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筛管砾石充填井筒附近压降计算方法

A New Calculation Method of the Pressure Drop Around the Wellbore of a Gravel-packed Perforated Well

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摘要: 认识到套管射孔砾石充填井井筒附近压降发生在 3 个流动区域内, 近井地带向射孔炮眼的汇聚流动区域, 炮眼内砾石层的线性流动区域以及筛套环空砾石层中的发散流动区域 以 Bernoulli 压降方程为基础导出了计算向炮眼的汇聚流产生的压降的新方法 以 Forchheimer 方程为基础导出了筛套环空锥形发散流的压降简化计算公式 结果表明: 井筒附近压降主要发生在汇聚流区域和炮眼内砾石层, 而环空砾石层的压降相对较小; 射孔参数及砾石渗透率是影响砾石充填井井筒附近压降的主要因素, 砾石充填井应采用孔径大于 15mm, 孔密 30 孔/m 左右的参数射孔, 砾石层渗透率至少应保持在 30～40μm² 以上

关键词: 防砂; 砾石充填; 炮眼; 压降; 计算模型

中图分类号: TE257⁺.3　　文献标识码: A

套管射孔砾石充填井中, 由于套管射孔炮眼的存在, 在距井筒一定距离处, 流体开始受套管和射孔炮眼的影响, 形成向炮眼的汇聚流动 在填满砾石的射孔炮眼中, 流体则是单向流动, 而在筛套环空砾石层中, 流体的流动是以射孔孔眼为起点向筛管的发散流动 这 3 个流动区域的压降构成了流体在井筒附近的主要压降(图 1). 以往的计算中, 通常不考虑地层向炮眼的汇聚流动产生的压降, 但实际上, 尤其低孔密时, 这个压降是不可忽略的 本文将以 Bernoulli 压降方程[2]为基础导出计算向炮眼汇聚流动产生的压降的新方法 筛套环空砾石层的发散流动不规则难以准确描述, 通常是将这种流动简化为单向流[3]或径向流[4], 但计算结果分别远远高于和低于实际值[5]. Yildiz T. 和 Langlinais J. P. 给出了描述这种发散流的数学模型[5], 但因模型求解复杂而难以实际应用, 并且没有考虑非达西流影响 下面将这种发散流简化为规则的锥形流, 首先确定锥底尺寸, 然后根据 Forchheimer 方程考虑达西流和非达西流推导计算压降的简化公式

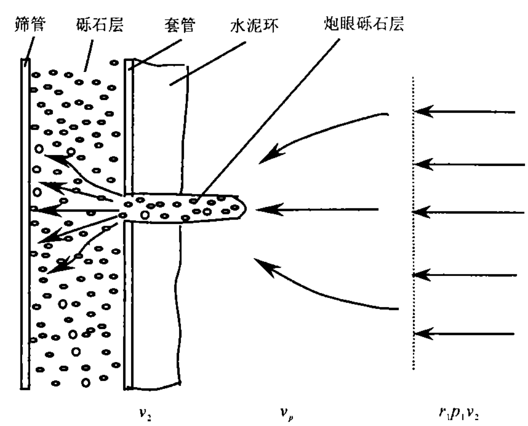

图 1　砾石充填井筒附近流动示意图

1　汇聚流压降模型

裸眼完井中, 由 Bernoulli 压降方程:

$$-\mathrm{d}p = \frac{1}{2}\rho \mathrm{d}v^2 + \mathrm{d}p_1 \quad (1)$$

得到汇聚流开始处到井筒之间的流动压降表达式:

$$p_1 - p_w = \frac{1}{2}\rho[v_2^2 - v_1^2] + p_1 \quad (2)$$

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式中: dp 为总压力损失MPa; $\frac{1}{2}\rho dv^2$ 为惯性压力损失MPa; dp_1为摩擦压力损失MPa; p_1为汇聚流开始处的压力,MPa; p_w'为裸眼井中井筒内压力MPa; ρ 为原油密度, kg/m^3; v_2 为流体在井筒边界 $r=r_w$ 处的流速,m/s; v_1 为汇聚流开始处的流速,m/s; p_1'为由于摩擦造成的压力损失, Pa.

