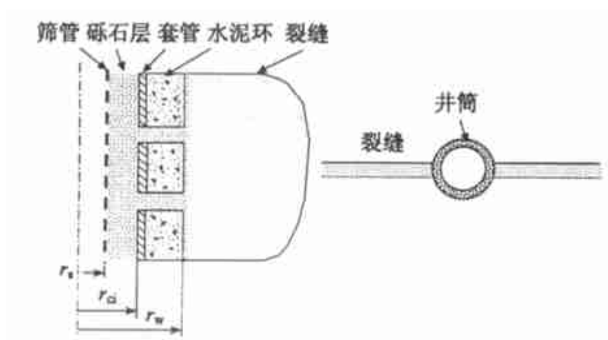

图1 压裂充填防砂井底示意图

$$R = R_p R_s \tag{1}$$

2.1 压裂增产倍数

增产倍数是压裂前后油气井采油指数的比值，它与油层和裂缝参数有关。对垂直缝压裂井，麦克奎尔—西克拉用电模型作出了垂直裂缝条件下增产倍数与裂缝几何尺寸和导流能力的关系

$$R_p = \frac{J_f}{J_o}\left[\frac{7.13}{\ln(0.472 r_e / r_w)}\right] = 1 + M \arctan\left(\frac{59 L_f}{r_e M}\right) \tag{2}$$

$$M = 7.27 + 6.09 \arctan\left(0.524 \ln \frac{X}{3}\right) \tag{3}$$

$$X = 3.28 \times 10^{-5} \frac{k_f W_f}{k} \sqrt{\frac{40}{2.471 A \times 10^{-4}}} \tag{4}$$

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$$W_{\mathrm{f}}=\frac{100C_{\mathrm{p}}}{(1-\phi_{\mathrm{p}})\cdot\rho_{\mathrm{p}}} \tag{5}$$

2.2　砾石充填防砂产能比

砾石充填产能比是油井砾石充填前后产能的比值，用来表示砾石充填对油井产能造成的影响[2]。对于压裂充填防砂井，砾石充填产能比可用下式计算

$$R_{\mathrm{s}}=\frac{\ln\frac{0.472r_{\mathrm{e}}}{r_{\mathrm{w}}}+S+S_{\mathrm{p}}}{\ln\frac{0.472r_{\mathrm{e}}}{r_{\mathrm{w}}}+S+S_{\mathrm{p}}+S_{\mathrm{SC}}} \tag{6}$$

$$S_{\mathrm{SC}}=S_{\mathrm{g}}^{\mathrm{l}}+S_{\mathrm{g}}^{\mathrm{t}}+S_{\mathrm{a}}^{\mathrm{l}}+S_{\mathrm{a}}^{\mathrm{t}} \tag{7}$$

(1)炮眼砾石充填层的表皮因数。充填砾石的射孔炮眼内为单向线性流动，其层流和紊流表皮因数分别为

$$S_{\mathrm{g}}^{\mathrm{l}}=\frac{hk}{h_{\mathrm{p}}k_{\mathrm{g}}}\frac{2L_{\mathrm{p}}}{D_{\mathrm{s}}r_{\mathrm{p}}^{2}} \tag{8}$$

$$S_{\mathrm{g}}^{\mathrm{t}}=q\cdot\frac{2kh\beta_{\mathrm{g}}\rho BL_{\mathrm{p}}}{\mu h_{\mathrm{p}}^{2}D_{\mathrm{s}}^{2}\pi r_{\mathrm{p}}^{4}} \tag{9}$$