为了求解 p_1', 将任一半径 r 处的流速 $v=\frac{q}{2\pi rh}$ 代入径向流 Forchheimer 方程

$$\frac{dp}{dr}=\frac{\mu}{k}v+\beta\rho v^2 \qquad (3)$$

并将方程两端从 $r=r_1(p=p_1)$ 到 $r=r_w(p=p_w')$ 之间积分也得到裸眼井汇聚流压降表达式:

$$p_1-p_w=\frac{q\mu}{2\pi k_f h}\ln\frac{r_1}{r_w}-\beta\rho\left(\frac{q}{2\pi h}\right)^2\left(\frac{1}{r_1}-\frac{1}{r_w}\right) \qquad (4)$$

式中: μ 为原油黏度, Pa·s; k_f 为地层渗透率, m^2; h 为油层射开厚度,m; r_1 为汇聚流开始处的半径,m; r_w 为井筒半径,m; β 为紊流速度系数,m^{-1}.

联立式(2), (4) 得到单位惯性压力损失下的摩擦压力损失

$$\frac{p_1}{\frac{1}{2}\rho(v_2^2-v_1^2)}=\frac{1}{\frac{1}{2}\rho(v_2^2-v_1^2)}\times\left[\frac{q\mu}{2\pi k_f h}\ln\frac{r_1}{r_w}-\beta\rho\left(\frac{q}{2\pi h}\right)^2\left(\frac{1}{r_1}-\frac{1}{r_w}\right)\right]-1 \qquad (5)$$

用 v_p 表示套管射孔完井中孔眼末端的流体汇聚流速, 则套管射孔完井中从 r_1 到孔眼末端的惯性压力损失为$\frac{1}{2}\rho[v_p^2-v_1^2]$. 根据单位惯性压力损失下的摩擦压力损失相等的原则, 有

$$\frac{p_1}{\frac{1}{2}\rho(v_2^2-v_1^2)}=\frac{1}{\frac{1}{2}\rho(v_2^2-v_1^2)} \qquad (6)$$

联立式(5), (6) 得到射孔完井中摩擦压力损失 p_1的表达式

$$p_1=\left[\frac{v_p^2-v_1^2}{v_2^2-v_1^2}\right]\times\left[\frac{q\mu}{2\pi k_f h}\ln\frac{r_1}{r_w}-\beta\rho\left(\frac{q}{2\pi h}\right)\left(\frac{1}{r_1}-\frac{1}{r_w}\right)\right]-\frac{1}{2}\rho(v_p^2-v_1^2) \qquad (7)$$

套管射孔完井, 从汇聚流开始处到射孔炮眼末端同样使用Bernoulli 方程得到

$$p_1-p_p=\frac{1}{2}\rho[v_p^2-v_1^2]+p_1 \qquad (8)$$

将式(7) 代入式(8) 整理得到套管完井从汇聚流开始到炮眼末端的压降方程

$$\Delta p_1=\frac{q\mu}{2\pi k_f h}\left[\frac{v_p^2-v_1^2}{v_2^2-v_1^2}\right]\left[\ln\frac{r_1}{r_w}-\frac{\beta\rho k_f q}{2\mu\pi h}\left(\frac{1}{r_1}-\frac{1}{r_w}\right)\right] \qquad (9)$$

根据已有研究结果[5], 汇聚流开始处的半径大约是井筒半径的 30 倍, 即 $r_1=30r_w$.

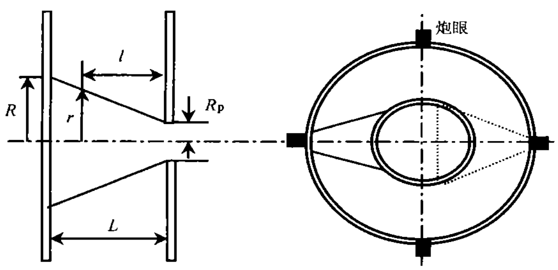
射孔孔眼末端流体流速用下式计算:

$$v_p=\frac{q}{2\pi h\rho_p r_p[L_p-(r_w-r_{ci})]} \qquad (10)$$

式中: ρ_p 为射孔密度,m^{-1}; r_p 为射孔炮眼半径,m; L_p 为射孔炮眼深度,m; r_{ci} 为套管内半径,m; Δp_1 为井筒附近汇聚流动区域压降,MPa.

2 砾石充填层压降模型

套管完井的油井进行砾石充填防砂后, 套管与筛管环空中充满砾石形成砾石层. 如图 1 所示, 砾石层中的流动是以射孔孔眼出口端为起点的不规则发散流动, 向筛管方向, 流体的流通面积变大, 流速降低, 为了便于描述这一流动, 将不规则的发散流简化为规则的锥形流动(如图 2 所示), 得到简化的锥型流压降模型.



(a)侧视图 (b)俯视图

图 2 锥形流示意图

2.1 锥形流底面半径的确定

假设由各射孔孔眼出口发散的锥形流到达筛管壁时, 各锥体的底面刚好铺满筛管外壁, 即各锥体底面积之和正好等于筛管外壁面积. 将各锥体底部的曲面圆等效为平面圆

$$h\rho_p\pi r_z^2=2\pi r_{so}h \qquad (11)$$

平面圆即锥体底部圆的半径为

$$r_z=\sqrt{\frac{2r_{so}}{\rho_p}} \qquad (12)$$

式中: L 为筛套环空间隙,m; r_{so} 为筛管外半径,m.

2.2 压降计算公式的导出

在锥形体中任取一截面 A, 到孔眼出口的距离为 l, 截面圆的半径为 r, 则

$$r = r_p + (r_z - r_p)\frac{l}{L} \tag{13}$$

每个射孔孔眼的流量及界面A 上流体流速分别为

$$q_p = \frac{q}{h\rho_p}, v = \frac{q_p}{\pi\left[r_p + (r_z - r_p)\frac{l}{L}\right]^2} \tag{14}$$

将式(14) 代入单向流 Forchheimer 方程得到

$$\frac{dp}{dl} = \frac{q_p\mu}{\pi k}\frac{1}{\left[r_p + \frac{r_z - r_p}{L}l\right]^2} + \frac{\beta_g\rho q_p^2}{\pi^2}\frac{1}{\left[r_p + \frac{r_z - r_p}{L}l\right]^4} \tag{15}$$

替换积分变量用 r 代替 l, 则

$$\frac{dp}{dr} = \frac{L}{r_z - r_p}\left[\frac{q_p\mu}{\pi k}\frac{1}{r^2} + \frac{\beta_g\rho q_p^2}{\pi^2}\frac{1}{r^4}\right] \tag{16}$$

将方程(9) 两边从 $r = r_p$ 到 r_z 分别积分, 得到环空砾石层中压降计算公式

$$\Delta P_2 = \frac{L}{r_z - r_p}\left[\frac{q_p\mu}{\pi k_g}\left(\frac{1}{r_p} - \frac{1}{r_z}\right) + \frac{\beta_g\rho q_p^2}{3\pi^2}\left(\frac{1}{r_p^3} - \frac{1}{r_z^3}\right)\right] \tag{17}$$

式中: μ 为原油黏度, Pa·s; k_g 为砾石充填层渗透率, m^2; β_g 为砾石层紊流速度系数, m^{-1}; Δp_2 为砾石充填层压降, MPa.

2.3 炮眼内砾石层压降计算

射孔炮眼内砾石层中的流动可以简单地视为单向流动, 压降为[4]:

$$\Delta P_3 = \left(\frac{q_p\mu}{\pi k_g r_p^2} + \frac{\beta_g\rho q_p^2}{\pi^2 r_p^4}\right)L_p \tag{18}$$

3 计算结果分析

(1) 将本文的环空砾石层压降模型与单向流、径向流以及 Yildiz T 和 Langlinais J P 的解析结果[5]比较, 压降随筛管尺寸变化的结果比较如表 1.