(2)环空砾石层表皮因数。套管与筛管的环空中充满砾石形成环空砾石层，计算其流动压降和表皮因数时可简化为锥形扩散流动，其达西和非达西流表皮因数分别为

$$S_{\mathrm{a}}^{\mathrm{l}}=\frac{2kh}{k_{\mathrm{g}}h_{\mathrm{p}}D_{\mathrm{s}}}\cdot\frac{r_{\mathrm{ci}}-r_{\mathrm{s}}}{r-r_{\mathrm{p}}}\left(\frac{1}{r_{\mathrm{p}}}-\frac{1}{r}\right) \tag{10}$$

$$S_{\mathrm{a}}^{\mathrm{t}}=q\cdot\frac{2kh\beta_{\mathrm{g}}\rho B}{3\mu\pi h_{\mathrm{p}}^{2}D_{\mathrm{s}}^{2}}\cdot\frac{r_{\mathrm{ci}}-r_{\mathrm{s}}}{r-r_{\mathrm{p}}}\left(\frac{1}{r_{\mathrm{p}}^{3}}-\frac{1}{r^{3}}\right) \tag{11}$$

若射孔相位角等于 0°或 180°

$$r=\sqrt{\frac{A_{\mathrm{r}}}{\pi h_{\mathrm{p}}D_{\mathrm{s}}}} \tag{12}$$

其中　$A_{\mathrm{r}}=2r_{\mathrm{s}}h_{\mathrm{p}}\arccos\left[\frac{r_{\mathrm{s}}-r_{\mathrm{p}}}{\sqrt{(r_{\mathrm{s}}-r_{\mathrm{p}})^{2}+r_{\mathrm{ci}}^{2}}}\right]$

若射孔相位角不等于 0°或 180°

$$r=\sqrt{\frac{2r_{\mathrm{s}}}{D_{\mathrm{s}}}} \tag{13}$$

2.3　产能预测计算程序

流入动态直接反映油井的供液能力，根据油井压裂充填前的生产测试资料可预测油井原始流入动态曲线或产液指数；然后根据上述方法计算压裂增产倍数和砾石充填产能比及总产能比，之后可计算压裂充填防砂后油井的流入动态曲线和产液指数。

设 I_{p0}为油井原始产液指数，则压裂充填防砂后的产液指数为

$$I_{\mathrm{p}}=RI_{\mathrm{p0}} \tag{14}$$

压裂充填防砂井产能预测步骤见图 2。

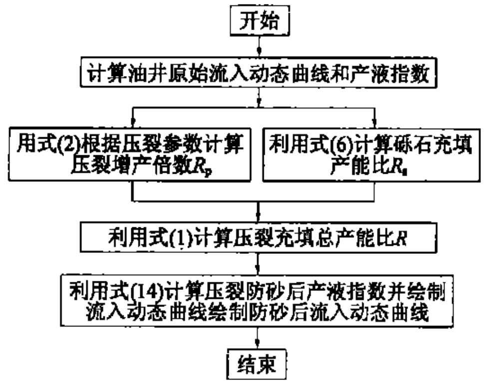

图 2　压裂防砂井产能预测计算框图

3　计算实例

吐哈油田雁 6－8 井基础数据及压裂充填防砂施工参数见表 1。

表 1　雁 6－8 井基础数据与施工参数

参数	数值
油层中深/m	1616
油层厚度/m	30.7
有效厚度/m	19.5
渗透率/$10^{-3}\mu m^2$	150
地层砂粒度中值/mm	0.138
地面原油粘度/mPa·s	3.66
套管外径/mm	139.7
油管外径/mm	73
油层静压/MPa	15.85
饱和压力/MPa	5.1
射开厚度/m	16.7
射孔密度/孔·m^{-1}	13
孔眼直径/mm	15
射孔相位/(°)	120
裂缝宽度/mm	8.8
裂缝长度/m	30
裂缝高度/m	32
生产压差/MPa	5.5
防砂后油井产液量/t·d^{-1}	19.8
含水率/%	1.94

用本研究方法对雁 6－8 井进行压裂充填防砂后的产能进行了预测，计算得到压裂增产倍数为 3.86，防砂产能比为 0.83，压裂充填后的总产能比为 3.2。预测的压裂充填后产液指数为 3.52t/(MPa·d)。预测得到的流入动态曲线见图 3。