表 1 环空压降随筛管尺寸变化结果对比

筛管尺寸/mm	环空砾石层压降/MPa			
	单向流	径向流	Yildiz 模型	本文模型
101.6	1.3360	0.00274	0.1509	0.1153
76.2	1.7047	0.00396	0.1550	0.1625
52.4	2.0499	0.00556	0.1616	0.2268
38.1	2.2443	0.00682	0.1655	0.2825

基础数据: 产量 $140m^3/d$ 的油井, 原油黏度为 2mPa·s, 原油密度为 $870kg/m^3$, 射孔有效厚度 3m, 射孔密度 13 孔/m, 120 相位角, 套管内径193.7 mm, 筛管外径 101.6mm, 砾石层渗透率为 $40\mu m^2$.

表 1 的计算结果表明, 锥形流模型的计算结果基本接近于 Yildiz T 和 Langlinais J P 的计算结果; 线性流的结果是 Yildiz 的结果及本文结果的 8 倍左右, 而径向流的结果又太小. 这说明, 在砾石层的压降计算中, 用线性流或径向流作简化计算是不合理的; 锥形流模型作为一种简化的模型, 计算结果比较合理而且使用简便, 可以取代复杂的 Yildiz 模型应用于实际.

(2) 表 2; 图 3, 4, 5, 6 给出某砾石充填油井井筒附近各部分压降随射孔及砾石参数的变化关系. 计算得到的各部分压降分别为汇聚流压降 0.97MPa, 炮眼砾石层 2.28MPa, 筛套环空砾石层 0.033MPa. 基础数据: 射开厚度 12.4m, 地层渗透率 $1.4\mu m^2$, 90 相位射孔, 孔密 20 孔/m, 原油相对密度 0.88, 地下原油黏度 15mPa·s, 充填后砾石层渗透率 $25\mu m^2$, 产油 30t/d.

表 2 汇聚流压降随射孔参数的变化

孔径/mm	12	14	16	17
孔密/(孔·m^{-1})	16	20	24	30
汇聚流压降/MPa	2.06	1.12	0.67	0.37

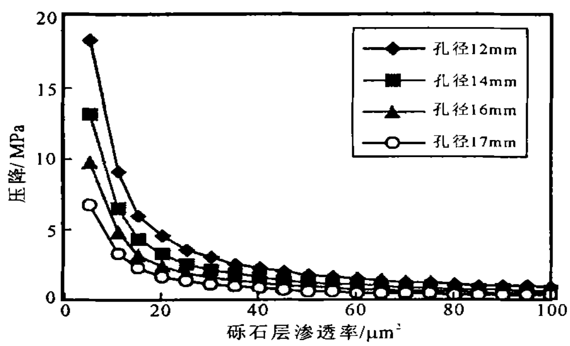


图 3 炮眼压降随砾石及孔眼参数变化
(孔密 20 孔/m)

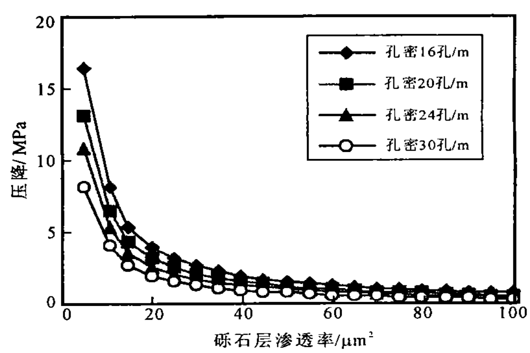


图 4 炮眼压降随砾石及孔眼参数变化
(孔径 14mm)

由计算结果可知, 筛套环空砾石层的压降随砾石层渗透率的变化较大, 但受射孔参数的影响很小;

与其他部分的压降相比, 环空砾石层压降所占比例很小, 在砾石层渗透率较高的情况下, 对砾石充填井的产能影响很小.

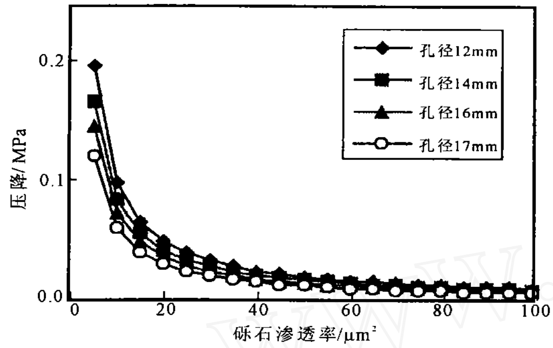


图 5　环空压降随射孔及砾石参数变化

(孔密 20 孔/m)

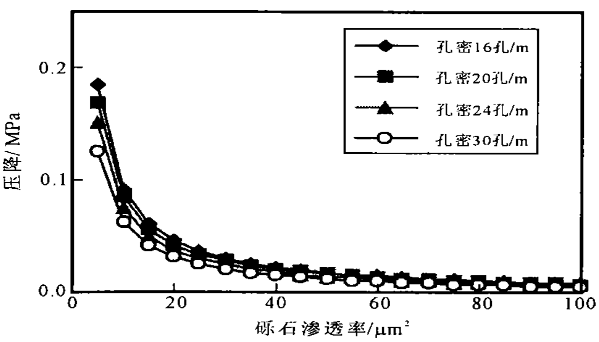


图 6　环空压降随射孔及砾石参数变化

(孔径 14mm)

砾石充填井井筒附近压降主要发生在炮眼砾石层和汇聚流动区域, 两者压降都随射孔参数变化较大, 随着孔眼流通面积的增大而减小. 由表 2, 图 3 和图 4 可以看到孔径大于 15mm、孔密在 30 孔/m 左右时, 无论是井筒附近汇聚流压降还是砾石层压降都比较小, 可获得较高的产能. 因此, 砾石充填作业前在套管强度允许的情况下, 应尽量采用大孔径、高孔密射孔或补孔, 孔径大于 15mm、孔密在 30 孔/m 左右为宜. 由图 3 和图 4 的比较还可知, 炮眼砾石层压降对孔径更为敏感, 增大孔径比增大孔密更能有效地降低井筒附近压降损失.

当砾石层渗透率低于 30～40μm^2 时, 炮眼及环空砾石层压降随渗透率的降低而急剧增大, 高于 30～40μm^2 时, 砾石层压降随渗透率变化趋于平缓. 因此实际砾石充填设计及作业中, 应尽量减小砾石在运输及泵送过程中的破碎, 以保持充填后的砾石层有较高的渗透率, 最少要在 30～40μm^2 以上, 否则会严重影响产能.

4　结论与认识

(1) 利用 Bernoulli 方程和 Forchheimer 方程分别导出了井筒附近汇聚流动的压降及筛套环空砾石层压降计算公式, 结合炮眼砾石层压降公式, 可以比较精确地计算砾石充填井井筒附近的压降损失.

(2) 在计算筛套环空砾石层中的的压降时, 按单向流或径向流简化得到的结果偏差较大. 锥形流简化模型计算结果在常用的 70～100mm 外径的筛管尺寸下与 Yildiz 模型的结果比较接近, 且计算简单, 可以取代其应用于实际.

(3) 砾石充填井井筒附近压降与射孔参数关系密切, 随着射孔流通面积的增加而减小. 建议在砾石充填作业前, 尽量采用大孔径, 高孔密射孔, 孔径大于 15mm, 孔密在 30 孔/m 左右为宜.

(4) 当砾石层渗透率低于 30～40μm^2 时, 砾石层压降随砾石层渗透率的降低而急剧增大, 高于这一临界值时变化平缓, 因此, 实际作业中应保证充填后的砾石层渗透率不低于 30～40μm^2.