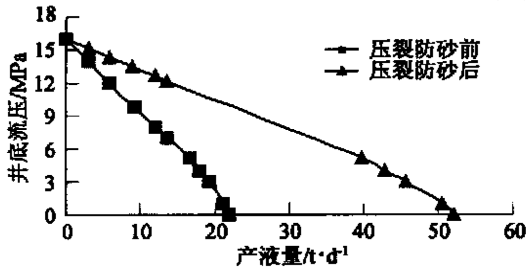

图 3　雁 6—8 井压裂充填前后流入动态曲线对比

该井于 2002 年 8 月进行压裂充填防砂后,效果良好。防砂前产液指数为 0.88t/(MPa·d),防砂后产液指数 3.64t/(MPa·d)。预测得到的产液指数与实际值误差 3.4%,与实际基本吻合。这表明利用本方法预测压裂充填防砂井产能是可靠的。

根据计算结果可知,压裂增产倍数大于 1,而防砂产能比小于 1,因此对于压裂充填防砂井,压裂措施对油井起增产作用,而砾石充填则起降产作用。但相比较增产占主导作用,在砾石、射孔等参数适当的情况下,砾石充填对油井产能的影响相对较小。

4　结论

(1)以油井原始流入动态为基础,利用增产倍数考虑压裂对油井的增产效应,用砾石充填产能比表示砾石充填对油井的降产效应,建立了一套压裂充填防砂井的产能预测方法。实例应用结果表明,利用该方法预测压裂充填防砂井产能是可行的。

(2)对于压裂充填防砂井,压裂措施对油井起增产作用,井筒砾石充填起减产作用,但压裂增产占主导作用,砾石充填对油井产能的影响相对较小。

(3)井筒砾石充填压裂防砂既获得了较好的挡砂效果,又提高了油井产量,具备压裂防砂条件的油井可优先考虑井筒砾石充填压裂防砂技术。

符　号　说　明

A——井控制面积,m^2;
B——原油体积系数;
D_s——射孔密度,孔/m;
h——油层厚度,m;
h_p——油层射孔段长度,m;
J_o、J——压裂前后的采油指数,$m^3/(MPa \cdot d)$;
k——地层渗透率,m^2;
k_f——支撑剂充填层渗透率,m^2;
k_g——砾石层原始渗透率,m^2;
L_p——射孔孔眼长度,m;
q——产油量,m^3/s;
r——筛管上锥形扩散底面圆等效半径,m;
r_{ci}——套管内半径,m;
r_e、r_w——供油半径及井半径,m;
r_p——射孔孔眼半径,m;
r_s——筛管半径,m。
R——压裂充填防砂总产能比,无量纲;
R_p——压裂增产倍数,无量纲;
R_s——砾石充填防砂产能比,无量纲;
S——油井固有表皮因数,如井斜、部分射开等造成的表皮因数;
S_a^l——筛套环空砾石层层流表皮因数;
S_a^t——筛套环空砾石层紊流表皮因数;
S_g^l——砾石充填炮眼层流表皮因数;
S_g^t——砾石充填炮眼紊流表皮因数;
S_p——为射孔表皮因数;
S_{SC}——由于砾石充填造成的附加表皮因数,对于压裂充填防砂井,S_{SC}包括流体通过炮眼砾石层、筛套环空砾石层的层流和湍流表皮因数以及通过筛管的表皮因数,由于筛管渗透率较高,其表皮因数可忽略;
W_f——支撑缝宽,cm;
β_g——炮眼砾石层紊流速度系数,m^{-1};
μ——原油粘度,Pa·s;
ϕ_p——支撑剂充填层孔隙度,小数;
ρ_p——支撑剂颗粒密度,kg/m^3。

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in Qibei-3 well. The rate of penetration of the TSP bit is bring up 56% ~67% on other bit. The developed TSP bit has widest applying foreground.