参 考 文 献:

[1]　万仁溥, 罗英俊. 采油技术手册(第七分册 防砂技术)[M]. 北京: 石油工业出版社, 1991.

[2]　Okonkwo F C, Onyekonwu M O. New pseudo-skin model for flow convergence to perforation in competent formations[J]. JPSE 1997, (17): 217-228.

[3]　Harun Ates, Kelkar M G. Two-phase pressure drop predictions across gravel pack[J]. SPE37512, 1997.

[4]　Oyeneyin M B. Optimum gravel sizing for effective sand control[J]. SPE 24801, 1992.

[5]　Yildiz T, Langlinais J P. Pressure losses across gravel packs[J]. Journal of Petroleum Science and Engineering, 1991, (6): 201-211.

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measures of profile control is taken, the increase of oil recovery efficiency is less than that when profile control is carried out earlier.

Key words: profile control; water shutoff agent; crude oil; recovery efficiency

LI Ke-hua, ZHAO Fu-lin, JIAO Cui, et al (Department of Chemical Engineeing, Jianghan Petroleum Institute, Jingzhou 434102, Hubei, China) JXAPI 2002 V. 17 N. 2 p. 30-32

A New Calculation Method of the Pressure Drop Around the Wellbore of a Gravel-packed Perforated Well

Abstract: The pressure drop around the hole of a gravel-packed perforated well takes place in following three areas: the convergent flow area from near well zone to a perforation channel, the linear flow area inside a perforation channel, and the divergent flow area between casing and screen tube. In this paper, the new model of calculating the pressure drop in the convergent flow area is derived on the basis of Bernoulli equation, and the simplified formula of calculating the pressure drop in the divergent flow area is also presented based on Forchheimer equation. The results of several cases show that the main part of the pressure drop takes place in the convergent flow area and the linear flow area, and the pressure drop in the divergent flow area is very little. The results also show that perforating parameters and the permeability of packed gravel are the key factors of affecting the pressure drop. The diameter of perforation channels had better be more than 15mm, and perforation density should be above 30 holes per meter. For high productivity, the permeability of packed gravel should be 30～40 Darcy at least.

Key words: sand control; gravel pack; perforation channel; pressure drop; calculation model

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Computation of the Operation Ability of Coiled Tubing

Abstract: The stiffness of coiled tubing (CT) is poor. When it bears longitudinal compressive load, coiled tubing is easy to bend into sine curve or helical curve, which is called as destabilization. The destabilizing conditions of coiled tubing are discussed. The mechanical model of the coiled tubing in the hole of arbitray track is established, and its boundary conditions in trip-out and trip-in operations are presented. According to these, it can be determined whether the coiled tubing can reach to the expected position in wellbore and exert the force designed for completing the desired work, and the magnitude and direction of the forces borne by the coiled tubing are also calculated to determine whether its well-service operation is safe. If the forces designed for the operation can not be obtained only by the weight of the coiled tubing, a power pusher and a pump are required in order to supply high pressure liquid into CT. The numerical solution in this case can be obtained by iteration method. Two examples are given in the two cases, and the calculated results are identical with the measured ones.

Key words: coiled tubing; bending; destabilization; operation ability

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Diagnosis of the Working State of a Hydraulic Jet Pump Production System and Adjustment of Its Parameters

Abstract: In order to make a jet pump production system work under optimal conditions and to increase the efficiency of the system, a method is put forward of calculating the working parameters of the jet pump according to the data measured in surface. The parameters include the pressure ratio, flow rate ratio and efficiency. Based on the parameters, the working state of the jet pump production system can be deduced, and the faults of it can be diagnosed. The inlet pressure of the jet pump can also be obtained by the pressure ratio, and it can be used for acquiring the productivity curve of an oil well. The fault diagnosis of the jet pump production system is carried out by this method without the termination of pumping and the downhole measurement of data. Two examples show that the method is feasible and effective.

Key words: jet pump; oil well; diagnosis of working state; jet nozzle; vertical pipeline flow

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