Key words formation property strength of rock TSP bit application

NEW PATTERN AND ITS RULES OF OIL NON-DARCY FLOW IN POROUS MEDIA

by Yao Yuedong, Ge Jiali, (Institute of Petroleum and Gas Engineering, University of Petroleum)

Abstract Through the application of dimensionless analysis, the data of fluid flow in porous media have been plotted to log-log type curve. In order to understand the rule of fluid flow in porous media. Based on test of much core, the pattern of petroleum flow in porous media have five forms: high speed, sub-high speed, linear, low velocity and super low velocity. And the marginal values of them have been obtained. Summarize, all pattern's equation can be described as follows: . The physical and mechanical analysis of low velocity and super low velocity patterns has demonstrated the same conclusion with the experiment. And the starting pressure gradient has been demonstrated. Based on the new non-Darcy flow theory, typical examples of transient flow are studied. It is clear that the new non-Darcy model proposed here has significant advantages for study on fluid flow in porous media, and it can guide oilfield development.

Key words non-darcy flow in porous media flow pattern

DISCUSSION OF THE PERMEABILITY INCREASING MECHANISM OF THERMAL TREATED ROCK

by Liu Junrong, Wu Xiaodong, (University of Petroleum)

Abstract An experimental study of high-temperature treatment was carried out on a lot of rock samples, which come from reservoir formation, to determine the effect of thermal treatment on permeability and porosity, which were measured under the atmospheric pressure and room temperature. Results indicated that the changes of permeability and porosity exist a threshold temperature and they increased with increasing temperature in the rang of 100 ℃ to 800 ℃. Up to 800 ℃, permeability increased two orders and porosity increased ten times. According to these experiment results, the permeability increasing mechanism of thermal treated rock was discussed and analyzed in this paper from the theories of pore structure characteristic、mineral dehydration and destruction、thermal stress concentration、chemical bond breakage、stress relaxation and so on.

Key words Rock Thermal Fracturing Permeability Increasing Mechanism Analysis

SOME PROBLEMS IN DEVELOPMENT AND PRODUCTION OF GAS CONDENSATE RESERVOIRS

by Li Xiangfang, Cheng Shiqing, Qin Bin, Tong Min, Guan Wenlong, (Institute of Petroleum and Gas Engineering, University of Petroleum)

Abstract The problems existed in traditional model of condensate and gas distribution in gas condensate reservoirs are pointed out in the paper. Three-zone model of flow in porous media is recommended, and multi-zone and multi-phase model of condensate and gas distribution in gas condensate reservoirs is firstly presented. The varying characteristics of dew point pressure and condensate and gas relative permeability during different development and production phases are analyzed. The concept of condensate and gas relative permeability varying with production is introduced into gas condensate well test analysis. The analysis methods of transient well test and production well test based on multi-zone and multi-phase condensate and gas distribution model are advanced. The present problems in determining production pressure difference of gas condensate reservoirs are indicated and principles and method to acquire reasonable production pressure difference are emphasized.

Key words gas condensate reservoirs relative permeability Well test production pressure difference

NEW MODEL FOR FRAC-PACKED WELL PRODUCTIVITY PREDICTION

by Qu Zhanqing, Zhang Qi, Dong Changyin, (University of Petroleum); Wang Dengqing

Abstract The productivity Prediction of the frac-packed well is the basis of frac-pack design. Stimulation effect caused by fracturing can be estimated by stimulation ratio. The effect of gravel-packing in screen-casing annular and perforations on the well productivity can be shown by gravel-pack productivity ratio, which can be calculated by the additional skin factor. The total productivity ratio of the frac-pack means the product of simulation ratio and gravel-pack productivity ratio. According to the IPR before the frac-pack job, which can be calculated by the testing data, the IPR curve of frac-packed well can be obtained, and the case study of Yan 6-8 well in Tuha oilfield proves the reliability of this new model.

Key words sand control productivity prediction stimulation ratio productivity ratio skin factor

FUZZY IDENTIFICATION AND QUANTATIVE CALCULATION METHOD FOR BIG PORE THROAT

by Liu Yuetian, Sun Baoli, (Institute of Petroleum and Gas Engineering, University of Petroleum,); Yu Yongsheng

Abstract Basing on the expert system fuzzy identi-